DOUBLE-CIRCUIT TRANSMISSION LINES WITH UNSYNCHRONIZED FAULT LOCATION BASED ON THE NEGATIVE-SEQUENCE VOLTAGE MAGNITUDE

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ABSTRACT-A new fault-location method for double-circuit transmission lines using the magnitudes of negative-sequence voltages measured at both ends of the faulted circuit is proposed in this paper. The proposed method can effectively locate the single-phase-to-ground, double phase-to-ground, and phase-to-phase faults disregarding the fault resistance and pre-fault conditions and without any need for fault classification and phase selection. A new approach to fault location for double-circuit transmission lines based on only the voltage data of both ends of the faulted circuit is proposed in this paper. This paper puts forward a novel algorithm for locating faults on double-circuit transmission lines using two-end unsynchronized current measurements. The ratio between the magnitudes of negative-sequence voltages measured at both ends of the faulted circuit is utilized to estimate the fault location. This paper puts forward a novel algorithm for locating faults on double-circuit transmission lines using two-end unsynchronized current measurements. The proposed method is fully analytical and does not cause much computing burden to the line relays. The accuracy and practicality of the proposed method make it an attractive function to implement in numerical relays.

Index Terms—Double-circuit transmission line, fault location, negative-sequence reactance, negative-sequence voltage magnitude, unsynchronized measurement.

INTRODUCTION

DOUBLE-CIRCUIT transmission lines have been extensively utilized in modern power systems to enhance the reliability and security for the transmission of electrical energy. Protecting double-circuit lines, in particular locating faults on them, are always challenging due to the mutual coupling between zero-sequence components of the two circuits.

Whether they are for single-circuit or double-circuit transmission lines, there are two types of fault-location methods known as one-end-based and two-end-based ones. The one-end-based methods [1], [2] may suffer from errors due to the variations of source impedance, fault incidence angle, and loading conditions while their major merit is that they need data of only one end [3]. To overcome the shortfalls of one-end-based methods, two-end-based methods were introduced. They can be classified into unsynchronized and synchronized ones. Unsynchronized methods do not need the data of both line ends to be synchronized while data synchronization is the first step in the synchronized methods. Different methods have been proposed for fault location on double-circuit transmission lines, most of which require data of both voltage and current [4]–[5]. A time-domain fault-location algorithm for parallel transmission lines using currents of both ends based on a differential component net. The sampling frequency required for the method is much higher than the practical one that is around 1 kHz [8].

Assuming both relays are provided with the source impedance behind them, which are available at load dispatch centers [9]. The faulted circuit is assumed to be known based on distance relays action and circuit-breaker (CB) status. In this method, to estimate fault location fault classification is not required. This is a specific feature in comparison to the fault locators that need to first classify the fault type. for long transmission lines even when the lumped model is employed with the proposed method is that the fault-location accuracy still remains high. It is true since the proposed method uses only the voltage data and the ratio between voltages of both ends. The proposed method is fully analytical even when the shunt capacitances are considered. The accuracy of the method, together with its practicality, makes it an attractive option to implement in the relays as a fault-location function.

PROPOSED METHOD

Consider a double-circuit transmission line as shown in Fig. 1, which is protected by distance relays. The relays are fed by only voltage transformers to emphasize that the proposed method is based on only the voltage data.

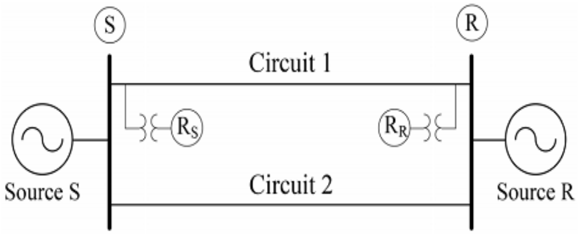

Fig. 1. Double-circuit transmission line protected by the distance relays of sending and receiving ends

In transmission systems, the resistances are negligible in comparison to the reactance's [5], and the mutual coupling between the negative-sequence components of each circuit is also negligible [6]. If an unbalanced fault occurs at distance [per unit (p.u.)] from relay in one circuit of the line, the negative-sequence circuit can thus be modeled as shown in Fig. 2.

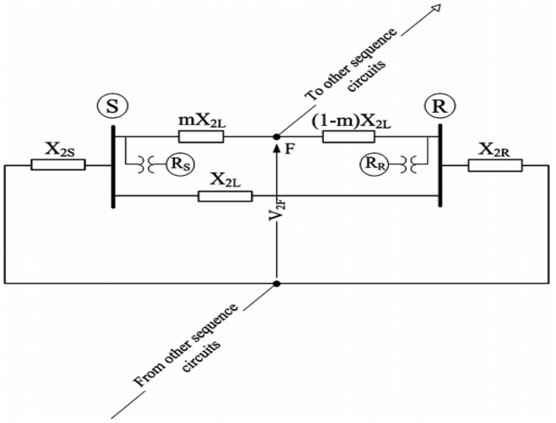

Fig. 2. Negative-sequence circuit of the double-circuit transmission line for an unbalanced fault occurring at location (in per unit) from relay

Converting the delta connection formed by the healthy circuit reactance and the source reactance's to Y connection, the negative-sequence circuit can be represented in a new form as shown in Fig. 3, where ,and can be obtained from Fig. 2 as

$$_2 = \frac{_2 \cdot _2}{} \qquad (1)$$

$$_2 = \frac{_2 \cdot _2}{} \qquad (2)$$

$$_2 = \frac{_2 \cdot _2}{} \qquad (3)$$

And

$$= {}_2 + {}_2 + {}_2 \qquad (4)$$

From Fig. 3, the following equations can be derived:

$$_2 = {}'_2 \frac{_2}{_2 + _2} + {}_2 \cdot {}'_2 \frac{1}{_2 + _2} + \frac{1}{1- \;\; _2 + _2}$$

(5)

$$_2 = {}'_2 \frac{_2}{1- \;\; _2 + _2} + {}_2 \cdot {}'_2 \frac{1}{_2 + _2} + \frac{1}{1- \;\; _2 + _2}$$

(6)

where is the voltage between the fault point and the star point of the Y connection in the negative-sequence circuit.

Considering only the phasor magnitudes and dividing (5) by (6) yields

$$= \frac{|\;_2|}{|\;_2|} = \frac{\frac{_2}{_2 + _2} + {}_2 \frac{1}{_2 + _2} + \frac{1}{1- \;\; _2 + _2}}{\frac{_2}{1- \;\; _2 + _2} + {}_2 \frac{1}{_2 + _2} + \frac{1}{1- \;\; _2 + _2}} \qquad (7)$$

Solving (7) in terms of m leads to

$$= \frac{21- \;\; _2 \; _2 + {}_2 \; _2}{_2 \; _2 + \;\; _2} \qquad (8)$$

As a result, knowing k (the ratio between the magnitudes of negative-sequence voltages at the sending, S, and receiving, R, ends of the faulted circuit) and the negative-sequence reactance of the sources and that of the line, the fault location in a double circuit transmission line can be estimated by using (8). It can be argued that the same results can also be obtained by using the zero-sequence circuit. The following outlines the reasons why the negative-sequence circuit rather than the zero-sequence one was chosen.

The first and an evident one is that the zero-sequence circuit does not exist in the case of ungrounded faults. The second is that there is mutual coupling between zero-sequence components of two circuits in double-circuit transmission lines. The third is that the zero-sequence parameters are not as accurate as the negative-sequence ones due to some unknown parameters that contribute to the zero-sequence circuits. It should be mentioned that the zero-sequence resistances cannot be assumed negligible in comparison to the zero-sequence reactance for developing a fault-location method since it might result in a large error.

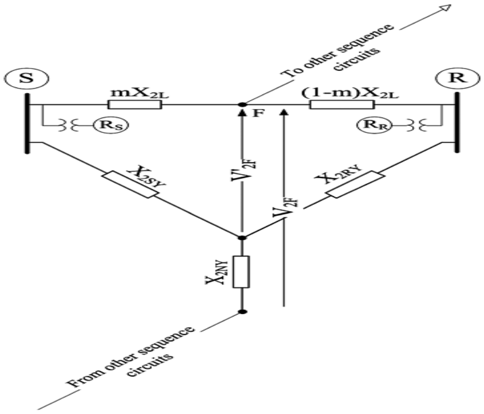

Fig. 3. Negative-sequence circuit of the double-circuit transmission line after converting the delta connection to the Y connection

The proposed concept can be readily developed for single-circuit transmission lines as well.

The major advantages of the proposed method can be summarized as follows.

- The proposed method considers the lumped parameter and PI models of a transmission line. It was found that even by considering the lumped parameter model the estimation errors are small for a long transmission line. The reason is that the proposed method does not use the current data and requires only the ratio between voltage magnitudes. Other existing methods may fail for long transmission lines if they do not consider shunt capacitances.
- Most of the existing methods require both voltage and current data at either one or both ends of

a transmission line. Since the proposed method needs only the voltage data at both ends of the line, it eliminates the errors produced by the CT measurement.

- One of the attributes of the proposed method is that it is independent of the fault resistance and fault type. The small differences in the estimation errors for different fault types and fault resistances are due to CVT measurement affected by the transients which contribute to computing errors.
    - Another interesting feature of the proposed method is that it requires only the magnitudes of negative-sequence voltages, which completely removes the need for synchronization.
- The proposed method is a purely analytical method, which effectively eliminates the computing burden to the relay.
- The only type of fault that cannot be located by the proposed method is the three-phase fault which hardly occurs on transmission lines.

CONSIDERATION OF SHUNT CAPACITANCES

To consider the effects of the line shunt capacitances on the proposed method, a PI model for the double-circuit transmission line is used. The PI model is quite accurate to obtain steady state results where the shunt capacitances should be considered.

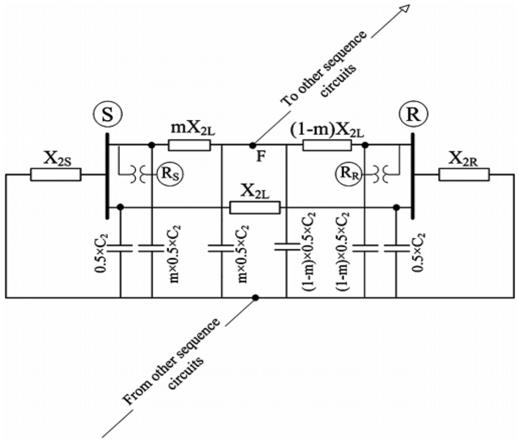

Fig. 4. Line shunt capacitances considered in the negative-sequence circuit of the double-circuit transmission line.

Based on the PI model, if an unbalanced fault occurs at location m (in p.u.) from relay in one circuit of the double circuit transmission line, the negative-sequence circuit will be as shown in Fig.4.

The capacitances of the healthy circuit are parallel to those of the faulted circuit at the sending and receiving ends. The equal capacitances at the sending and receiving ends will then be obtained as follows:

$$_2 = \frac{1+}{2}\ _2 \qquad (9)$$

$$_2 = \frac{2-}{2}\ _2 \qquad (10)$$

The equal capacitances given in (9) and (10) are parallel with the source reactances and , respectively.

SENSITIVITY ANALYSIS

It is a worthy practice to study the sensitivity of the proposed method to the required parameters. The source parameters and line parameters and are required for estimation of fault location. It is assumed that the expected value of (the ratio of negative-sequence voltage magnitude at the sending-end relay to the one at the receiving-end relay) is first measured while the fault location varies along the line.

Taking the derivative of (8) in terms of yields the sensitivity factor to the source reactance behind the sending-end relay as

$$= \ _2 = \frac{-}{\frac{\ _2}{2}} = \frac{2}{}\cdot\frac{2}{_2 + \ _2{}^2}\cdot\left[21 - \frac{2}{2} + 1\right]$$

(11)

The sensitivity factor to the source reactance behind the receiving-end relay is obtained.

EVALUATION AND SIMULATION RESULTS

The proposed method is based on the voltage data, capacitive voltage transformers (CVTs) were modeled. Different fault cases presented in Table I were considered to evaluate the proposed method.

TABLE I: DIFFERENT FAULT CASES CONSIDERED FOR EVALUATION STUDIES

Case	Fault type	Fault resistance (Ω)	Actual fault location (km)
1	Ph-G	10	[5…195] every 1 km
2	Ph-G	50	
3	Ph-G	100	
4	Ph-Ph	5	
5	Ph-Ph	20	
6	Ph-Ph	50	
7	Ph-Ph-G	10	
8	Ph-Ph-G	50	
9	Ph-Ph-G	100	

A. Accuracy Evaluation

Figs. 5–13 show the estimation errors of fault location for the different fault cases of Table I. The errors were calculated by

$$\% = \frac{-}{} * 100. \qquad (12)$$

To provide a better vision of the accuracy of the method, here it is preferred to present the real value of the percentage errors, not their absolute values. The absolute values of the estimation errors Error (%) have been used to provide the maximal and mean values of the errors shown in Table II.

TABLE II

MAXIMAL AND MEAN VALUES OF ABSOLUTE ERRORS FOR EACH FAULT CASE BASED ON THE LUMPED AND PI MODELS

Case	Lumped Model		PI Model	
	Max |Error (%)|	Mean |Error (%)|	Max |Error (%)|	Mean |Error (%)|
1	0.2311	0.1484	0.2436	0.0877
2	0.2272	0.1493	0.2437	0.0886
3	0.2245	0.1515	0.2442	0.0901
4	0.2424	0.1497	0.2430	0.0851
5	0.2399	0.1486	0.2443	0.0853
6	0.2258	0.1492	0.2454	0.0865
7	0.2823	0.1458	0.2550	0.0862
8	0.2801	0.1461	0.2524	0.0860
9	0.2805	0.1466	0.2523	0.0861

The results confirm that the proposed fault-location method is independent of the fault type and fault resistance. The small difference in the estimation errors when the fault type and fault resistance vary can be attributed to the errors generated by the instrument transformers (CVTs) and numerical calculation. It can be seen that the accuracy of the method will be quite high if the required parameters are close enough to their real values.

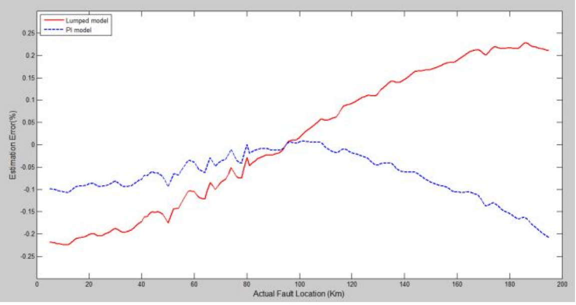

Fig. 5. Estimation errors for Case 1 based on the lumped and PI model.

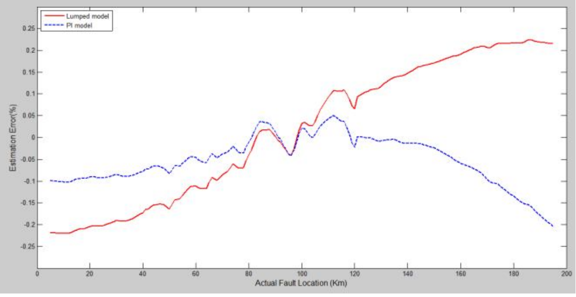

Fig. 6. Estimation errors for Case 2 based on the lumped and PI model.

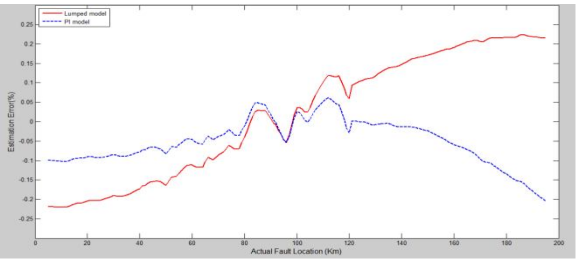

Fig. 7. Estimation errors for Case 3 based on the lumped and PI model.

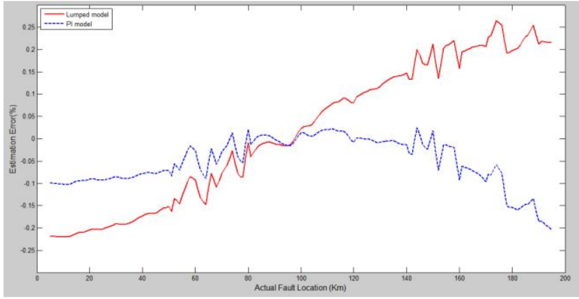

Fig. 8. Estimation errors for Case 4 based on the lumped and PI model.

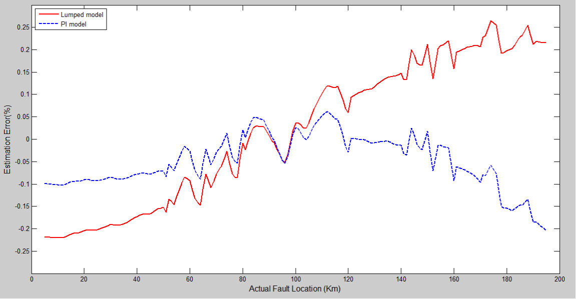

Fig. 9. Estimation errors for Case 5 based on the lumped and PI model.

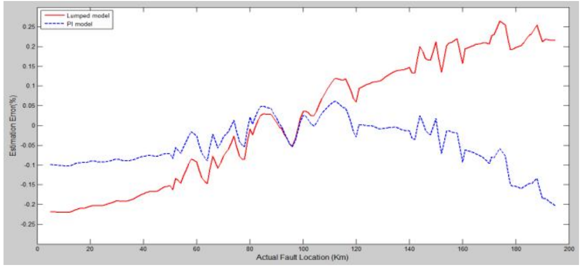

Fig. 10. Estimation errors for Case 6 based on the lumped and PI model.

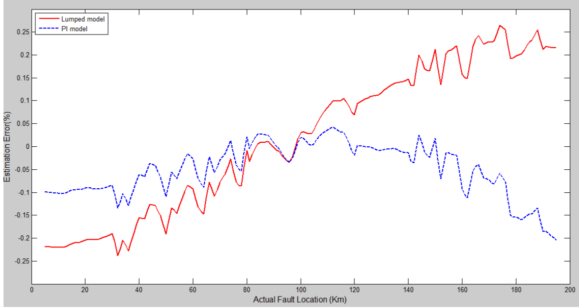

Fig. 11. Estimation errors for Case 7 based on the lumped and PI model.

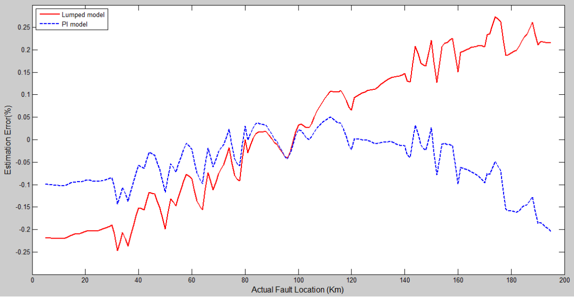

Fig. 12. Estimation errors for Case 8 based on the lumped and PI model.

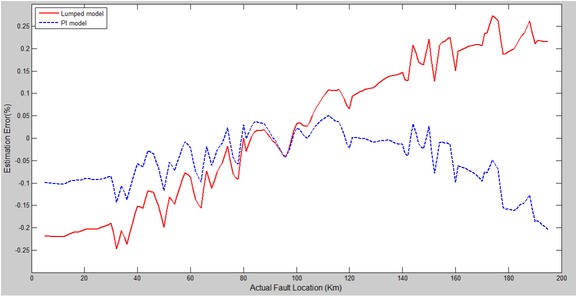

Fig. 13. Estimation errors for Case 9 based on the lumped and PI model.

B. Sensitivity Evaluation

Fig. 14 shows the measured value of for different fault locations in the simulated system. The normalized sensitivity factors to and are, respectively, represented by and and shown in Figs. 15 and 16. In case of a fault location farther from relay , the accuracy will even be higher.

It is worth investigating how much the estimation errors would be if both source reactance simultaneously deviate from their real values. To do this, it was assumed that the source reactance used.

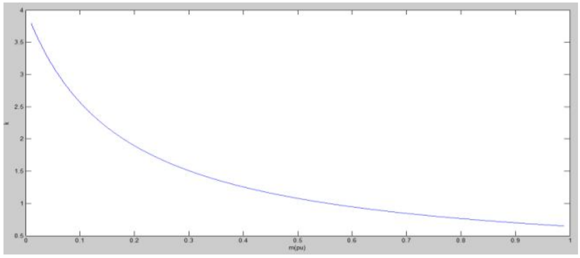

Fig. 14. Variation of k for different fault locations.

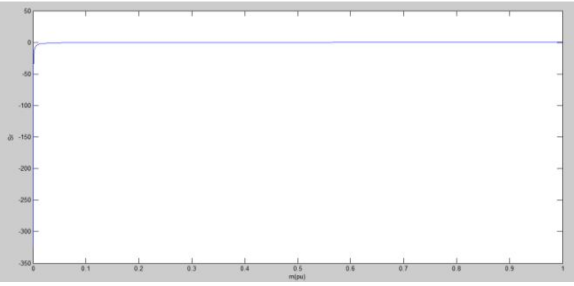

Fig. 15. Sensitivity factor to the source reactance behind the receiving-end relay for different fault locations based on the lumped model.

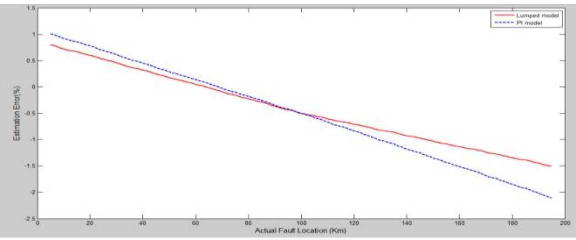

Fig. 16. Estimation errors for a deviation of 10% in source reactances (case: 1.1 X and 1.1 X).

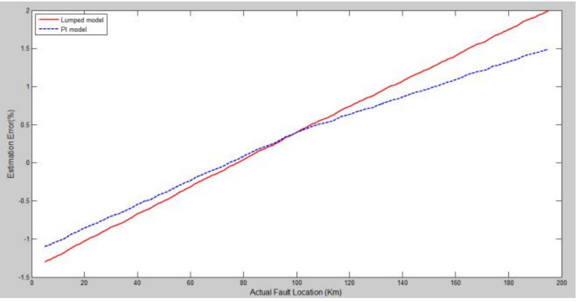

Fig. 17. Estimation errors for deviation of 10% in sourcereactances (case: 0.9 X and 0.9 X).

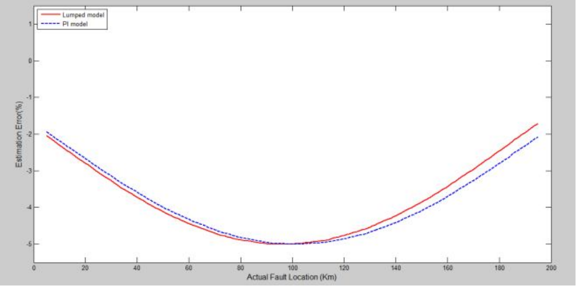

Fig. 18. Estimation errors for deviation of 10% in source reactances (case: 1.1 X and 0.9 X)

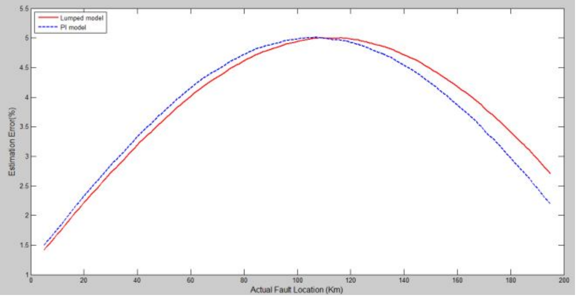

Fig. 19. Estimation errors for deviation of 10% in source reactances (case: 0.9 X and 1.1 X).

CONCLUSION

A new fault-location method for double-circuit transmission lines is proposed in this paper. It is a steady-state-based method based on the ratio of negative-sequence voltage magnitudes at both ends of the line. The proposed method can effectively locate the single-phase-to-ground, double phase-to-ground, and phase-to-phase faults disregarding the fault resistance and pre-fault conditions and without any need for fault classification and phase selection. A new approach to fault location for double-circuit transmission lines based on only the voltage data of both ends of the faulted circuit is proposed in this paper. This paper puts forward a novel algorithm for locating faults on double-circuit transmission lines using two-end unsynchronized current measurements. By using the simulation results we can analyze the proposed method.

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