A Synchronized Current Based Fault Location Algorithm for Parallel Transmission Lines

Abstract—**Accurately locating the faults on the transmission lines is important to fast service restoration and it has drawn attention from the researchers and engineers for years. The impedance-based fault locating algorithms are currently most widely used due to their convenient and economical implementations. However, a number of factors such as the line charging current, Capacitive Voltage Transformer (CVT) transient, inaccuracy of line parameters, synchronizing errors, etc. present challenges to these algorithms. These factors may introduce singnificant errors to the fault location results. In order to overcome these problems, a new fault location algorithm is proposed for the parallel transmission lines. This proposed algorithm uses the current signals from both terminals of the parallel lines. Simulations show that the performance of this new algorithm yields better results than previously presented techniques. This algorithm can totally eliminate the adverse effect of CVT transients and greatly reduce the impacts of time-synchronization error, inaccuracy of line parameters, the distributed charging current, etc. Comparisons with the traditional impedance-based algorithm are also included to demonstrate the superiority of this proposed algorithm.**

Index Terms—**fault location algorithm, parallel lines, impedance, protection relay, CVT transient, EMTDC**

I. INTRODUCTION

TRANSMISSION lines are often subject to faults and consequently isolated from the rest of the power systems by protective relays. If the fault locations are estimated accurately, the amount of time spent in searching for the faults can be kept at minimum and the service can be restored quickly. Fault location techniques have attracted the attention of researchers and engineers for a number of years. Many techniques have been proposed. Because of the constraint of right-of-way as well as economic considerations, parallel transmission lines are becoming very popular. Therefore, it is desirable to accurately pinpoint the fault locations on the parallel lines.

The impedance-based fault location algorithms are most widely used because of their easy implementations. These algorithms can be implemented as either an add-on feature to the digital relays and digital fault recorders (DFRs) or stand-alone functions in fault locators. The impedance-based algorithms can use either one terminal signals or multi-terminal signals. Because of the inherent limitation of one terminal algorithms as well as the development of communication technologies, multi-terminal algorithms are getting popular. With the introduction of synchrophasor based on the Global Positioning System (GPS), multi-terminal algorithms can produce more accurate results.

The majority of the existing impedance-based fault locating algorithms use the straightforward method to calculate the fault loop impedance (i.e. Z=V/I). However, it is sometimes difficult for these methods to achieve accurate results because a number of factors, such as the distributed line charging currents, CVT transients, inaccurate line parameters, fault resistance, time synchronization errors, etc. can introduce significant errors. For parallel transmission lines, mutual inductance is another source of errors.

CVTs are widely used in high-voltage systems because they provide a cost-efficient way of obtaining secondary voltages. However, their secondary outputs may fail to follow the primary voltage because of the energy storage elements in CVTs. During a line fault when the primary voltage collapses and the energy stored in the stack capacitors and the tuning reactor of a CVT needs to be dissipated, the CVT may generate severe transients with significant magnitude and relatively long duration. Many factors such as the fault inception angles, source impedance ratios, stack capacitors, ferroresonance suppression circuit and burden will influence the severity of the CVT transient. The voltage at the CVT point can be as low as a few percent of the nominal voltage after a fault. Such a small signal is buried beneath the CVT transient, making it very difficult to extract the desired nominal frequency components. If the fault location algorithm has to utilize the transient voltage signal, significant errors are inevitable.

In order to eliminate or reduce the abovementioned adverse impact on fault location results, this paper presents a new fault location algorithm for parallel lines that only uses the current signals. This new algorithm utilizes the synchronized currents from both terminals of the double circuits. With the wide application of GPS and the advancement of communication technologies among electric utilities, it is fairly convenient and economical to obtain the synchronized current signals from different terminals of the transmission lines. Synchrophasors are now available in some digital relays without any additional cost [1]. At the same time parallel transmission lines are very popular due to the limitation of right-of-way and economic reason. It is, therefore, desirable to locate the faults accurately for quick service restoration.

The rest of the paper is organized as follows: Part II describes the principle of the proposed algorithm. Part III presents the simulation results based on EMTDC [2] software. Comparisons with the previous algorithms are also included to show the superiority of the proposed technique. Part IV is a brief summary. It is worth mentioning that the simulation results are better than expected even when large synchronization errors, inaccuracy of line parameters and large capacitive charging currents are present.

II. PRINCIPLE OF THE PROPOSED ALGORITHM

This part describes the principle of the current-based fault location algorithm. Fig.1 shows a single line diagram of two parallel lines, each with a length of L. Fault occurs at F point of line 1 at the distance of D from terminal S. I_{S1}, I_{S2}, I_{R1} and I_{R2} are the currents of both terminals of the two parallel lines, where the subscripts S and R denote the terminal S and R respectively, whereas 1 and 2 denote line 1 and 2 respectively. V_S, V_R and V_F are the voltages of terminals S and R and the fault point F respectively.

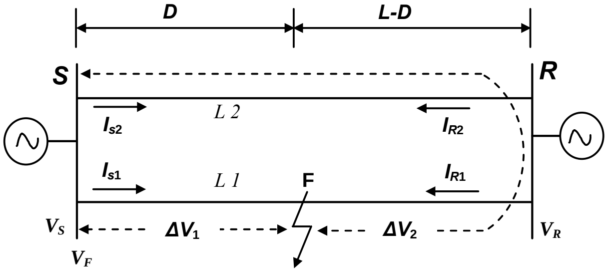


Fig.1. Single line diagram of a fault in line 1 of the parallel line pair

Define:

$$\Delta V_1 = V_S - V_F \qquad (1)$$

$$\Delta V_2 = (V_S - V_R) + (V_R - V_F) = V_S - V_F \qquad (2)$$

where ΔV_1 and ΔV_2 are the voltage drops from terminal S to the fault point F via two different routes as shown in Fig.1. It is obvious that the two voltages should be equal as in (3).

$$\Delta V_1 = \Delta V_2 \qquad (3)$$

ΔV_1 and ΔV_2 can be expressed as the functions of the line currents, line impedances and fault location D. After deriving ΔV_1 and ΔV_2, substitute them into (3). Since the currents and line parameters are known, the only unknown in (3) is the fault location D and therefore can be solved.

The following sections describe the mathematic derivations for different fault types. According to expressions of ΔV_1 and ΔV_2, the derivations are divided into phase to ground fault and phase to phase fault.

A. Phase to Ground fault

First take the example of a single phase to ground fault. For two or three phases to ground fault, the expressions are very similar and therefore are not included. Fig.2 shows an '*a*' to ground fault. R_g is the fault resistance. The voltages of the two routes of phase *a*, ΔV_{a1} and ΔU_{a2}, are employed in Fig.2 to replace ΔV_1 and ΔU_2 in Fig.1. The currents of phase *a* (i.e. I_{aS1}, I_{aS2}, I_{aR1} and I_{aR2}) and zero sequence currents (i.e. I_{0S1}, I_{0S2}, I_{0R1} and I_{0R2}) of both terminals of the parallel lines are also employed. ΔV_{a1} and ΔV_{a2} can be expressed as (4) and (5) respectively.

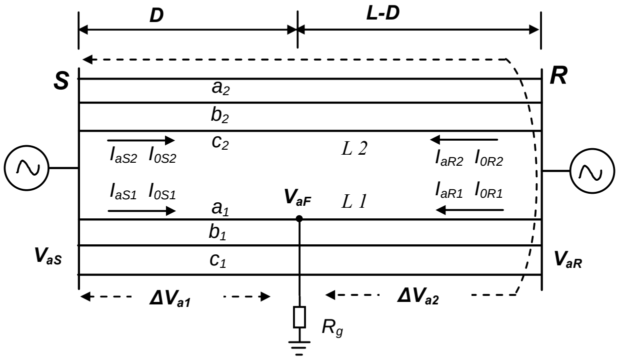


Fig.2. Phase a to ground fault in line 1 of the parallel line pair

$$\Delta V_{a1} = D*(Z_{I1} * I_{aS1} + k_{I0} * Z_{I1} * I_{0S1} + Z_m * I_{0S2}) \quad (4)$$

$$\Delta V_{a2} = (L - D) * (Z_{I1} * I_{aR1} + k_{I0} * Z_{I1} * I_{0R1} + Z_m * I_{0R2}) + V_{aSR} \quad (5)$$

$$V_{aSR} = Z_{II1} * L * ((I_{aS2} - I_{aR2}) + k_{II0} * (I_{0S2} - I_{0R2}))/2 + D * Z_m * I_{0S1} + (L - D) * Z_m * I_{0R1} \quad (6)$$

where Z_{I1} and Z_{II1} are the positive sequence impedances of line 1 and 2 respectively, k_{I0} and k_{II0} are the zero sequence compensation factors of line 1 and 2 respectively and Z_m is the mutual impedance between line 1 and 2. k_{I0} and k_{II0} are defined as:

$$k_{I0} = (Z_{I0} - Z_{I1}) / Z_{I1} \quad \text{and} \quad k_{II0} = (Z_{II0} - Z_{II1}) / Z_{II1}$$

In (6), the AVERAGE phase current and zero sequence current of both terminals of line 2 are employed to compensate the charging current of line 2. Simulation reveals that this method is effective in eliminating the impact of charging current of line 2.

Substituting (6) into (5) and because of ΔV_{a1} equal to ΔV_{a2}, (7) can be derived.

$$\begin{aligned} D * (Z_{I1} * I_{aS1} + k_{I0} * Z_{I1} * I_{0S1} + Z_m * I_{0S2}) &= (L - D) * (Z_{I1} * I_{aR1} + k_{I0} * Z_{I1} * I_{0R1} + Z_m * I_{0R2}) \\ &+ Z_{II1} * L * ((I_{aS2} - I_{aR2}) + k_{II0} * (I_{0S2} - I_{0R2}))/2 + D * Z_m * I_{0S1} + (L - D) * Z_m * I_{0R1} \end{aligned} \quad (7)$$

In (7), the only unknown is the fault location D; therefore, it can be solved.

B. Phase to Phase Fault

The following section describes the derivation of the phase to phase fault. The derivation uses *b-c* fault as an example and it is suitable for any type of phase to phase faults such as two- or three- phase faults with or without fault resistance. Phase to phase fault differs from phase to ground fault in that the zero sequence current does not exist (or very limited if the line are not ideally transposed) and thus the mutual inductance has no effect.

Fig.3 shows a two-phase (*b-c*) fault. R_f is the fault resistances. The phase-to-phase voltages (i.e. ΔV_{bc1} and ΔV_{bc2}) of the two fault loops can be expressed as (9) and (10).

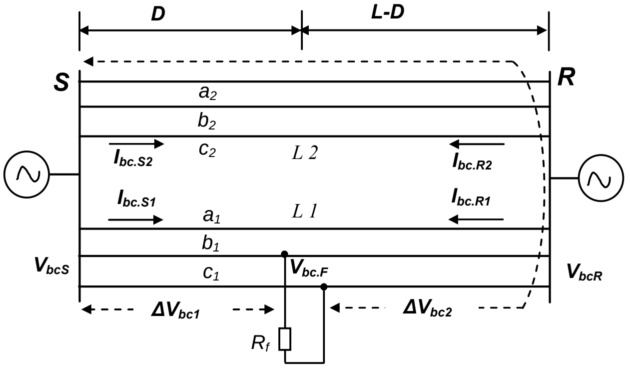


Fig.3. phase to phase fault (b-c) in line 1 of the parallel line

$$\Delta V_{bc1} = D * Z_{I1} * I_{bc.S1} + V_{bc.F} \quad (9)$$

$$\Delta V_{bc2} = (L - D) * Z_{I1.R1} * I_{bc.R1} + L * Z_{II1} * (I_{bc.S2} - I_{bc.R2})/2 + V_{bc.F} \quad (10)$$

Where $U_{bc.F}$ is the voltage of phase b to c at the fault point F. Because ΔU_{bc1} is equal to ΔU_{bc2}, (11) can be derived.

$$D * Z_{I1} * I_{bc.S1} = (L - D) * Z_{I1.R1} * I_{bc.R1} + L * Z_{II1} * (I_{bc.S2} - I_{bc.R2})/2 \quad (11)$$

From (11), the only unknown fault location D can be solved. Like the single phase to ground fault, the average phase-to-phase current (I_{bc}) of both terminals in line 2 is employed in order to eliminate the charging current impact of line 2.

In (11), if $Z_{\text{I}1}$ and $Z_{\text{II}2}$ are equal or have a fixed ratio, then the impedance terms can be cancelled, which means that the absolute value of the line impedance will not affect the fault locating result. This feature is important when the line parameters are not accurate.

From the above descriptions, the fault location, *D*, can be determined if the synchronized current signals are obtained from the parallel lines. By using the average current of both terminals, the impact of charging current is reduced. Also, if the line impedance has a fixed ratio or change in the same pattern, the line parameters will not greatly affect the results. Since no voltage signals are used, the effect of CVT transient will be totally eliminated. The next part will show the simulation results based on EMTDC.

III. PERFORMANCE AND SENSITIVITY STUDIES OF THE PROPOSED FAULT LOCATING ALGORITHM

Section II described the principle of the new fault location algorithm. This section will focus on the evaluation of the proposed fault locating algorithm. This evaluation is to test the performance of the proposed algorithm for parallel lines with different lengths, fault resistances, unsynchronized sampling and tolerance of inaccuracy of line parameters. In order to demonstrate the superiority of the proposed algorithm, comparisons with traditional impedance-based algorithms (both ideal VT and CTV) are presented.

The simulation is carried out using EMTDC/PSCAD [2]. The simulation system is 230kV and 60Hz with two parallel lines and power sources at both terminals. The parameters of the two parallel lines are identical.

The traditional impedance-based method in this simulation uses the local voltage signal and current signals from both terminals as depicted in (12).

$$Z_{pu} = \operatorname{Im}(U_S(I_S + I_R)^*) / \operatorname{Im}(Z_1(I_S + Z_m I_{0S1})(I_S + I_R)^*) \qquad (12)$$

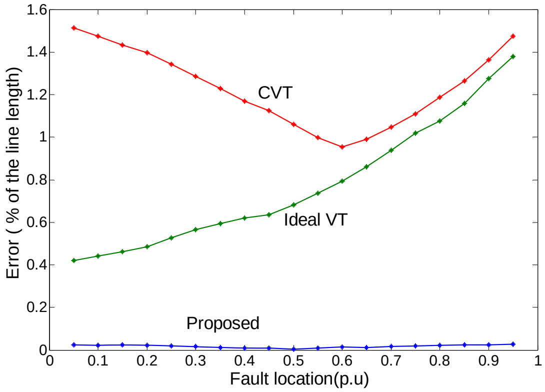
Where Im(.) denotes the imaginary part of the element, and the superscript (*) denotes the conjugate of the complex element. For all the simulation, the lumped parameters of the parallel lines are employed.

The sampling rate in this simulation is 36 samples per cycle. The Least Square Fitting (LSF) algorithm is employed to estimate the phasors of voltages and currents [3]. The data window of LSF is full cycle starting from half cycle after the inception of the fault. This is because the fault transient components (especially noise) decayed to some extent after one half cycle. On the other hand, after one and a half cycles, the circuit breakers may have started to open (typical breaker operating time about 3 cycles on the transmission lines) and additional resistances due to breaker internal arcing will been added to the fault loop.

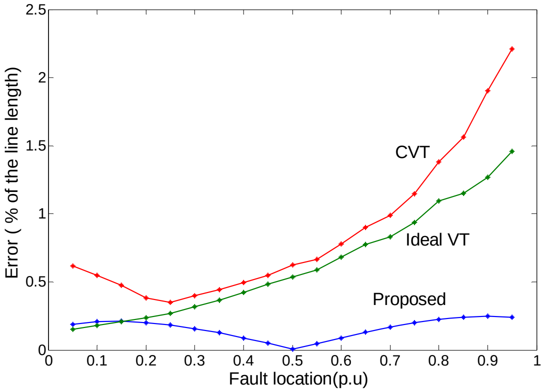
A. The effect of the length of the parallel lines

This study is to test the fault location errors at different lengths of the parallel lines. The simulations are carried out for parallel lines of 50, 150 and 300km. Faults are set to 5% to 95% along the lines with an incremental step of 5%. The results of the proposed algorithm and the straightforward algorithm for both ideal VT and CVT are presented in Fig.4 (a) to (c). The maximum errors (both in percentage and absolute distance) of different simulations are presented in Tables I to III.

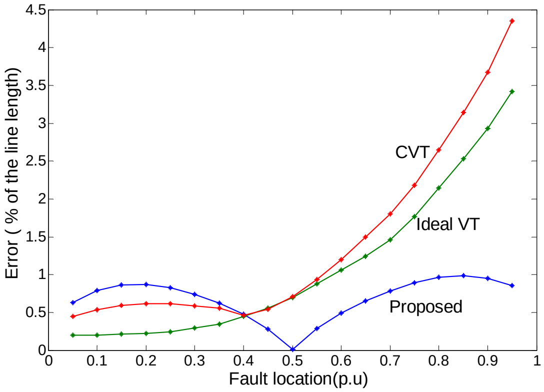
From Fig. 4 (a) to (c) and Tables I to III, it can be seen that the proposed algorithm yields better estimate in most cases and the maximum errors are much smaller than the straightforward algorithm. When the CVT is considered, the accuracy of the results based on traditional fault location technique deteriorates greatly. It can also be seen that the error increases for longer line. This is because of the larger charging current and inaccuracy of long line parameters when using lumped model.



(a) Line length = 50km



(b) Line length = 150km



(c) Line length = 300km

Fig. 4. Absolute errors in the fault location estimate using the proposed and conventional algorithms

TABLE I
MAXIMUM ERRORS IN FAULT LOCATION ESTIMATE FOR 50KM LINE

	Proposed	Ideal VT	CVT
Max error (%)	0.0323	1.7422	12.8026
Max error (km)	0.0162	0.8711	6.4013

TABLE II
MAXIMUM ERRORS IN FAULT LOCATION ESTIMATE FOR 150KM LINE

	Proposed	Ideal VT	CVT
Max error (%)	0.2437	1.9839	4.3740
Max error (km)	0.3655	2.9758	6.5610

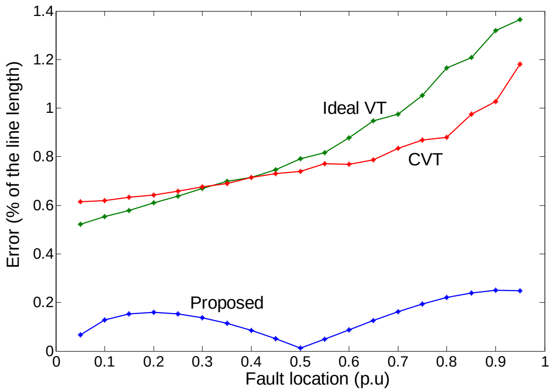
TABLE III
MAXIMUM ERRORS IN FAULT LOCATION ESTIMATE FOR 300KM LINE

	Proposed	Ideal VT	CVT
Max error (%)	0.9681	4.5065	5.2483
Max error (km)	2.9043	13.5195	15.7449

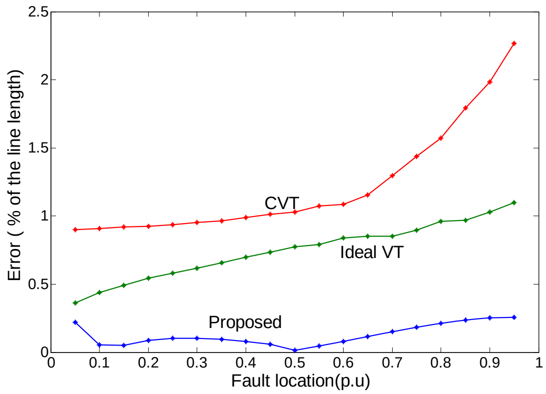
B. The Effect of the Fault Resistance

The fault resistance influences the residual voltage of the faulted line and the charging current along the line. Therefore, it will affect the result of the fault location. The fault locating algorithms should be able to tolerate the reasonable fault resistance.

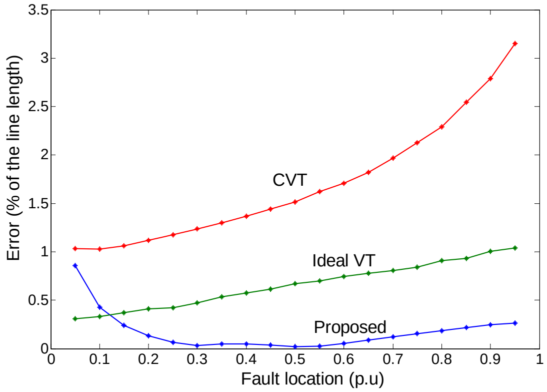
This simulation is carried out at the parallel lines of 150km. The fault resistance is chosen at 20, 50 and 100Ω respectively. The results are shown in Fig. 5



(a) Fault resistance = 20 Ω



(b) Fault resistance = 50 Ω



(c) Fault resistance = 100 Ω

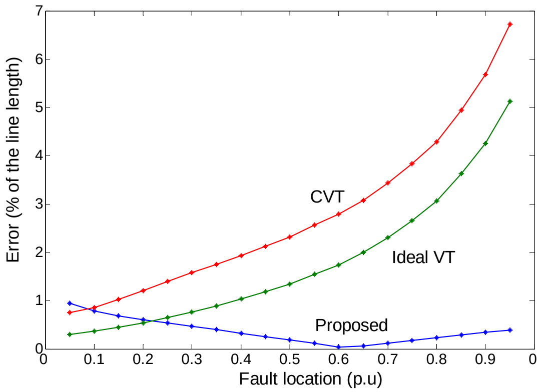
Fig. 5 Effect of fault resistance

C. *Effect of the Synchronization Errors*

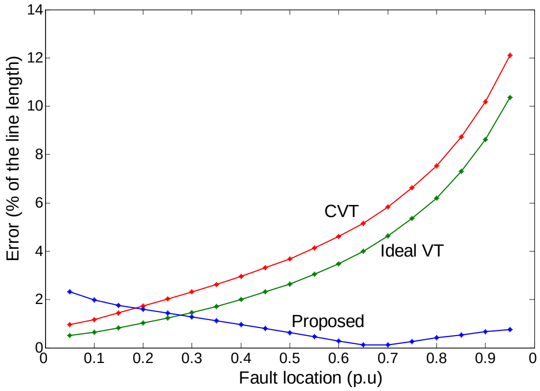
With the application of GPS, the synchronization errors among different substations are very small, normally within 1us or 0.0216^0 for 60Hz power system. This error can be negligible. However, sometimes GPS may not be applied, or is temporally out of service due to various reasons. At such occasions, larger synchronization errors can be introduced. Therefore, fault locating algorithms should have reasonable tolerance to the synchronization errors when multi-terminal data are employed.

In this study, the synchronization error, δ, is set from 1 to 3 samples, which corresponds to 10^0 to 30^0 for 36 samples/cycle. This range can satisfy the maximum synchronization errors even for unsynchronized data because coarse synchronization can be achieved just by referring to the common reference of fault inception.

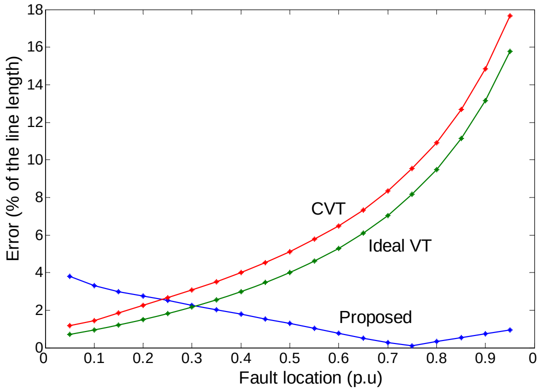
The results are shown in Fig. 6. It can be seen that the overall performance of the proposed algorithm is much improved when compared to the straightforward algorithms.



(a) $\delta = 10^0$



(b) $\delta = 20^0$



(c) $\delta = 30^0$

Fig. 6 Effects of Synchronization Errors

D. Different Types of Faults

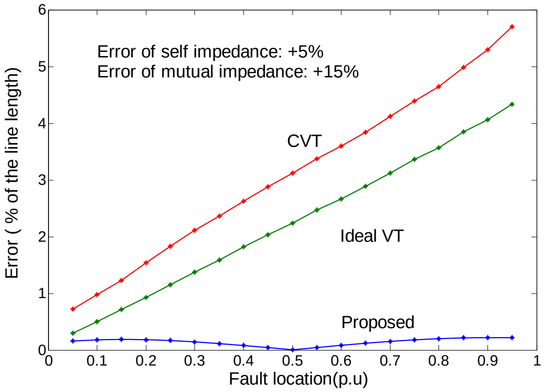
The above are about single phase to ground fault. Other types of faults such phase-to-phase, two phases to ground and three phase faults are also simulated. The results are very close to single phase to ground phase and are not shown here.

E. Tolerance to the Inaccuracy of Line Parameters

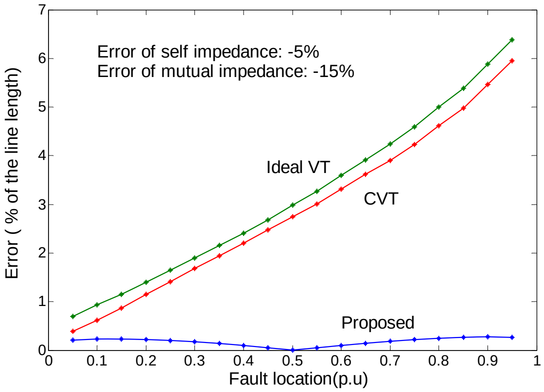
It is sometimes very difficult to develop an exact set of transmission line parameters. Per IEEE Std C37.114™-2004, a 20% error of line parameter can introduce15% error on fault location result [4]. Inaccuracy of the transmission lines may come from many aspects. The first of those aspects is the initial model error. The second is the changing environment, e.g., the load flow and ambient conditions will affect the temperature and length of the conductors, the wind will affect the relative positions of the conductors, the soil conductivity changes with the humidity, etc. Because inaccuracy of transmission line parameters is inevitable, fault locating algorithms should have reasonable tolerance to the inaccuracy of the line parameters.

The sensitivity of the proposed algorithm to the inaccuracy of transmission line parameters is investigated. The range of inaccuracy of line parameters is that the self-impedances are ±5% off the actual values, whereas the mutual impedances are ±15% off the actual values. This range normally satisfies the maximum errors of line parameters.

The results are shown in Fig.7. From Fig.7, it can be seen that the new algorithm has better tolerance than the traditional algorithms. For the new algorithm, the fault location estimates are hardly, if not absolutely any, affected by the inaccuracy of the line parameters. This is because, for the proposed algorithm, the absolute values of the line parameters are not important as shown in (11). However, the traditional algorithms are very sensitive to the inaccuracy of line parameters because they are based on the estimation of the absolute impedances and thus determining the fault location.



(a) Parameters with positive errors



(b) Parameters with negative errors

Fig. 7 Sensitivity to inaccuracy of transmission line parameters

IV SUMMARY

This paper has presented a new fault location algorithm for parallel transmission lines based on synchronized current signals. The principle of this algorithm has been described in detail. The performance of the proposed algorithm has been evaluated and compared with the previously proposed techniques. Simulations show that the new algorithm yields more accurate results. It eliminates the adverse impact from CVT transient because the voltage signals are not utilized. It can also reduce the negative impact from line parameter inaccuracy, synchronization error, distributed charging current and fault resistance. With the add-on feature of synchrophasor in microprocessor-based relays and widely used digital communication technique among utilities, the new algorithm can be easily implemented with no additional cost. It can improve the accuracy of the fault location result for parallel transmission lines and reduce the outage due to a fault.

V. REFERENCES

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