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Analysis of Performance of Impedance based and Travelling based Fault Location Algorithms on 400kV Transmission Line

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***Abstract*— For the past fifty years, electric power systems have rapidly grown. This has resulted in a large increase of the number of lines in operation and their total length. These lines experience faults which are caused by storms, lightning, snow, freezing rain, insulation breakdown and short circuits caused by birds and other external objects. In most cases, electrical faults manifest in mechanical damage, which must be repaired before returning the line to service. The restoration can be expedited if the location of the fault is either known or can be estimated with reasonable accuracy. Speedy and precise fault location plays an important role in accelerating system restoration, reducing outage time and significantly improving system reliability. This paper provides a comprehensive review of the conceptual aspects as well as recent algorithmic developments for fault location on 400kV high voltage transmission line. Several fundamentally different approaches are discussed in the paper together with the factors affecting the assumptions of the underlying concepts and the various criteria used in the different approaches are reviewed.**

***Index Terms*—Wavelet Transform; Fault current distribution factor; distance to fault location; Transmission line;WMM;fault inception angle; fault resistance; traveling waves.**

I. INTRODUCTION

An Electric Power System comprises of generation, transmission and distribution of electric energy. Transmission lines are used to transmit electric power to distant large load centers. The rapid growth of electric power systems over the past few decades has resulted in a large increase of the number of lines in operation and their total length. These lines are exposed to faults as a result of lightning, short circuits, faulty equipments, mis-operation, human errors, overload, and aging. Many electrical faults manifest in mechanical damages, which must be repaired before returning the line to service. The restoration can be expedited if the fault location is either known or can be estimated with a reasonable accuracy. Faults cause short to long term power outages for customers and may lead to significant losses especially for the manufacturing industry.

II. WAVELET TRANSFORM

Wavelet transform (WT) is a mathematical technique used for many application of signal processing. Wavelet is much more powerful than conventional method in processing the stochastic signals because of analyzing the waveform time-scale region. In wavelet transform, the band of analysis can be adjusted so that low frequency and high frequency components can be windowing by different scale factor. Recently WT is widely used in signal processing applications, such as denoising, filtering, and image compression. Many pattern recognition algorithms have been developed based on the wavelet transforms. It also has been used widely by the power system researchers. According to scale factor, wavelet categorized different section. In this paper the wavelet which is named Discrete Wavelet Transform (DWT) by two scale factor was used. For any function (f). The function is the base Wavelet if it satisfies the equation

$$\int_{-\infty}^{\infty} |\Psi(t)|^2 dt < \infty \quad (1)$$

The function family $\Psi_{s,b}(t)$ generated through dilation parameter ‘s’ and transmission parameter ‘b’ is defined as,

$$\Psi_{s,b}(t) = \frac{1}{\sqrt{s}} \Psi\left(\frac{t-b}{s}\right), s, b \in R, s \neq 0 \quad (2)$$

Where R is a set of real numbers. The wavelet transform of any function x(t) is defined as,

$$W_f(s,b) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t)\, \Psi^* \left(\frac{t-b}{s}\right) dt \quad (3)$$

$\Psi^* \left(\frac{t-b}{s}\right)$ is a conjugate of Wavelet transform $\Psi\left(\frac{t-b}{s}\right)$.

Wavelet transform Wf (s,b) depends on scale factor and translation factor. Through variation of scale factor, the wavelet transform can be applied to high frequency components where

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short time intervals are necessary. Therefore, it is a suitable approach to analyze the traveling waves. If s= $\frac{1}{2^j}$ (j ∈ Z, Z is a set of integers) and b ∈ R (R is a set of real numbers), then it is a dyadic wavelet transform. It is translation invariant and hence used in signal edge detection.

Wavelet Modulus Maxima (WMM) of wavelet transforms are the local maxima of wavelet transform satisfying the following condition:

$$|W_m\, x(t)| \leq A\, s^{\alpha} \qquad (4)$$

where, $W\,x(t)_m$ is the WMM of signal $x(t)$, A is constant, and α is the Lipschitz exponent.

Modulus maxima represent the singularity of step signal. The polarity of WMM is identical to polarity of sudden change of the signal and its magnitude depends on the amplitude and gradient of the sudden change of the signal. In this paper, WaveLab is used to obtain WMM. WaveLab which is available from Stanford University can be used as an alternative to the MATLAB wavelet toolbox.

III. FAULT LOCATION ALGORITHMS

A.Impedance Based Alorithm

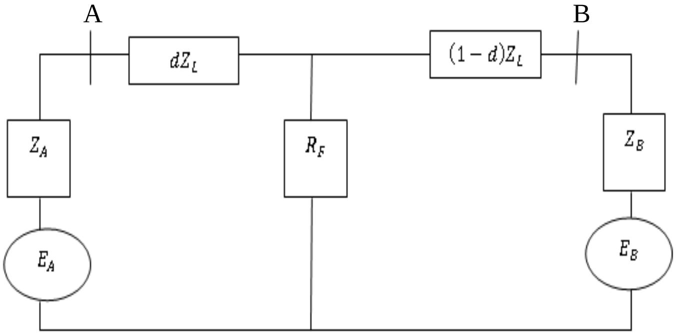

Fig.1 fault network

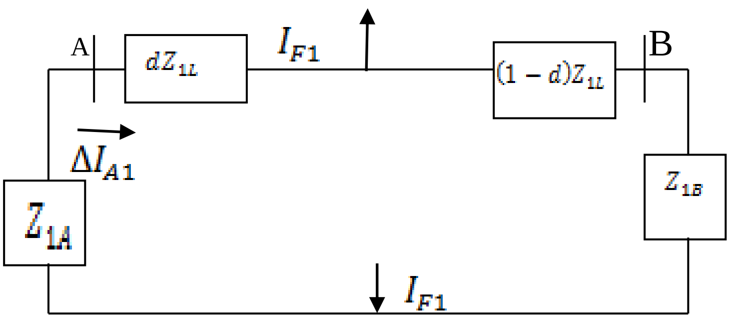

Fig.2 Incremental positive sequence network for method

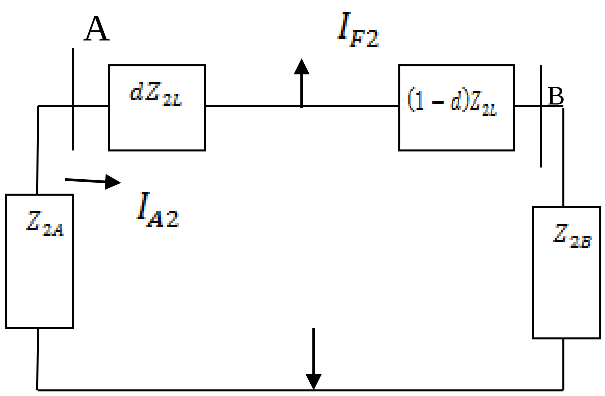

Fig.3 Negative sequence network for method

In the Fig.1, Fig2 and Fig.3

d	Estimated distance to the fault (units: p.u)
V_{A_P}	Protective distance relay voltage at the line end A
I_{A_P}	Protective distance relay current at the line end A
I_F	Total fault current
Z_L	Total line impedance
V_F	Fault voltage
Z_A, Z_B	Source impedances at terminals A and B respectively
E_A, E_B	Source voltages at terminals A and B respectively
ΔI_{A1}	Incremental positive sequence current.
I_{A2}	Negative sequence current
Z_{1L}	Total positive sequence line impedance
Z_{2L}	Total negative sequence line impedance
Z_{1A} , Z_{1B}	Positive sequence source impedances at terminals A and B respectively
Z_{2A} , Z_{2B}	Negative sequence source impedances at terminals A and B respectively.

To derive the Fault location algorithm, the fault loop composed according to the fault classified type is considered. This loop contains the faulted line segment (between points AA and F) and the fault path itself. A generalized model for the fault loop is stated as fallows

$$V_{A\_P} - dZ_{1L} * I_{A\_P} - I_F * R_F = 0 \qquad (5)$$

Where

$$I_F = a_{F1} * I_{F1} + a_{F2} * I_{F2} + a_{F0} * I_{F0} \qquad (6)$$

Fault loop voltages and current can be expressed interns of the local measurements and with using coefficients gathered in Table 1.

$$V_{A\_P} = a_1 V_{A1} + a_2 V_{A2} + a_0 V_{A0} \qquad (7)$$

$$I_{A\_P} = a_1 I_{A1} + a_2 I_{A2} + a_0 \frac{Z_{0L}}{Z_{1L}} I_{A0} \qquad (8)$$

Table 1. Coefficients for determining signals defined in Equations (7) and (8)

Fault Type	a_1	a_2	a_0
AG	1	1	1
BG	a^2	a	1
CG	a	a^2	1
$AB, ABG, ABC, ABCG$	$1-a^2$	$1-a$	0
BC, BCG	a^2-a	$a-a^2$	0
CA, CAG	$a-1$	a^2-1	0
$a = exp(j2\pi/3)$			

Voltage drop across the fault path (as shown in the third term in Equation (5)) is expressed using sequence components of total fault current (I_{F0}, I_{F1}, I_{F2}). Determining this voltage drop requires establishing the weighting coefficients. These coefficients can accordingly be determined by taking the boundary conditions for particular fault type. However, there is some freedom for that. Thus, it is proposed firstly to utilize this freedom for avoiding zero sequence quantities. This is

The total fault current (I_F) is expressed as weighted sum of its symmetrical components (I_{F1}, I_{F2}, I_{F0}), which can be determined with use of fault current distribution factors:

$$I_{F1} = \frac{\Delta I_{A1}}{k_{F1}} \quad (15)$$

$$I_{F2} = \frac{I_{A2}}{k_{F2}} \quad (16)$$

Table 2: Alternative sets of weighting coefficients

Fault type	Set I			Set II		
	a_{F1}	a_{F2}	a_{F0}	a_{F1}	a_{F2}	a_{F0}
AG	0	3	0	3	0	0
BG	0	$-1.5+j1.5\sqrt{3}$	0	$-1.5-j1.5\sqrt{3}$	0	0
CG	0	$-1.5-j1.5\sqrt{3}$	0	$-1.5+j1.5\sqrt{3}$	0	0
AB	0	$1.5-j0.5\sqrt{3}$	0	$1.5+j0.5\sqrt{3}$	0	0
BC	0	$j\sqrt{3}$	0	$-j\sqrt{3}$	0	0
CA	0	$-1.5-j0.5\sqrt{3}$	0	$-1.5+0.5\sqrt{3}$	0	0
ABG	$1.5+j0.5\sqrt{3}$	$1.5-j0.5\sqrt{3}$	0	$1.5+j0.5\sqrt{3}$	$1.5-j0.5\sqrt{3}$	0
BCG	$-j\sqrt{3}$	$j\sqrt{3}$	0	$-j\sqrt{3}$	$j\sqrt{3}$	0
CAG	$1.5-j0.5\sqrt{3}$	$1.5+j0.5\sqrt{3}$	0	$1.5-j0.5\sqrt{3}$	$1.5+j0.5\sqrt{3}$	0
$ABC, ABCG$	$1.5+j0.5\sqrt{3}$	$1.5-j0.5\sqrt{3}$	0	$1.5+j0.5\sqrt{3}$	$1.5-j0.5\sqrt{3}$	0

Well known that the zero sequence impedance of a line is considered as unreliable parameter. This is so due to dependence of this impedance upon the resistivity of a soil, which is changeable and influenced by weather conditions. Moreover, as a result of influence of overhead ground wires, the zero sequence impedance is not constant along the line length. Thus, it is highly desirable to avoid completely the usage of zero sequence quantities when determining the voltage drop across the fault path. This can be accomplished by setting $I_{F0} = 0$ as shown in Table 2, where the alternative sets of the weighting coefficients are gathered. Secondly, the freedom in establishing the weighting coefficients can be utilized for determining the preference for using particular quantities. The negative sequence (Table 2) or the positive sequence (Table 2) can be preferred

For example, considering AG fault one has:

$$\begin{vmatrix} I_{F0} \\ I_{F1} \\ I_{F2} \end{vmatrix} = \frac{1}{3} * \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} * \begin{vmatrix} I_{FA} \\ 0 \\ 0 \end{vmatrix} \quad (9)$$

Thus, symmetrical components of a fault current are:

$$I_{F0} = I_{F1} = I_{F2} = \frac{1}{3} * I_{FA} = I_F \quad (10)$$

It follows from Equation (10) that the total faults current ($I_F = I_{Fa}$) can be expressed in the following alternative ways, depending on which symmetrical component is preferred:

$$I_F = 3 * I_{F1} \quad (11)$$

$$I_F = 3 * I_{F2} \quad (12)$$

$$I_F = 3 * I_{F0} \quad (13)$$

$$I_F = 1.5 * I_{F1} + 1.5 * I_{F2} \quad (14)$$

$$I_{F0} = \frac{I_{A0}}{k_{F0}} \quad (17)$$

Taking into account a set of weighting coefficients that for zero sequence: $a_{F0} = 0$ and expressing the symmetrical components of total fault current with use of fault current distribution factors and one obtains:

$$I_F = a_{F1}\frac{\Delta I_{A1}}{k_{F1}} + a_{F2}\frac{I_{A2}}{k_{F2}} \quad (18)$$

Considering that for the fault current distribution factors for positive- and negative-sequence, with respect to their magnitude and angle, we have

$$k_{F1} = k_{F2} = |k_F| e^{j\gamma} \quad (19)$$

$$\gamma = angle(k_{F1}) = angle(k_{F2}) \quad (20)$$

The Equation (18) can be rewritten as

$$I_F = \frac{a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2}}{|k_F| e^{j\gamma}} \quad (21)$$

Substitute Equation (21) in the basic Equation (5)

$$V_{A\_P} - dZ_{1L} * I_{A\_P} - \frac{a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2}}{|k_F| e^{j\gamma}} * R_F = 0 \quad (22)$$

Multiplying the Equation (22) by the term$(e^{j\gamma}(a_{F1}\Delta I_{A1} + a_{F2} I_{A2})^*)$ yields

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$$V_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^* * e^{j\gamma} - dZ_{1L} * I_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^* * e^{j\gamma} - \frac{R_F}{|k_F|} = 0 \quad (23)$$

Eliminating the term $\frac{R_F}{|k_F|}$ by taking imaginary parts of the Equation (23) and then rearranging, the resultant formula for the sought distance to fault (d (p.u.)) is obtained as follows:

$$d = \frac{Im\left(V_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^* * e^{j\gamma}\right)}{Im\left(Z_{1L} * I_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^* * e^{j\gamma}\right)} \quad (24)$$

$$d = \frac{Im\left(V_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^*\right)}{Im\left(Z_{1L} * I_{A\_P} * (a_{F1} * \Delta I_{A1} + a_{F2} * I_{A2})^*\right)} \quad (25)$$

The signals that are processed in the fault-location algorithm (25) are determined from measurements acquired at one line terminal (here, at the terminal A).Table 2 shows how to set the coefficients involved in the algorithm.

In formula (24), the angle of the current distribution factor (for the positive or negative-sequence) is involved. In it is proposed to assume that this angle equals zero ($\gamma = 0$), i.e., that the fault current distribution factor is a real number. In practice, this assumption is not completely fulfilled and thus there is a certain error due to this.

B.Travelling Wave Based Algorithm

The proposed fault location algorithm using Wavelet Transform is show in the following steps :

1. Get the signals from transducer output.
2. Transform the signals into modal domain.
3. Apply Discrete Wavelet Transform and obtain the Wavelet Transform Coefficients (W_{mm}).
4. If the mode 0 (W_{mm0})is zero, then the fault is identified as an ungrounded fault and the fault distance is given by the equation :

$$d = (v \times t_d)/2 \quad (26)$$

where d is the fault location from source A, v is the wave velocity of mode 1 having magnitude slightly less than velocity of light, and t_d is the time gap between first two peaks of WTC of mode 1.

5. If the mode 0(W_{mm0}) is nonzero, then the fault is identified as a grounded fault and the calculate the time gap t_{dm} between the first peaks of mode 0 and mode 1.

If $t_{dm} > t_{l/2}$, then

$$t_d^l = (2l/v) - t_x \quad (27)$$

$$d = (v \times t_d^l)/2 \quad (28)$$

where $tl/2$ is the travel time delay between mode 0 and mode 1 if the fault is located at the center of the line, x is the distance to the fault, v is the wave velocity of mode 1, and tx is the time delay between two consecutive peaks of the WTC mode 1.

Else, the fault distance using (Fault is in second half section of line).

$$d = (v \times t_d)/2 \quad (29)$$

IV. POWER SYSTEM MODEL

The SimPowerSystem which is an extension to the Simulink of MATLAB software was used to simulate the double end fed power system. The 100 km, 400 kV single circuit transmission line was modeled using distributed parameter model as shown in Fig.3

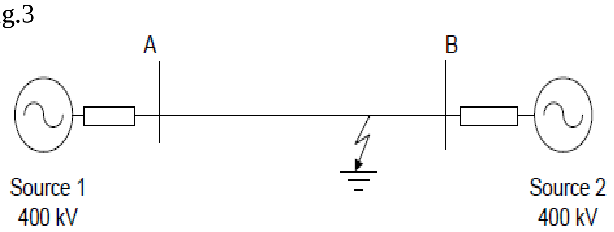

Fig.4 Power System model

The transmission line parameters are as follows:

Positive Sequence Resistance, R_1 : 0.0275 Ω / km
Zero Sequence Resistance, R_0 : 0. 275 Ω/km
Zero Sequence Mutual Resistance, R_{0m} : 0.21 Ω/km
Positive Sequence Inductance, L_1 : 0.00102 H/km
Zero Sequence Inductance, L_0 : 0.003268 H/km
Positive Sequence Capacitance,C_1 : 13 $e^{-0.009}$ F/km
Zero Sequence Capacitance, C_0 : 8.5 $e^{-0.009}$ F/km

V.SIMULATION RESULTS

The simulation is carried out for these algorithms by varying various fault parameters like fault inception angle, fault resistance, fault type, fault location. The accuracy of fault location of these three algorithms are compared and shown in Table.3.

Table 3. Test results for R_F=54 ohms and FIA=72^0 for 400KV Transmission line

Fault Type	Actual fault location	Impedance Based Alogirthm		Travelling Wave Based Algorithm	
		d_{esti}	Error%	d_{esti}	Error%
AG	10	9.6817	0.3183%	9.7584	0.241%
BG	20	19.7033	0.2967%	19.661	0.338%
CG	30	29.36	0.639%	29.334	0.665%
AB	40	40.0723	0.0723%	39.317	0.682%
BC	50	49.20	0.793%	49.220	0.779%
CA	60	59.18	0.812%	59.179	0.820%
ABG	70	69.23	0.766%	69.224	0.775%
BCG	80	79.36	0.637%	79.357	0.64%
CAG	85	84.364	0.636%	84.678	0.322%
ABC,A BCG	90	89.96	0.039%	89.988	0.012%

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The fault location error is calculated as

$$Error(\%) = \frac{|Calculated\ Fault\ Location - Actual\ Fault\ Location|}{Total\ Line\ Length} * 100 \quad (30)$$

VI. CONCLUSION

An accurate traveling wave based algorithm for fault distance location on double circuit transmission line fed from sources at both ends is presented covering all types of faults in both the circuits. The algorithm effectively eliminates the effect of varying fault type, fault location, fault resistance, fault inception angle, mutual coupling and remote source infeed. The complexity of all ten types of faults, fault locations (0-100km), fault inception angles (0-90^0), fault resistance (0-100 Ω) are considered. The simulation results show that all ten types of faults are correctly located with fault location error less than 1%.

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