Protection of Power Transmission Line

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Abstract -- This paper investigates travelling wave based protection schemes developed for high voltage transmission systems and their adaptation to medium voltage distribution networks in order to enable ultra-high speed relaying (within a quarter of a cycle of the power frequency) on a medium voltage level. This further demonstrates that the travelling wave based protection provides a high speed and very accurate fault detection. The given method compares the polarities of current and voltage travelling waves measured immediately after the fault inception to determine the fault direction.

Indexed Terms: Travelling Wave, Protection, Transmission Line, Fault Point, High Frequency Electromagnetic signal, Relay, Busbar

I. INTRODUCTION

A public supply system is set up to transport and distribute electrical energy from the generators to the users. Due to the interconnection of a large number of generators (power plants) high reliability is expected. An important role in maintaining this high reliability is played by the power protection system. The function of the protection system is to disconnect defective lines and apparatus from the system without delay. This paper concerns the detection and disconnection of faults on high-voltage lines (Bollen, 1989).

Before the turn of the century, power system protection was mainly affected by using fuses. This century showed the introduction of protective relays in combination with circuit-breakers. The relay to detect the fault and circuit breakers to isolate the faulted section. The protective relay uses voltages, currents or both to detect a fault. Then, a tripping signal is sent to the circuit breaker which disconnects the faulted section of the power system. At first, simple relays were used, like time overcurrent relays, directional-power relays, voltage relays, etc. The selectivity of these relays needs to be improved in order to meet the pre-set day demand.

The distance protection relay is one of these new developments. From one end of the line, they measure the total line impedance and operate when the measured impedance is lower than the pre-set value.

To ease fault clearance, the distance relay is zoned for proper discrimination: Zone 1 reach covers about 80% of the line from the relay end. Zone 2 covers additional 40 to 45%. That is,120 - 125% of the line from the relay end and zone3 covers about 250% of the line. These settings can be adjusted by the protection engineer to suit the environment (Ezechukwu, 2012).

The timings of the protection zones are such that $t_1<t_2<t_3$. Where t_1, t_2 and t_3 are zones 1, 2 and 3 operating times respectively. Usually, t_1 is to operate instantaneously and t_2 and t_3 depend on the area's protection time grading. Sometimes, zone3 is required to look backwards in order to cover faults at the busbar and at times the transformer feeding the circuit breaker and the relay. The reach of zone 3 reverse (-ve offset) is usually set between 15 to 20% of the line.

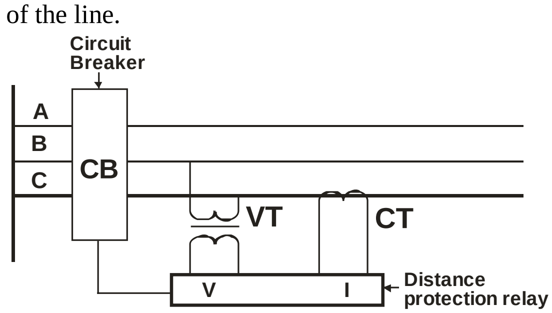

Figure 1: Protection of a high-voltage line by means of distance relay

When reliable communication links are available it is possible to use information from both 1ine terminals. In that case each fault on the line wi11 be seen by the two relays at both ends before tripping can be initiated. A relay uses impedance of the line. If the impedance seen by the relay is lower than the pre-set impedance, a tripping signal is generated.

II. TRAVELING WAVE PROTECTION

A fault on a line generates a travelling wave (inception angle ≠ 0°). The wave propagates close to the speed of light.

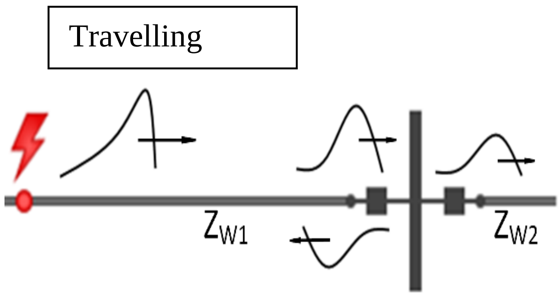

Figure 3: Wave movement for a fault at the end of the line.

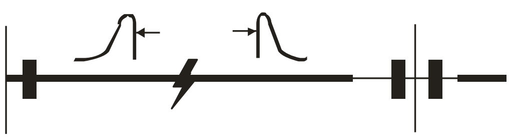

Figure 3: Wave movement for a fault in-between supports

All conductors of a transmission line have resistances and inductances distributed uniformly along the length of the line. It is, however, assumed in most applications that the resistance and inductance of a conductor is lumped and is, therefore, replaced by a single value. This is also true for the conductance and capacitance of a conductor.

Transmission lines cannot be analyzed with lumped parameters, when the length of the line is considerably small compared to the wavelength of the signal applied to the line. Power lines, which operate at 50Hz and are more than 50km long, are considered to have distributed parameters (Omicron, 2017).

To illustrate the travelling wave phenomena, the Bewley Lattice diagram can be used. Figure 4 shows the Bewley diagram of a single phase power system. The transmission lines connect two sources at busbars , A. and B to the middle busbar, R. The voltage and current signals are measured at the busbar, R. For a relay which protects line RB located at busbar R, the forward direction is considered as RB and the reverse direction is RA. When a line to ground fault in forward direction occurs at point F as shown, the fault generated wave fronts will travel along both directions of the line from the fault location, see fig.5. The wave fronts which travel from the fault location F towards the measuring point, R under a forward fault are known as backward travelling waves. These wave fronts will travel past R and reflect at busbar A. The reflected waves will then travel back towards the fault location F. The wavefronts which travel towards the forward direction from the relay location R are known as forward travelling waves. When these waves reach F, part of it will reflect from the fault point F while the remaining part propagates towards the busbar B. These two components are known as reflected and transmitted waves, respectively. The magnitude of the reflected and transmitted wavefronts will depend on the fault impedance and the impedance of the transmission line. The reflected wave component will travel back towards R again. The wavefronts which travel towards the busbar B from the fault location F will reflect from busbar B and reach F again. Part of them will be transmitted towards R and the other part will be reflected back towards busbar B. The wavefronts will continue to propagate and reflect in this manner until they are damped out.

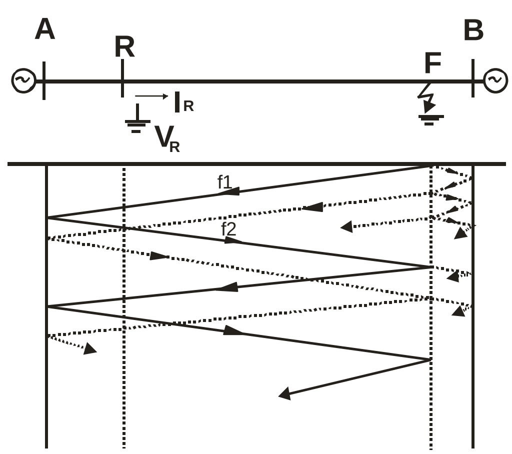

Figure 4: Bewley lattice diagram of wave front generated by a fault.

The voltage and current signals on a transmission line can be considered to be a summation of a backward travelling wave F1 and a forward travelling wave F2 (Vajira, 2004). These waves propagate with a constant amplitude at a velocity slightly less than the speed of light. The amplitude and the shape of these waves may change in a lossy line.

III. TRAVELING WAVE RELAYS

Several traveling wave relays have been proposed in the past, but all of them use analog technology. Due to the limitations in detecting high frequency waves, these techniques have not been used in commercial devices. The basic concept of previously proposed techniques is presented in this section. A fault on a transmission line can be replaced by a fictitious source. Let the voltage and current injected at the fault be f_v and f_i. These injected signals can be calculated by subtracting the pre-fault voltage and current from the postfault voltage and current. Fault injected components; therefore, can be expressed in terms of the forward and backward traveling waves as (Harijindar, 2004).

$V_f(x,t)= F^+[t - \frac{x}{v}] +F^-[t + \frac{x}{v}]$ (1)

$I_f(x,t) = \frac{1}{Z_0}[f^+(t- \frac{x}{v}) - f^-(t + \frac{x}{v})]$ (2)

where,

f^+ is a function representing the forward traveling wave,

f^- is a function representing the backward traveling wave,

v is velocity of propagation of traveling waves,

Z_0 is surge impedance of the transmission line, and x is the distance travelled by the travelling waves. Rearranging equation 1 and 2;

$2f^+(t - \frac{x}{v}) = v_f(x,t)+Z_0 i_f(x,t)$ (3)

$2f^-(t + \frac{x}{v}) = v_f(x,t) - z_0 i_f(x,t)$ (4)

IV. METHODOLOGY DEVELOPMENT USING TRAVELLING WAVES

The developed methodology according to (Bollen, 1989) includes:

1. Calculation of propagation velocity and frequency of travelling waves.
2. Derivation of forward and backward travelling wave.
3. To obtain the relaying signal and to calculate the fault location.

To have velocity of propagation of travelling waves, positive and zero sequence inductances and capacitances have to be known.

$V_0=\sqrt{(1/L_0C_0)}$ m/sec (5)

$V_1=\sqrt{(1/L_1C_1)}$ m/sec (6)

Where,

υ_0= velocity of propagation of 0 mode waves.

υ_1= velocity of propagation of α and β mode waves.

L_0 & C_0 = zero sequence inductance & capacitance respectively.

L_1 & C_1 = positive sequence inductance & capacitance respectively.

Frequency of travelling waves for 0 and αβ modes,

$f_0 = \frac{V_0}{L}$ Hz (7)

$f_1 = \frac{V_1}{L}$ Hz (8)

Where L= length of transmission line.

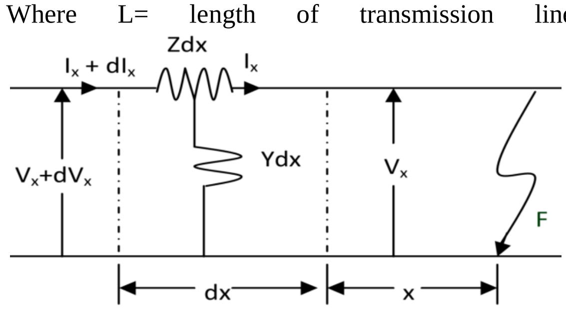

Figure 5: Schematic diagram of a long transmission line.

The following differential relationships can be written across the elemental section:

$dVx = IxZdx$ or $dVx/dx = ZIx$ (9)

$dIx = VxYdx$ or $dIx/dx = YVx$ (10)

Differentiating Eq. (9) with respect to x;

$d^2V_x/dx^2 = Z\, dI_x/dx$

Substituting the value of dIx/dx from Eq. (10) in above Eq,

$d^2V_X/dx^2 = YZVx$ (11)

This is a nonlinear differential equation whose general solution can be written as follows:

$V_x=C_{1e}^{Yx} + C_{2e}^{Yx}$ (12)

Where,
$\Upsilon = \sqrt{yz}$ and is called the propagation constant
C1 and C2 are arbitrary constants to be evolved.
Differentiating Eqn. (12) with respect to x;

$dVx/dx = C1\Upsilon e^{\Upsilon x} + C2\Upsilon\, e^{-\Upsilon x}$
$= zI_x$ (13)
Hence
$I_x=(C_1/Z_1)e^{\Upsilon x} - (C_2/Z_c)e^{-\Upsilon x}$ (14)

Where,
$Z_c = (z/y)^{1/2}$ and is referred to as the characteristic impedance of the line.

The constants C_1 and C_2 may be evaluated by using the end conditions, i.e. when x = 0, $V_x = V_f$ and $I_x = I_f$. Substituting these values in Eq (12) and Eq (14) gives,

$V_f = C_1 + C_2$ (15)
$I_f = (C_1 - C_2)/Z_c$ (16)
Which upon solving yield
$C_1 = \frac{(V_f + Z_c I_f)}{2}$ (17)
$C_2 = \frac{(V_f - Z_c I_f)}{2}$ (18)

Where,
V_f and I_f are post fault voltage and current respectively.
Substituting the values of C_1 and C_2 in Eqs (12) and (14) give,
$V_x = ((V_f + Z_c I_f)/2)e^{\Upsilon x} +$
$((V_f - Z_c I_f) / 2)e^{-\Upsilon x}$ (19)
$I_x=((V_f /Z_c+I_f)/2)\, e^{\Upsilon x} -$
$((V_f/Z_c - I_f)/2)\, e^{-\Upsilon x}$ (20)
Now, γ is a complex number which can be expressed as,
$\Upsilon=\alpha + j\beta$ (21)
Where,
α = attenuation constant
β = phase constant
Hence, instantaneous value of V_x (t) can be written as,
$V_x=((V_x + Z_c I_f)/2)e^{\alpha x}e^{j(wt+\beta)} +$
$((V_f - Z_c I_f)/2)e^{-\alpha x}e^{-j(wt+\beta x)}$ (22)
Similarly I_x (t) can be written as,
$I_x = ((V_f /Z_c + I_f) / 2)e^{\alpha x}e^{j(wt+\beta x)}$
$- ((V_f/Z_c - I_f)/2)e^{-\alpha x}e^{-j(wt+\beta x)}$ (23)

The above two equations are the travelling wave equations at any point on the line at a distance x from the fault point (Bollen, 1989). Now V_x consists of two terms each of which is a function of two variables time and distance. Thus they represent two travelling waves,

i.e. $V_x = V^f + V^r$ (24)
Where,

$V^f = ((V_f + Z_c I_f) / 2)e^{\alpha x}e^{j(wt+\beta x)}$ and is referred to as forward travelling voltage wave.
$V^r = ((V_f - Z_c I_f) / 2)e^{-\alpha x}e^{-j(wt+\beta x)}$ and is referred to as reverse travelling voltage wave.
Similarly,
$I_x=I^f - I^r$ (25)

Where,
$I^f = ((V_f /Z_c + I_f) / 2)e^{\alpha x}e^{j(wt+\beta x)}$ is referred to as forward travelling current wave.
$I^r = ((V_f /Z_c - I_f) / 2)e^{-\alpha x}e^{-j(wt+\beta x)}$ is referred to as reverse travelling current wave. Hence using the above equations, forward and backward travelling waves for all phases can be found.

V. CONCLUSION

When a transmission line fault occurs, there is sudden change in voltage or current at the fault point. This results in the generation of a high frequency electromagnetic signal known as travelling wave. This travelling wave moves along the line in both directions away from the fault point. The travelling wave theory based method uses the information of voltage and current for locating the fault. Based on the total length of the faulted line, propagation velocity and time of waveforms, the location of fault is known. This method is mostly used for very high voltage transmission lines instead of distribution lines. This is because distribution system has many subsections like laterals and feeders. The subsections can generate disturbances for the travelling waves on the lines.

The travelling wave theory based method for fault location includes two methods which are the single ended method and the double ended method. In the single ended method, only one fault locator is installed at one substation. The location of the fault is estimated based on the arrival time of waves at the substation. Two fault locators are installed at two substations in double-ended method; the fault location is calculated depending on the arrival time of waves at both stations. This process involves using very expensive equipment like Global Positioning System (GPS) to record the exact arrival times.

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