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CIGRÉ- 324

2013 CIGRÉ Canada Conference
The Westin Calgary
Calgary, Alberta, September 9 - 11, 2013

Accurate Fault Location Estimation in Transmission Lines under High dc-offset and Sub-harmonic Conditions

U. S. ANNAKKAGE, N. PERERA, V. LIYANAGE
ERLPhase Technologies
CANADA

SUMMARY

Transmission lines are considered as very important parts of the power system which provide a reliable service from the power plant to the consumers. To maintain an economical power supply, identifying fault locations is very important [1]. In most of the industrial distance relays, the fault distance estimation is done using the Takagi algorithm [2]. However this task can be difficult under high dc offset conditions and high resistive fault situations [3]. In addition, sub harmonic conditions that occur in series compensated lines have made the estimation of fault location more challenging [4]. In some practical conditions, faults are cleared within two cycles and the fault distance estimation with such a short data window is difficult [5]. In literature, several attempts have been made to overcome the aforementioned problems [6-9]. These methods involved the use of different filtering approaches. Although such filtering methods are being used in most of the distance relays, their behavior is not satisfactory under all practical conditions described above [10].

This paper investigates the development of an enhanced single-ended impedance based fault location algorithm for numerical distance relays, suitable under high dc off-set and sub-harmonic conditions. The proposed solution includes the use of filters to eliminate the effects of the dc off-set and sub-harmonics. The modified Takagi fault location algorithm was used as the basis. Performance of the proposed algorithm was evaluated using faulty waveforms generated from an electromagnetic transient (EMT) type simulation program. In this study, two transmission systems were considered (i.e. a mutually coupled double circuit transmission line and a series compensated single circuit transmission line). Different types of faults (phase-to-ground, phase-to-phase, three-phase, etc.) simulated with different fault inception angles were considered.

Results obtained from this study show that the algorithm is capable of estimating the fault location in uncompensated double circuit transmission line with a low maximum percent error of 1.62%. The maximum error observed in the series compensated line under high sub-harmonic conditions was 2.1%. In addition, performance of the proposed algorithm was also evaluated for short duration faults. For this study, faults generated from the uncompensated double circuit transmission line were considered. The results showed errors less than 2% and 3% for the 2 cycle and 1.5 cycle duration faults respectively.

A laboratory prototype is being implemented and more results will be presented in the full paper.

KEYWORDS

fault location, distance relay, dc off-set, sub-harmonics

1 INTRODUCTION

Transmission lines are considered as very important parts of the power system which provide a reliable service from the power plant to the consumers. To maintain an economical power supply, identifying fault locations is very important [1]. In most of the industrial distance relays, the fault distance estimation is done using the Takagi algorithm [2]. However this task can be difficult under high dc offset conditions and high resistive fault situations [3]. In addition, sub harmonic conditions that occur in series compensated lines have made the estimation of fault location more challenging [12]. In some practical conditions, faults are cleared within two cycles and the fault distance estimation with such a short data window is difficult [5]. In literature, several attempts have been made to overcome the aforementioned problems [6-9]. These methods involved the use of different filtering approaches.

Although such filtering methods are being used in most of the distance relays, their behavior is not satisfactory under all practical conditions described above [10]. This research investigates the development of an accurate and efficient algorithm that is capable of identifying the fault distance using two cycle information under high dc off-set and sub-harmonic conditions.

The rest of the paper is organized as following. Section II gives a brief description on the enhanced fault location method proposed in this research. Results obtained using detailed simulation studies are presented in Section III. Finally, the conclusions are given in Section IV.

2 PROPOSED METHOD

2.1 Algorithm

Fig-1 shows the calculation steps involved in the proposed algorithm. First, voltage and current signals are passed through a high-pass filter to eliminate the dc offset and sub-harmonics. Next, phasor quantities are estimated using the recursive discrete furrier transform. The phase selector calculations are performed subsequently to identify the faulted phase. Finally, the modified Takagi fault location algorithm [2] is applied to estimate the fault distance. More details on each of these computational elements are given below.

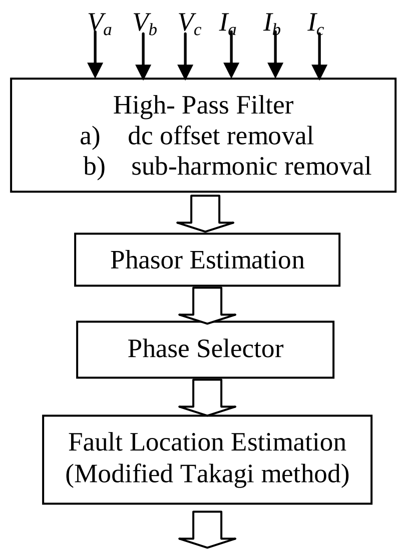

Fig. 1. Steps involved in fault location estimation

2.2 DC Offset Removal Filter

In order to remove dc offsets in the measurement waveforms with less computations and minimal delay time, an Infinite Impulse Response (IIR) filter was selected. The IIR filter used in this paper has two forward sections and one feedback section. Therefore, the dc component can be eliminated by finding the difference in the two forward sections while keeping these coefficients equal in magnitude. The digital implementation of the proposed IIR filter used for dc offset removal is given in (1).

$$I_{Filt} = 0.8 * I(i) - 0.8 * I(i-1) + 0.6 * I_{Filt}(i-1) \quad (1)$$

The output response of the dc removal filter is shown in Fig.2.

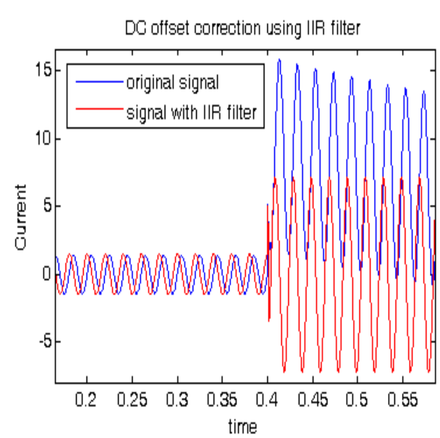

Fig. 2. DC offset removal from a current waveform

2.3 Sub-Harmonic Removal Filter

Sub-Harmonics make fault location estimation challenging especially for short duration faults. A high pass filter to remove these sub-Harmonics is designed so that the pass band has a constant gain with a sharp edge yet the time delay is not too large. To accomplish this, a 5th order Butterworth high pass filter with a cutoff of frequency of 45Hz was used. The output response of selected filter is shown in Fig.3.

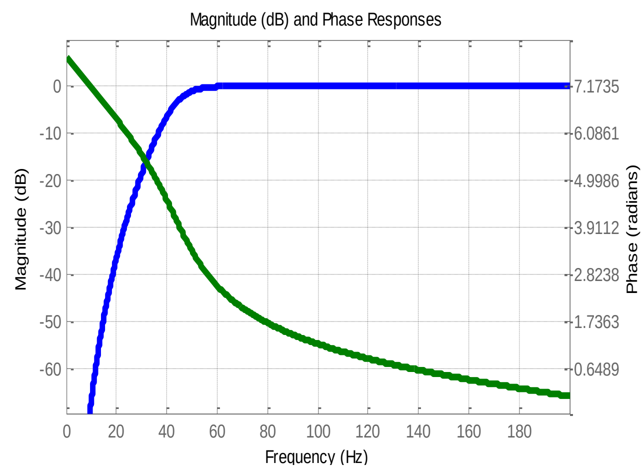

Fig. 3. Sub-harmonic removal filter response

2.4 *Phasor Estimation*

The recursive discrete furrier transform (RDFT) was used to estimate the voltage and current phasors.

2.5 *Phase Selection*

Phase selector determines the type of the fault (AG, BG, CG, AB, BC, etc.) which is required for accurate fault location estimation.

2.6 *Fault Location Calculation*

The single-ended modified Takagi algorithm for fault location was used. This method does not use the source impedance which is practical since the source impedance is not always available. Pre-fault current is required along with line impedances and system voltage and current measurements to accurately estimate the fault location.

2.7 *Adjustments for Mutual Compensation*

The use of parallel lines on transmission towers is increasingly more common as the electricity consumption and demands increase. The introduction of parallel lines can cause mutual coupling effects. These mutual coupling effects provide inaccurate impedance measurements and fault distance estimations in distance relays. Therefore, in this algorithm mutual line compensation is taken into consideration by making necessary adjustments to the original equation [1]-[2].

3 SIMULATION

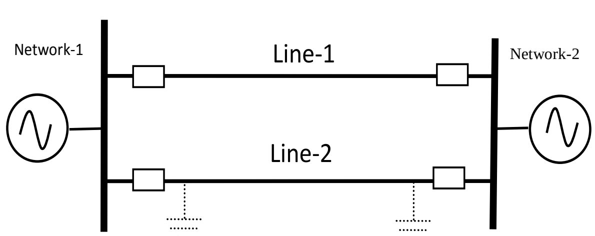

Fig. 4. Single-line diagram of the double circuit transmission system under analysis

TABLE I

CONDITIONS TESTED

CONDITION	STATE OF LINE 2
1	ACTIVE PARALLEL LINE
2	OPEN BUT NOT GROUNDED
3	OPEN AND GROUNDED

TABLE II

CONDITION 1 FAULT DETECTION RESULTS

FAULT TYPE	ACTUAL LOCATION (KM)	CALCULATED LOCATION (KM)	% ERROR
AG	12.5	12.52	0.21
BG		12.53	0.26
CG		12.53	0.26
ABG		12.52	0.13
BCG		12.52	0.12
CAG		12.52	0.12
AG	50	50.03	0.06
BG		50.03	0.05
CG		50.03	0.06
ABG		50.15	0.29
BCG		50.03	0.06
CAG		50.15	0.30
AG	125	125.06	0.05
BG		125.04	0.03
CG		125.06	0.05
ABG		125.02	0.02
BCG		125.02	0.02
CAG		125.03	0.02
AG	200	200.36	0.18
BG		200.34	0.17
CG		200.35	0.17
ABG		200.23	0.11
BCG		200.23	0.11
CAG		200.25	0.12

The cases that were analyzed are practical scenarios that were simulated on a Real Time Digital Simulator (RTDS) to allow for a real-time generation. Fig. 4 shows the 400kV, 250 km double circuit transmission system under analysis. In this simulation, the transmission line is simulated with mutual effects. The system parameters are given in the Appendix-A.

3.1 Fault Location Results

In this study, for active line-1 three different conditions were considered for line-2, as given in Table 1. For all the conditions, the power flow is from Bus A to Bus B sending 100MVAr and 500MW across the line.

TABLE III
CONDITION 2 FAULT DETECTION RESULTS

FAULT TYPE	ACTUAL LOCATION (KM)	CALCULATED LOCATION (KM)	% ERROR
AG	12.5	12.54	0.29
BG		12.53	0.27
CG		12.53	0.26
ABG		12.52	0.13
BCG		12.52	0.15
CAG		12.53	0.25
AG	50	50.06	0.12
BG		50.06	0.13
CG		50.06	0.11
ABG		50.06	0.12
BCG		50.06	0.13
CAG		50.06	0.12
AG	125	125.44	0.35
BG		125.44	0.35
CG		125.45	0.36
ABG		125.90	0.72
BCG		125.57	0.45
CAG		125.57	0.46
AG	200	202.01	1.00
BG		202.02	1.01
CG		202.02	1.01
ABG		202.44	1.22
BCG		203.23	1.62
CAG		202.42	1.21

For each condition, six different fault types were evaluated which include the faults occurring at 5%, 20%, 50%

and 80% of the line. Tables II, III and IV show the fault location results for the various line locations corresponding to each condition.

3.2 Effect of Fault Duration

TABLE IV
CONDITION 3 FAULT DETECTION RESULTS

FAULT TYPE	ACTUAL LOCATION (KM)	CALCULATED LOCATION (KM)	% ERROR
AG	12.5	12.56	0.45
BG		12.55	0.42
CG		12.56	0.45
ABG		12.52	0.19
BCG		12.52	0.19
CAG		12.53	0.21
AG	50	50.02	0.05
BG		50.03	0.06
CG		50.02	0.05
ABG		50.10	0.20
BCG		50.06	0.11
CAG		50.05	0.10
AG	125	124.38	0.50
BG		124.38	0.49
CG		124.39	0.49
ABG		125.14	0.11
BCG		125.11	0.09
CAG		125.14	0.11
AG	200	197.89	1.05
BG		197.93	1.04
CG		197.92	1.04
ABG		200.63	0.32
BCG		200.66	0.33
CAG		200.67	0.33

TABLE V
EFFECT OF FAULT DURATION

FAULT TYPE	ACTUAL LOCATION (KM)	2 CYCLE CALCULATIONS		1.5 CYCLE CALCULATIONS		1 CYCLE CALCULATIONS	
		LOCATION	% ERROR	LOCATION	% ERROR	LOCATION	% ERROR
AG	50	50.43	0.8	49.52	0.9	61.33	22.6
BG		50.07	0.1	49.69	0.6	73.14	46.2
CG		50.32	0.6	49.48	1.0	54.41	8.8
ABG		49.40	1.1	50.58	1.1	56.75	13.5
BCG		50.25	0.5	50.85	1.7	62.79	25.5
CAG		50.40	0.8	48.29	3.4	47.22	5.5
AG	125	126.44	1.1	123.2	1.4	133.8	7.0
BG		125.40	0.3	125.9	0.7	160.7	28.5
CG		125.24	0.1	123.5	1.2	119.7	4.2
ABG		126.25	1.0	124.3	0.5	138.6	10.8
BCG		126.68	1.3	125.5	0.4	141.5	13.2
CAG		124.44	0.4	121.3	2.9	143.3	14.6
AG	200	202.59	1.2	196.8	1.6	217.4	8.7
BG		200.70	0.3	198.1	0.9	244.5	22.2
CG		200.89	0.4	197.8	1.1	194.6	2.7
ABG		200.00	0.0	202.2	1.1	208.7	4.3
BCG		201.98	0.9	196.5	1.7	228.6	14.3
CAG		200.6	0.3	200.1	0.1	218.8	9.4

Determining fault location can be difficult if the fault is recognized and cleared within a short duration of time such as within two cycles. A good fault location method should be able to give accurate results for faults with short durations. In order to evaluate the performance of the proposed method for short duration faults, two cycle, one and a half cycle, and one cycle faults were analyzed. These waveforms were obtained by using the same set of waveforms as in Section III-A, but disregarding values after the desired number of cycles. In this study, the Condition-1(i.e. active parallel line) faults were considered only. The fault location results are summarized in Table V. As it can be seen from these results, the proposed method is capable of estimating the fault location within 2% limit based on two cycle data.

3.3 Effect of Sub-harmonics

In order to evaluate the performance of the proposed fault location algorithm under sub-harmonic conditions, the single circuit, series compensated transmission line shown in Fig.5 was simulated in RTDS. As shown in Fig.5, the capacitor bank was simulated with Metal Oxide Varistors (MOVs) capable of by-passing the capacitors under high fault current conditions. Different types of faults (AG, BC, BCG, etc.) were simulated at different distances of the transmission line with different fault inception angles. Fig. 6 shows the current and voltage signals observed with sub harmonics during a BC fault at 75% of the line. The fault estimation results are summarized in Table-VI. As seen from the results, proposed algorithm was able to determine the fault location with a maximum error of 2.1%.

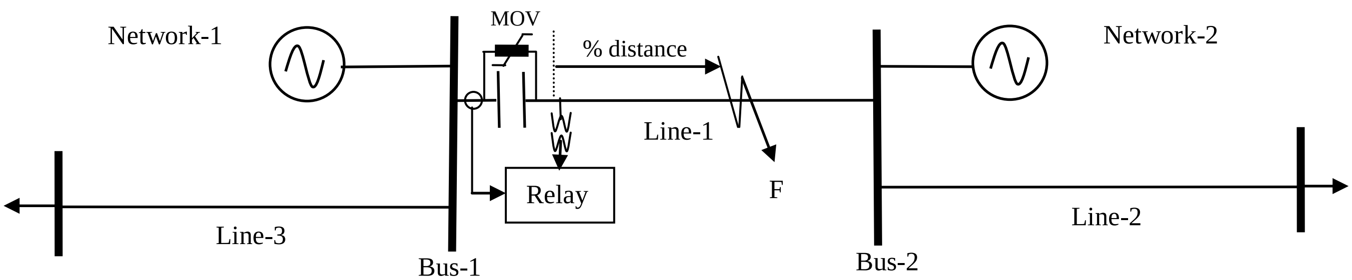

Fig. 5. Single-line diagram of the single circuit series-compensated transmission system under analysis

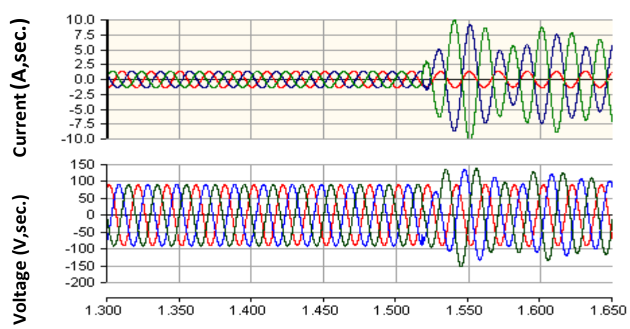

Fig. 6. Currents and voltages observed during the fault

TABLE VI
EFFECT OF SUB-HARMONIC CONDITIONS

FAULT TYPE DETECTED	ACTUAL LOCATION(KM)	CALCULATED LOCATION (KM)	% ERROR
AG	4.71	4.7	0.3
BC		4.7	0.3
BCG		4.7	0.3
ABC		4.8	1.8
AG	58.92	58.7	0.4
BC		59.1	0.3
BCG		59.5	0.9
ABC		59	0.1
AG	117.85	118.2	0.3
BC		116.4	1.2
BCG		116.4	1.2
ABC		116.3	1.3
AG	176.77	178.6	1.0
BC		177.9	0.6
BCG		177.2	0.2
ABC		180.5	2.1

4 PROTOTYPE IMPLEMENTATION AND TESTING

4.1 Prototype Implementation

In order to further evaluate the performance of the proposed fault location method under real-time operating conditions, a laboratory prototype was implemented on a numerical distance relay environment [10].

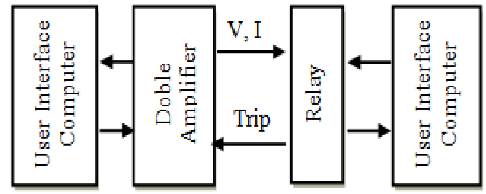

Fig. 7. Test System

4.2 Test Setup

Fig.7 shows the test setup used for this evaluation. The recorded waveforms generated using the RTDS were played back using a Doble transient playback unit [12]. User interfacing for the relay and the amplifier was provided using personal computers (PCs).

4.3 Test System

Fig.8 shows the single line diagram of 400kV, 250 km transmission line model used to evaluate the performance of the relay. The transmission line used here is a double circuit, series compensated line. System parameters of the transmission line are given in the Appendix. Transmission lines were modeled using frequency dependent line characteristics with mutual effect. The series capacitor bank was modeled with a parallel MOV protection arrangement. Current transformers (CTs) and potential transformers (PTs) were also included in the simulation. The CT and PT ratios used are 1000:1 and 40000:110 respectively. A power flow of 750 MW and 250 MVar, flowing form Station-A to Station-B was assumed. As the system used here is a double circuit transmission line, current signals from the mutual line were used to compensate the mutual effects during ground faults. Quadrilateral impedance characteristics were assumed for both ground element and phase element settings of the distance relay.

4.4 Results

In this study, different types of faults (AG, BC, BCG and ABC) are simulated on Line-1 at different distances form Relay-1 as shown in Fig.8. Recorded waveforms were played back to the relay through the amplifier. Fig.9 shows the variation of voltage and current signals observed by the relay during an ABC fault simulated at 62.5 km.

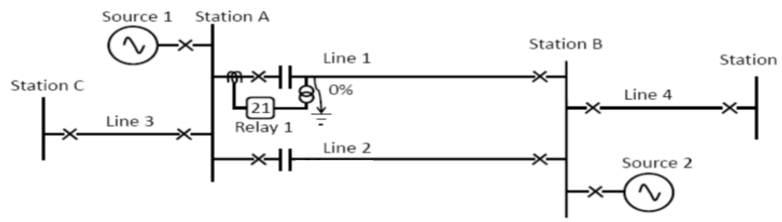

Fig. 8. Single-line diagram of the double circuit series-compensated transmission system under analysis

Fig.9 clearly shows the presence of sub harmonics in current waveforms generated due to the effect of the series capacitor. The variations of phase impedances (Zab, Zbc and Zca) calculated by the relay during the fault are shown in Fig.10. As it can be seen from Fig.9 and Fig.10, the relay shows a correct

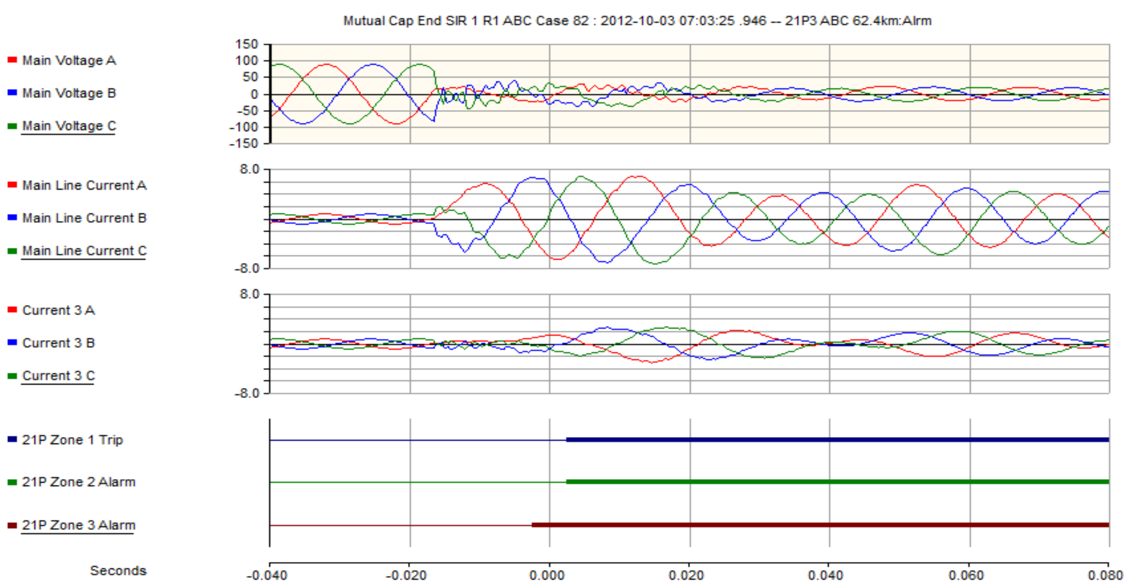

Fig. 9. Observations during ABC fault at 62.5 km

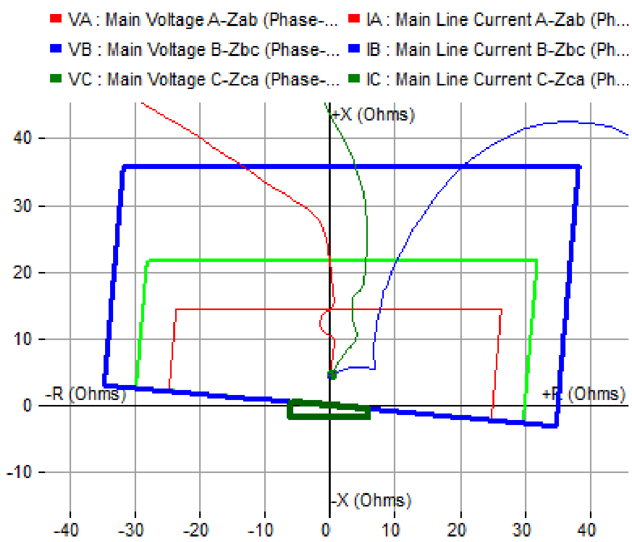

Fig. 10. Variation of phase impedances during the ABC fault

TABLE VII
RESULTS FROM PROTOTYPE

FAULT TYPE DETECTED	ACTUAL LOCATION(KM)	CALCULATED LOCATION (KM)	% ERROR
AG	25	24.7	1.2
BC		25.2	0.8
BCG		25	0.0
ABC		24.8	0.8
AG	62.5	61.7	1.3
BC		63.6	1.8
BCG		62.9	0.6
ABC		62.4	0.2
AG	125	126.6	1.3
BC		127.0	1.6
BCG		126.2	1. 0
ABC		125.9	0.7
AG	187.5	191	1.9
BC		190.7	1.7
BCG		190.7	1.7
ABC		190.7	1.7

Testing was repeated for several fault cases and a selected set of results are summarized in Table-VII. As it can be seen from the results, the maximum fault location error observed from prototype testing was 1.9%.

5 CONCLUSION

In this paper, applicability of different filtering methods to eliminate the effects of the sub-harmonic conditions and the dc-offset conditions was investigated for accurate and fast fault distance estimation in transmission lines. An offline program of the proposed fault location algorithm was developed in MATLAB. Performance of the off-line program was evaluated using recorded waveforms obtained from an electromagnetic transient (EMT) type simulation program. Results obtained from the off-line analysis showed a maximum fault location estimation error of 2.1% based on the two-cycle fault information under high dc-offset conditions and sub harmonic conditions. Finally, a laboratory prototype was implemented and tested using the simulated waveforms played back via a real-time playback system. The maximum fault location error observed from the prototype was 1.9%.

Results presented in this paper show the potential for developing an accurate fault location method for distance relays using the proposed filters.

APPENDICES

A. Parameters of double circuit transmission line

Table-VIII shows the transmission line parameters for the double circuit transmission line. In this simulation, a source to line impedance ratio (SIR) of 1.0 was assumed.

TABLE VIII
LINE PARAMETERS: DOUBLE CIRCUIT LINE

	Line
Positive	$77.2<84.6^0$ ohms
Zero	$263.7<75.7^0$ ohms
Mutual	$165.6<69.8^0$ ohms
Length	250 km

B. Parameters of single circuit series compensated transmission line

Parameters of the series compensated line are shown in Table IX. In this simulation modal, a SIR of 0.2 was assumed. The amount of the compensation used was 40%.

TABLE IX
LINE PARAMETERS: SERIES COMPENSATED LINE

	Line-1	Line-2	Line-3
Positive	72.7<84.6 ohms	30.9<84.6^0 ohms	30.9<84.6^0 ohms
Zero	248.7 <75.7 ohms	105.8<75.7^0 ohms	105.8 <75.7^0 ohms
Length	235.7 km	100 km	100 km

C. Parameters of double circuit series compensated transmission line

TABLE X
LINE PARAMETERS: DOUBLE CIRCUIT LINE

	Line 1&2	Line 3	Line 4
Positive	77.2<84.6^0 ohms	30.9<84.6^0 ohms	46.4<84.6^0 ohms
Zero	263.7<75.7^0 ohms	105.8<75.7^0 ohms	158.7<75.7^0 ohms
Mutual	165.6<69.8^0 ohms	N/A	N/A
Length	250 km	100 km	150 km

Table-X shows the transmission line parameters for the double circuit series compensated transmission line. In this simulation, a source to line impedance ratio (SIR) of 1.0 was assumed. The amount of the compensation used was 40%.

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