Fault Location on Transmission Line Using High Frequency Travelling Waves

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Abstract **– This paper describes how travelling wave caused by a fault on a transmission line can be used for fault location. Information extracted from the secondary currents and voltages, measured at one terminal, is used to determine the location of fault on transmission line. The fundamental idea is to correlate the initial transients at the relaying terminal from fault point with the afterwards transients. The algorithm is insensitive to fault type, fault resistance, fault inception angle and system source parameters.**

Keywords – Travelling waves, Transmission lines, Fault location

I. INTRODUCTION

Conventional methods of fault location and protection for transmission lines, such as distance and phase comparison schemes, are based on fundamental components of faulted waveforms of voltages and currents measured at line terminals. The idea of using high frequency travelling waves generated by faults for protection purposes was initially proposed by Dommel and Michels [1]. Several researchers have reported work in this area, where some of recent ones can be found in References [2-9]. The protection requirements of reliability, speed and selectivity can be better achieved by this method. However, due to hardware deficiency the idea could not be put in practice until quite recently, when the advent of powerful processors combined with Global Positioning Systems (GPS) has brought first generation of this type of relays into market. Fault location can be provided by comparing the arrival time of initial transients at two terminals of a line. The arrival time can be time stamped using GPS. Arrival time difference at the terminal would gives the deviation of fault location from mid-point of the line.

II. TRAVELLING WAVES GENERATED BY FAULTS

Following the occurrence of a fault on a transmission line, changes of stored energy in line capacitance and inductance produce travelling waves, which travel from fault point to the line terminals. During a short circuit fault the line capacitance reduces in faulted phases, causing discharge of its stored energy. This discharging and charging phenomenon generates waves travelling at a speed near light velocity. Travelling waves have oscillating and damping nature. Their frequency of oscillation and damping time are dependent on the line parameters and fault loop impedance, which includes source impedance, line impedance and fault path impedance. The frequency of travelling waves ranges from a few Hz. to several 10 kHz.

In general, for a single phase faulted system shown in Fig. 1 the fault generated travelling waves are given by the following equations:

$$v_A(t) = V\left[\frac{L_S}{L_S + L_{AF}} e^{-t/\tau} \cos\beta \cos(\omega_h t)\right] \quad (1)$$

$$i_A(t) = -I\left[h e^{-t/\tau} \sin\alpha \sin(\omega_h t)\right] \quad (2)$$

$$\omega_h = \sqrt{\frac{L_S + L_{AF}}{C L_S L_{AF}}} \quad (3)$$

where in the above equations:

$$h = \frac{\omega}{\omega_h} \quad , \quad I = \frac{V}{\omega(L_S + L_{AF})}$$

$$\tau = \frac{2L}{R} \quad , \quad R = R_S + R_{AF}, L = L_S + L_{AF}$$

$$\alpha = \beta - \tan^{-1}(\omega \frac{L}{R})$$

and

A: the relaying point
F: the fault point
β: Voltage angle at fault inception
R_S, L_S: source resistance and inductance
R_{AF}, L_{AF}:Line resistance and inductance from relaying point to fault point

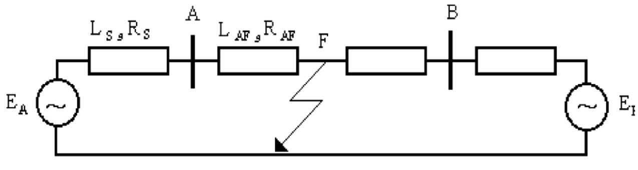

Fig. 1 Transmission line equivalent circuit

III. TRANSMISSION LINE MODELLING

For the simulation of a transmission line for travelling wave studies, the distributed nature and frequency dependency of the line should be considered. Constant line parameters at power frequency are valid for steady state studies of the power system under normal conditions and cannot be used for transient states analysis over a wide range of high frequency modelling, as this would overestimate high frequency components.

Several methods of accurate frequency dependant modelling have been reported in the literature. However, the frequency dependency of line parameters differs for different ranges of frequency and therefore most methods are not efficient. Although line simulation in frequency domain is more convenient, it could not be used for the study of nonlinear behaviour of power system elements and transient states phenomena such as switching and arcing faults. It is therefore more convenient and efficient to use step by step solution in time domain. The complexity and difficulties arisen from time domain simulation has been overcome by the advent of powerful computers. In the work presented in this paper the transmission line modelling is based on a frequency dependent modelling of transmission lines proposed by Marti [10].

From the foregoing it is evident that the Transient Electromagnetic Program (EMTP) has played an important role nearly in all travelling wave studies reported so far. The work presented here is also based on this powerful tool for power system transient studies.

IV. Fault Location Method

When a fault occurs on a transmission line, the fault initiated travelling waves are transmitted from the fault point to the line terminals at nearly speed of the light in free space. The faulted voltage and current waveforms at any point on the line can be considered of two components; one is due to sinusoidal steady state condition, the other due to the application of fault. The latter component is often called the superimposed quantity and is simply equal to the change in the current and/or voltage due to a disturbance [11]. The superimposed component of the faulted waveform is used for the fault location method. There are both voltage and current waves induced by fault, V_f and I_f, that are related by characteristic impedance and each composed of a forward and a backward component as given by the following equations:

$$v_f(x,t)=(F_1(t-x/c)+F_2(t+x/c))/2$$
$$i_f(x,t)=(F_1(t-x/c)-F_2(t+x/c))/2Z_0 \quad (4)$$

where C is the propagation velocity, Z_0 is the characteristic impedance and x is the distance travelled by waveform. For the relaying point this is the distance to the fault. Based on the forward and backward travelling waves two relaying signals are defined as below:

$$s_F(t)=v_f(x,t)+Z_0 i_f(x,t)=F_1(t-x/c)$$
$$s_B(t)=v_f(x,t)-Z_0 i_f(x,t)=F_2(t+x/c) \quad (5)$$

In the above equations s_F and s_B represent forward and backward waveforms, respectively.

The fault location method can be best explained by referring to Fig. 2, which shows the lattice diagram for a single phase transmission line. The superimposed voltage at the fault point F and its associated superimposed current propagates towards the relaying point R. If the relaying signal s_F is formed from the above voltage and current initiated by a fault at F and travels to R is reflected by the impedance discontinuity behind the relay. The reflected voltage and current waves then propagate back towards the fault, where they are reflected back towards end R. Assuming the arcing fault resistance at the fault point is negligible compared with the line characteristic impedance, as this is the most common case, then the coefficient of reflection at the fault point would equal to minus unity. The important conclusion from this analysis is that the relaying signal s_F that leaves the relay point towards the fault would be reflected back to the relay, with almost the same magnitude but opposite polarity. A similar analysis can be carried out with regard to s_B reveals that it is changed at the relaying point , in exactly the same manner as the signal s_F. It follows that if the time between like changes in s_F and s_B is equal to t_f, with the known propagation velocity v, the distance to fault can be obtained from the following equation:

$$x_f=\frac{v.t_f}{2} \quad (6)$$

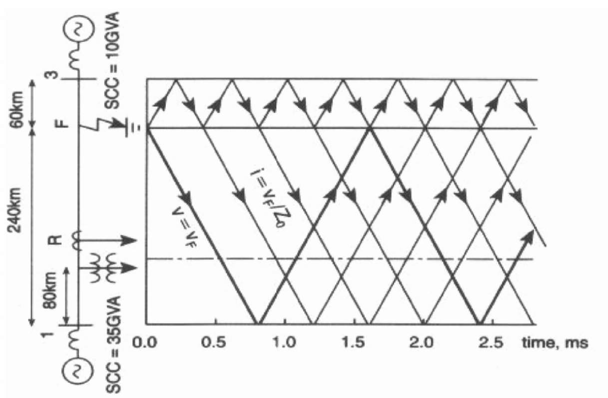

Fig. 2 Faulted transmission line and lattice diagram

The main idea of the fault location here is based on the correlation of the incident and reflected waves at the relaying point. Following a fault, the arrival of initial transients of forward signal can easily be detected. If this waveform is correlated with the reflected waveform, the next maximum will occur only when the reflected waveform has arrived at the relaying point again. The time difference between these two peaks would be t_f, and then by using Eqn. (6) the distance to fault can be measured. It should, however, be noted that the reflected waveform from the fault point has opposite polarity and therefore the correlation should be carried out with minus of the reflected waveform from the relaying point.

A. Identifying Desired Reflected Wave

By using the correlation function the desired reflected wave can be easily identified from many other waves, which are present at the relaying point. Theory of correlation is well documented in mathematics text books. By general definition, similar changes of two variables is called correlation. When changes are in the same direction it is called positive correlation, while their opposite changes is negative correlation. When changes of two variables are irrelevant of each other, they are not correlated. Carl Pearson defines the coefficient of correlation between two variables of x and y as below:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\left[\sum(x-\bar{x})^2\sum(y-\bar{y})^2\right]^{1/2}} = \frac{\operatorname{cov}(x,y)}{\sigma_x\sigma_y} \quad (7)$$

where $\bar{x}$ and $\bar{y}$ are mean values of x and y, respectively. σ_x and σ_y are standard deviations of x and y respectively. Cov(x,y) is the covariance of x and y.

For the fault location algorithm here x is the first transmitted wave from the fault point sampled at a frequency of 20 kHz. Variable y is obtained from the subsequent travelling waves measured at the relaying point. In practice, x and y are the forward and backward waveforms given by Equation 5.

The correlation between x and y is evaluated. The variable window of y is moved forward for one sample once the correlation function has been calculated for the previous sample. This continues until the desired wave is identified. The time difference between x and the identification of desired reflected wave is used to calculate the fault distance from Eqn. (6).

B. Modal Analysis

The above analysis is only valid for single-phase transmission line. It is well known in power system analysis that a three phase perfectly balanced system can be decomposed into equivalent symmetrical components of positive, negative and zero sequences. However, the symmetrical transformation matrix cannot be used for this study as they are complex values for phasor analysis and here travelling wave theory is used for real time study. Different real value transformation matrices are available, such as Wedepohl, Karrenbauer, and Clark transformation [11]. For this study the Karrenbauer transformation below has been used.

$$S = Q = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -2 \\ 1 & 1 & -2 \end{bmatrix} \quad (8)$$

V. SIMULATION RESULTS

EMTP has been used to study the performance of the fault location algorithm under different fault conditions. Many simulation tests have been carried out for different line and source configurations for faults at different locations with various fault resistances. For the simulation results here, a typical British 400kV transmission line with horizontal configuration and two earth-wires has been used. Phase conductors resistance and reactance are respectively 0.052 and 0.27 ohm/km, where for the earth conductor these values are 0.36 and 0.1 ohm/km. The skin effect coefficient for phase conductor is 0.32 and for the earth conductor is 0.18. Number of bundles for all conductors are 4. The line has been considered completely transposed. The source impedances have a resistance of 5 ohms and a reactance of 180mH.

A. Single Phase to Earth Fault

A single phase to earth fault on phase A has been applied at 420km of the line. The voltage angle of phase A at fault instant was 150 degrees. Fig. 3 shows the magnitude of correlation function along the line for a 50 ohms fault resistance. It can be seen that the fault point is at 425.65 km from the relaying point, which has an acceptable accuracy.

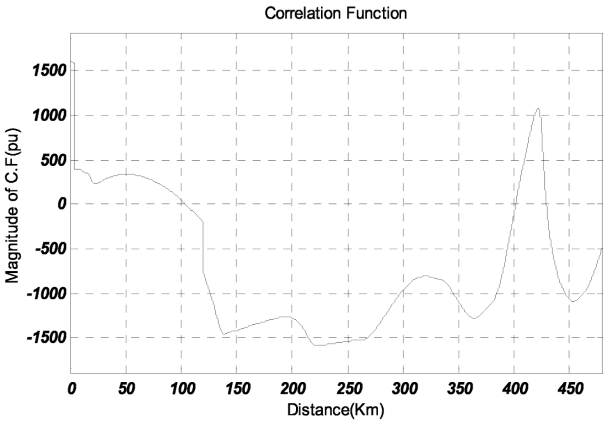

Fig. 3 Correlation function for single phase to earth fault

B. Double Phase to Earth Fault

A double phase to earth fault involving phases A and C has been applied at 85km from the relay point. The fault resistance was zero and voltage angles for phases A and C were150 degrees and -90 degrees, respectively, at the instant of the fault. Fig. 4 shows the resultant correlation function along the line length. A fault location of 85.35km can be measured from the figure, which is an accurate result.

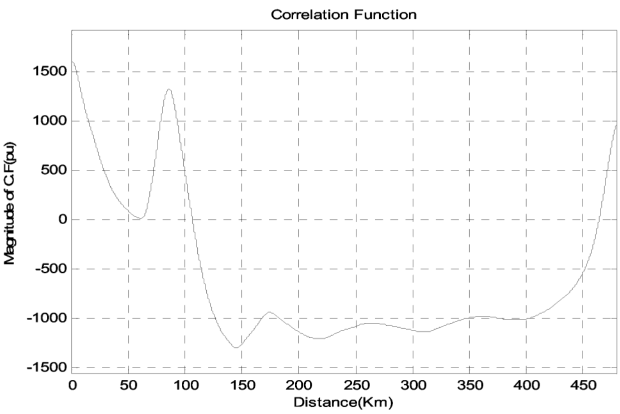

Fig. 4 Correlation function for double phase to earth fault

C. Three Phase to Earth Fault

For this case a fault has been applied at 250km from the relay point. The phase A voltage angle was 150 degrees. The algorithm response has been given for 50 ohms fault resistance in Fig. 5. The fault location has been measured at 251.65 km, which is also an accurate result.

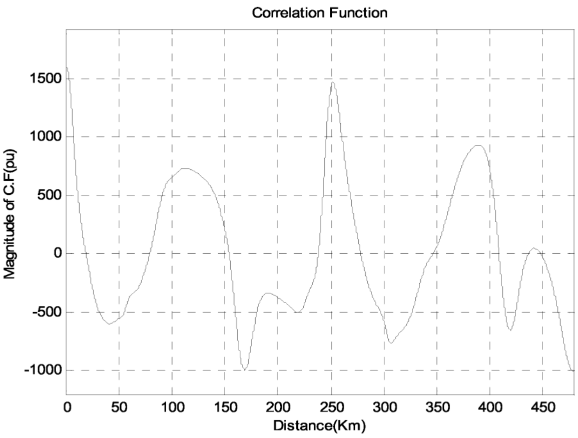

Fig. 5 Correlation function for three phase fault

VI. CONCLUSIONS

A travelling wave based fault location algorithm has been studied by using EMTP. The technique which is based on correlating the first incident wave from the fault point with the subsequent reflected waves, gives accurate result for fault location on long transmission lines. The fault location is not affected by fault resistance, source impedance, and fault inception angle. It is also important that accuracy of the fault location is not affected by line length. For long lines, say, longer than 100km, the line capacitance is considerable. This is a major source of error for most conventional fault locators, which ignore line capacitance for simplicity.

The processing time for fault location is only few milli-seconds, which makes it possible to use the algorithm for protection purposes as well.

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