Transmission Line Protection based on Travelling Waves

ANURADHA S DESHPANDE, Associate Professor in Electrical Engineering, Department of Electrical Engineering, Faculty of Technology & Engineering, Maharaja Sayajirao University of Baroda, Vadodara – 390001, Gujarat, INDIA Email:asdeshpande-eed@msubaroda.ac.in, <u>http://www.msubaroda.ac.in</u> MS. GRISHMA S. SHAH, Assistant professor, Department of Electrical engineering, Babariya Institute of Technology Vadodara, Gujarat, INDIA Email:grishma_shah87@yahoo.com

Abstract:

Major problem of tripping signal of a relay based on steady state component does not warranty faster tripping schemes for protection of extra high voltage transmission lines. Proposed work has made an attempt to find solution to the problem of fault detection and location by relay using post fault high frequency signals. Transmission line protection using travelling waves generated at the time of fault are used as trip signals of a travelling wave relay.Paper has made an attempt to obtain travelling waves components in the form of forward wave and backward waves from post fault components of voltage and current. These have been used for getting 0, α and β components using clarke's transformation which further reduces to d_f and d_r respectively forming trip signals for tripping travelling wave relay. The proposed methodology is tested on a 500KV test system for different types of fault and different fault locations.Results obtained by proposed methodology are in total comparison to those obtained by correlation technique described in [1].

Key-words:- travelling waves, transmission line protection, postfault voltage, surge impedence, relaying signals

1 Introduction

Extra high voltage transmission line protection are areas for new developments today. Switching and lighting surges are high frequency signals prevailing on transmission lines. Major problem today is to devise faster protection schemes for protection of transmission lines. Relay tripping based on steady state component of voltage requires tripping time of few cycles and therefore does not give fast isolation. Fast fourier transform, Discrete transform, wavelet transform are based on sampling comparators and have inherent draw back of boiling down to computation based on steady state components for trip signals. The accuracy of computation and in turn isolation are need of the hour as part of fast tripping, to reduce the over all period to micro seconds. Therefore tripping schemes based on high frequency signals and not based on steady state components are desirable today. Also trip signals generated should be part of the post fault voltages of current and voltage. Also some kind of back up protection is required incase the main tripping schemes are susceptable to fail. [1] has described protection of transmission line based on post fault voltages evaluated and detected by corelation output of the comparator.Different fault distances and fault inception angles, are considered in the paper[1]. Proposed work has developed tripping schemes based on relay trip signals obtained from $0,\alpha$ and β components using clark's transformation. Post fault voltages are resolved in to forward waves and backward waves which travel on transmission lines

with speed of light. $0,\alpha$ and β components are used to get relay trip signals d_f and d_r. Proposed work has also calculated distance, relay trip signals from steady state post fault voltages and currents respectively. Thus proposed work has designed trip signals for travelling wave relay and distance relay from post fault voltages and currents respectively. Thus back up protection is also obtained for the system. Also hybrid relay trip signals can be derived and can ensure complete protection of transmission line. Thus proposed method is a solution technique for transmission line.

2 **Problem formulation**

At present power engineers are mainly concerned with power system stability because of the interconnected networks in the deregulated power supply system. Since fault can destabilize the power system, they must be isolated quickly. There is therefore a need for ultra high speed clearing of the fault, which improves the transient stability of the power system. The need of the hour is to devise faster tripping schemes where trip time is not in cycles but in few mili second.

Moreover finding the accurate location of a fault has always been a challenge for electric utility. Conventional method of fault location is to use the voltage and current data measured at one or more points along the power networks. Knowing the line impedance per unit length, the fault distance can be approximated from the calculated impedance obtained from voltage and current data. This impedance method, however, is subjected to errors caused by e.g. high resistance ground faults, teed circuits topologies, and the interconnection to multiple sources.

While technique based on travelling waves helps in determining the location of fault accurately. Moreover it is undoubtedly the quickest possible scheme for fault detection as it utilizes the high frequency components.

3 Methodology Development Using Travelling Waves

The developed methodology includes,

- 1. Calculation of propagation velocity & frequency of travelling waves.
- 2. Derivation of forward & backward travelling waves.

3. To obtain relaying signals & to calculate fault location.

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

 $\upsilon_0 = \sqrt{(1/L_0C_0)}$ m/sec

 $\upsilon_1 = \sqrt{(1/L_1C_1)}$ m/sec

Where,

 v_0 = velocity of propagation of 0 mode waves.

 v_1 = velocity of propagation of $\alpha \& \beta$ 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 $0\alpha\beta$ modes,

 $f_0 = v_0/l \text{ Hz}$

 $f_1 = v_1/l \text{ Hz}$

Where l= length of transmission line



Fig 1 Schematic diagram of a long line The following differential relationships can be written across the elemental section:

$$dV_x = I_x z dx$$
 or $dV_x/dx = zI_x$... (1)

$$dI_x = V_x y dx$$
 or $dI_x / dx = y V_x$... (2)

Differentiating Eq. (1) with respect to x;

$$d^2 V_x/dx^2 = z dI_x/dx \qquad \dots (3)$$

Substituting the value of dI_x/dx from Eq. (2) in above Eq,

$$d^2 V_x/dx^2 = yzV_x \qquad \dots (4)$$

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

$$V_{\rm x} = C_1 e^{\gamma x} + C_2 e^{-\gamma x}$$
 ... (5)

Where,

 $\gamma = \sqrt{yz}$ and is called as the propagation constant

 C_1 and C_2 are arbitrary constants to be evolved.

Differentiating Eq. (5) with respect to x;

$$dV_x/dx = C_1 \gamma e^{\gamma x} - C_2 \gamma e^{-\gamma x} = zI_x \qquad \dots (6)$$

Hence $I_x = (C_1/Z_c) e^{\gamma x} - (C_2/Z_c) e^{-\gamma x}$... (7)

Where,

 $Z_c = (z/y)^{1/2}$ and is called 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 Eqs (5) and (7) gives,

$$V_{\rm f} = {\rm C}_1 + {\rm C}_2 \qquad \dots (8)$$

 $I_{\rm f} = (C_1 - C_2)/Z_{\rm c}$... (9)

Which upon solving yield

$$C_1 = (V_f + Z_c I_f) / 2$$
 ... (10)

$$C_2 = (V_f - Z_c I_f) / 2$$
 ... (11)

Where,

 $V_{\rm f}$ and $I_{\rm f}$ are post fault voltage and current respectively.

Substituting the values of C_1 and C_2 in Eqs (5) and (7) gives,

$$V_{\rm x} = ((V_{\rm f} + Z_{\rm c} I_{\rm f})/2) e^{\gamma x} + ((V_{\rm f} - Z_{\rm c} I_{\rm f}) / 2) e^{-\gamma x} \qquad \dots (12)$$

$$I_{\rm x} = ((V_{\rm f}/Z_{\rm c}+I_{\rm f})/2) e^{\gamma x} - ((V_{\rm f}/Z_{\rm c}-I_{\rm f})/2) e^{-\gamma x} \dots (13)$$

Now, γ is a complex number which can be expressed as,

$$\gamma = \alpha + j \beta \qquad \dots (14)$$

Where,

 α = attenuation constant

β = phase constant

Hence, instantaneous value of V_x (t) can be written as,

 $V_{\rm x} = ((V_{\rm f} + Z_{\rm c}I_{\rm f})/2)e^{\alpha x}e^{j(\omega t + \beta x)} + ((V_{\rm f} - Z_{\rm c}I_{\rm f})/2)e^{-\alpha x}e^{-j(\omega t + \beta x)}$...(15)

Similarly $I_x(t)$ can be written as,

$$I_{x} = ((V_{f}/Z_{c} + I_{f}) / 2) e^{\alpha x} e^{j(\omega t + \beta x)} - ((V_{f}/Z_{c} - I_{f}) / 2) e^{-\alpha x} e^{-j(\omega t + \beta x)} \dots (16)$$

The above two Eqns. are the travelling wave equations at any point on the line at a distance x from the fault point. 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.

$$V_{\rm x} = V^{\rm f} + V^{\rm r} \qquad \dots (17)$$

Where,

 $V^{\rm f} = ((V_{\rm f} + Z_{\rm c} I_{\rm f}) / 2) e^{\alpha x} e^{j(\omega t + \beta x)}$ and is called as forward travelling voltage wave.

 $V^{r} = ((V_{f} - Z_{c} I_{f}) / 2) e^{-\alpha x} e^{-j(\omega t + \beta x)}$ and is called as reverse travelling voltage wave. Similarly,

$$I_{\rm x} = I^{\rm f} - I^{\rm r} \qquad \dots (18)$$

Where,

 $I^{f} = ((V_{f} / \mathbb{Z}_{c} + I_{f}) / 2) e^{\alpha x} e^{j(\omega t + \beta x)}$ and is called as forward travelling current wave.

 $I^{r} = ((V_{f}/Z_{c} - I_{f})/2) e^{-\alpha x} e^{-j(\omega t + \beta x)}$ and is called as reverse travelling current wave. Hence using the above equations, forward and backward travelling waves for all phases can be found.

Using the Clarke transformation, forward and backward travelling waves of three phases are being transformed into $0\alpha\beta$ components. The Clarke transformation,

$$\begin{bmatrix} V_{0} \\ V_{\alpha} \\ V_{\beta} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} V_{a} \\ V_{b} \\ V_{c} \end{bmatrix}$$
....(19)
$$\begin{bmatrix} I_{0} \\ I_{\alpha} \\ I_{\beta} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix}$$
....(20)

As the voltage at any point on the line is addition of forward and reverse travelling waves, voltage at any point on a 3- Φ transmission line is,

$$V_0 = V_0^{\rm f}(\mathbf{x} - v_0 t) + V_0^{\rm r}(\mathbf{x} + v_0 t) \qquad \dots (21)$$

$$V_{\alpha} = V_{\alpha}^{f} (\mathbf{x} - \upsilon_{1} \mathbf{t}) + V_{\alpha}^{r} (\mathbf{x} + \upsilon_{1} \mathbf{t}) \qquad \dots (22)$$

$$V_{\beta} = V_{\beta}^{f} (x - v_{1}t) + V_{\beta}^{r} (x + v_{1}t) \qquad \dots (23)$$

And current on $3-\Phi$ transmission line,

$$I_0 = I_0^{\rm f} - I_0^{\rm r} \dots (24)$$

$$I_{\alpha} = I_{\alpha}^{f} - I_{\alpha}^{r} \qquad \dots (25)$$

$$I_{\beta} = I_{\beta}^{f} - I_{\beta}^{r} \qquad \dots (26)$$

The discriminant function d_f and d_r associated with the forward and reverse waves will be uses as the forward and backward relaying signals in the travelling wave relay.

Where,

$$\mathbf{d}_{\mathbf{f}} = V + ZI \qquad \dots (27)$$

$$\mathbf{d}_{\mathrm{r}} = V - \mathbf{Z}I \qquad \dots (28)$$

V and *I* are the modal voltages and currents (0, α or β components) at the relay location.

The relay treats the currents flowing into the line as positive. Hence the forward current wave I^{f} appears as positive to the relay; while the reverse current wave I^{r} appears to be negative.

$$\mathbf{d}_{\mathbf{f}} = V + \mathbf{Z}I \qquad \dots (29)$$

$$= (V^{f} + V^{r}) + Z (I^{f} - I^{r}) \qquad ... (30)$$

$$= (V^{f} + ZI^{f}) + (V^{r} - ZI^{r}) \qquad ... (31)$$

$$= V^{f} + Z I^{f}$$
 (since $V^{r} = Z I^{r}$) ... (32)

$$\mathbf{d}_{\mathbf{f}} = \mathbf{2}V^{\mathbf{f}} \qquad (\text{ since } V^{\mathbf{f}} = ZI^{\mathbf{f}}) \qquad \dots (33)$$

Similarly,

$$\mathbf{d}_{\mathbf{r}} = V - \mathbf{Z}I \qquad \dots (34)$$

$$\mathbf{d_r} = \mathbf{2V^r} \qquad \dots (35)$$

Note that d_f and d_r must ideally have zero magnitude when the power system operates under steady state conditions.

The discriminant function d_f picks up when relay sees forward travelling wave and d_r picks up when relay sees backward travelling wave. Below Fig. shows the discriminant functions at relay location.



Fig 2 discriminant functions for the relay

If the fault is behind the relay, d_f will pick up first, and d_r will pick up later due to reflections at fault or at bus. If the fault is in forward direction, d_r will pick up first, and d_f will pick up later due to reflections at fault or at bus. Thus using this concept, the direction of fault can be determined.

3.1 Fault location

The discriminant function can be used to determine the direction of the fault. The relay is set up to operate on a forward fault. However, the relay must be able to determine whether the disturbance occurred within the zone of protection. To determine whether the fault is within the zone of protection, the distance to the fault can be used. The distance to the fault is evaluated using the time difference between an identified forward wave front at the relay point and the corresponding wave front reflected from the fault point. As shown in Fig.2 the first wave front f_1 reaches the relay point at time τ_1 and at this instant d_r goes high, a forward fault is detected. At time τ_2 , a forward wave front is detected at relay point. Once the forward wave is detected, relay starts counting time. The wave front f_1 will reflect at the fault point which is now f_2 and it will return to the relay point at time τ_3 . The distance to the fault can be now calculated by,

$$\mathbf{x}_{f} = (\tau_{3} - \tau_{2}) \upsilon / 2$$
 meter ... (36)

Where τ_2 and τ_3 can theoretically be calculated using distance covered by the wave and velocity of travelling wave.

Using the above formula, the fault location can be calculated by which it can be known that whether the fault is within the zone of protection or not.

Hence it can be concluded that *if relay first sees* backward wave and distance to the fault is within the zone of protection, relay will trip.

3.2 Limitation of the proposed method and solution

The protection scheme based on travelling waves has to face reliability issues as it fails to detect faults under certain conditions [1]. The main concern has been identified:

- When a fault occurs close to the relaying point (close-up fault), the repeated reflection of wave fronts between the fault and discontinuity behind the relay will occur. So travelling wave protection scheme will find difficulty to distinguish between the arrival of consecutive wave fronts and handling fast computations is also difficult.
- The operating time of the impedance relay is comparatively low for close-up faults. Hence there is less requirement for a travelling wave measurement technique in order to speed up the relay trip time. Hence impedance relay can provide fast protection against close-up faults and for rest of other faults, travelling wave technique provides fast protection.
- Hence new method can be developed which \geq combines the information contained in the fault-generated wave fronts with the impedance measurement at the relay location in a single relay. This protection scheme is known as hybrid protection scheme, as it is a combination of impedance measurement scheme and travelling wave scheme. This will give a reliable but high-speed protection scheme. Using this scheme, full length line can be protected which implies that relay reach can be improved by implementing this scheme. And if the fault is too close to be detected by the travelling wave scheme, the impedance relay acts as a fast backup.

4. Implementation of methodology on a test system

4.1 500 kv test system



Fig 3 Line configuration of 500 kV system

Fig 3 shows transmission line configuration including line transposing intervals. As shown in Fig. one major 500 kV transmission line connecting Dorsey and Forbes, 537 km long is considered.



Fig 4 relay location. Above Fig shows the relay location. Relay is placed at R, near the Dorsey and it protects the line section DF. If fault occurs between R and F (Forbes), it is considered as forward fault for which relay should operate.

Below Fig shows the configuration of conductors in a three phase test system.



Fig 5 conductor configuration of 500 kV system

Line configuration data:

- Height of outer conductors, $h_c = 28.956$ m
- Height of centre conductor, $h_c+h_o = 38.648$ m
- Horizontal space between phases, $X_c = 6.71m$
- Conductor radius, $r = 1.65354 \times 10^{-2} \text{ m}$
- No. of conductor in a bundle N = 3

Line parameter:

Conductor DC resistance = $0.0489 \Omega/km$

4.2 Calculation of volteges, currents, travelling wave components, distance to the fault and relay signals

The proposed methodology has been tested by implementing it on a 500 kV test system with different types of faults at different locations on a transmission line. The results obtained using proposed method, have been compared with the reference [1].

Pre-fault voltages and currents of all phases are as below;



Fig 6 Pre-fault voltages and currents for 500 kV transmission line

4.2.1 Case1 525 Km

When 3-ph to ground fault occurs at a distance of **525 km** away from the relay location at an inception angle 90°, the results obtained using MATLAB programming are as below;

Post-fault phase voltages and currents for all phases



Fig 7 post-fault voltages



Fig 8 post-fault currents

High frequency forward and backward voltage travelling waves



Fig 9 Voltage travelling waves

High frequency forward and backward currents travelling waves



Fig 10 Current travelling waves



0, α and β components of voltage and current

Fig 11 0, α and β components of travelling waves Relaying signals and fault location



Fig12 Relaying signals d_r and d_f

 d_r is equal to -6043.2 and it picks up at 1.7371 msec d_f is equal to 9932.9 and it picks up at 1.7437 msec

 $\tau_3 = 5.2179$ msec, $\tau_2 = 1.7437$ msec

Hence distance to the fault x = 524.99 km (calculated)And Distance to the fault = 525 km (Estimated)

Mho characteristic



Fig 13 Impedance measured by the mho relay

4.2.2 Case2 25 Km

When L-g fault occurs on phase B at a distance of **25** km away from the relay location at an inception angle 210°, the results obtained using MATLAB programming are as below;

Post-fault phase voltages and currents for all phases



Fig 14 post-fault voltages



Fig 15 post-fault currents

High frequency forward and backward voltage travelling waves

Figure 16 Voltage travelling waves

High frequency forward and backward currents travelling waves

Fig 17 Current travelling waves

0, α and β components of voltage and current travelling waves

Fig 18 0, α and β components of travelling waves

Relaying signals and fault location

 d_r is equal to -1.3584×10^4 and it picks up at 0.0827 msec

 $d_{\rm f}$ is equal to $1.7037{\times}10^4~$ and it picks up at 0.0893 msec

 $\tau_3 = 0.2548$ msec, $\tau_2 = 0.0893$ msec

Hence distance to the fault x = 25.01 km (calculated)

And Distance to the fault = 25 km (Estimated)

Mho characteristic

Fig 20 Impedance measured by the mho relay

4.2.3 Case3 220 Km

When L-g fault occurs on phase A at a distance of **220** km away from the relay location at an inception angle 154°, the results obtained using MATLAB programming are as below;

Post-fault phase voltages and currents for all phases

Fig 21 post-fault voltages

Fig 22 post-fault currents

High frequency forward and backward voltage travelling waves

Fig 23 Voltage travelling waves

High frequency forward and backward currents travelling waves

Fig 24 Current travelling waves

0, α and β components of voltage and current travelling waves

Fig 25 0, α and β components of travelling waves Relaying signals and fault location

Fig 26 Relaying signals d_r and $d_{\rm f}$

 d_r is equal to -224.2786 and it picks up at 0.7279 msec d_f is equal to 301.6277 and it picks up at 0.7345 msec

 $\tau_3 = 2.1904$ msec, $\tau_2 = 0.7345$ msec

Hence distance to the fault x = 220.006 km (calculated)

And Distance to the fault = 220 km (Estimated)

Mho characteristic

Fig 27 Impedance measured by the mho relay

4.2.4 Case 4 195 Km

When L-g fault occurs on phase C at a distance of **195** km away from the relay location at an inception angle 3°, the results obtained using MATLAB programming are as below;

Post-fault phase voltages and currents for all phases

Fig 28 post-fault voltages

Fig 29 post-fault currents

High frequency forward and backward voltage travelling waves

Fig 30 Voltage travelling waves

High frequency forward and backward currents travelling waves

Fig 31 Current travelling waves

0, α and β components of voltage and current travelling waves

Fig 32 0, α and β components of travelling waves

Relaying signals and fault location

Fig 33 Relaying signals d_r and d_f

dr is equal to -421.5232 and it picks up at 0.6452 msec

 d_f is equal to 1909.9 and it picks up at 0.6518 msec

 $\tau_3 = 1.9422$ msec, $\tau_2 = 0.6518$ msec

Hence distance to the fault x = 194.99 km (calculated)

And Distance to the fault = 195 km (Estimated)

Mho characteristic

Fig 34 Impedance measured by the mho relay

4.3 COMPARISON AND ANALYSIS

The method has been implemented on 500 kV test system given in Reference paper [1]. The results shown in chapter 4 are obtained and are compared with the results given in reference paper [1]. In reference paper [1], correlation technique is used. According to correlation technique, for the relay to trip, relaying signal S_1 should pick up first, pick value of relaying signals must be higher than the threshold value and pick value of output of correlator must be larger than the threshold value.

4.3.1 Comparison of post-fault voltages and currents for 525Km

3-ph to ground fault at 525 km away from the relay location.

By proposed method:

Fig 35a Post fault voltages

Fig 35b Post fault currents

Using simulation by PSCAD:

Fig 36 Post fault voltages and currents

4.3.2 Comparison of Relay signals for 525 Km:

By proposed method:

Fig 37 relay signal

Using simulation by PSCAD:

Fig 38 relay signal

The relaying signal d_r picks up first in the proposed method and also according to the result shown Ref.paper [1], S₁ picks up before S₂. Both cases identify forward fault.

4.3.3 Comparison of post-fault voltages and currents for 25Km

L-g fault on phase B at 25 km away from the relay location.

By proposed method:

Fig 39a Post fault voltages:

Fig 39b Post fault currents:

Using simulation by PSCAD

Fig 40 Post-fault voltages and currents

4.3.4 Comparison of Relay signals for 25 Km:

By proposed method:

By proposed method:

Fig 41 relay signal

Using simulation by PSCAD:

Fig 42 relay signals

The relaying signal d_r picks up first in the proposed method and also according to the result shown in Ref. paper [1], S₁ picks up before S₂. Both cases identify forward fault.

4.3.5 Comparison of post-fault voltages and currents for 220Km L-g fault on phase R at 220 km away from the relay location.

Fig 43a Post-fault voltages

Fig 43b Post-fault currents

Using simulation by PSCA

Fig 44 Post-fault voltages and currents

4.3.6 Comparison of Relaying signals for 220 Km:

By proposed method:

Fig 45 relay signals

Fig 46 relay signals

The relaying signal d_r picks up first in the proposed method and also according to the result shown in Ref. paper [1], S₁ picks up before S₂. Both cases identify forward fault.

4.3.7 Comparison of post-fault voltages and currents for 195Km

L-g fault on phase B at 195 km away from the relay location.

By proposed method:

Fig 47aPost-fault voltages

Fig 47b Post-fault currents

Using simulation by PSCAD:

Fig 48 post-fault voltages and currents

4.3.8 Comparison of Relaying signals for 220 Km:

By proposed method:

2000					relay s	ignals			,	
1500										- dr - df
1000										
1000										
500										
-500	0.2	0.4	0.6	0	8	1 1	2 1	.4 1	.6 1	8 2
time (msac)										

Fig 49 relay signal

Using simulation by PSCAD:

Fig 50 relay signal

The relaying signal d_r picks up first in the proposed method and also according to the result shown in Ref. paper [1], S₁ picks up before S₂. Both cases identify forward fault.

4.4 COMARISON OF FAULT LOCATION

Table 1: Results using MATLAB programming

Typ e of		Xt	w	τ		
Fau It	x	By propos ed metho d	By Ref. paper	By prop osed meth od	By Ref. paper	
3- ph to gro un d	525	524.99	526.3	1.73 7	1.7	
B-g	25	25.01	38.4	0.08 2	0.1	
A-g	220	220.00 6	229	0.72 79	0.76	
C-g	195	194.99	-	0.64 52	0.75	

X = Distance to fault in *km*.

 X_{tw} = Distance calculated using the proposed method in *km*.

 τ = Time at which relay identifies first travelling wave in *msec*.

4.5 ANALYSIS OF RESULTS

- As seen from the relay signals in all above cases, d_r picks up before d_f. Hence in all cases fault is in forward direction. Moreover distance to the fault calculated in all cases are within the zone of protection as travelling wave relay is provided to protect the full 537 km length.
- Although theoretically d_r picks up first in case of B-g fault at 25 km, travelling wave relay will not trip for this fault as it is a close-up fault which is a limitation of travelling wave relay.
- Travelling wave relay will operate for all cases mentioned above except for the close-up fault.
- In case of 3-ph to ground fault at 525 km, looking from Fig. 13, Mho relay can not operate as fault is out of its reach (relay reach is considered as 80% of the length of line). For all other faults, Mho relay can operate.
- Mho relay provides comparatively faster protection in case of close-up fault. Hence if hybrid protection scheme is implemented, the limitation of travelling wave relay will be overcome by Mho relay. 3-ph to ground fault at 525 km is the case where Mho cannot operate while travelling wave relay operates and provides faster protection too. And for the cases where both relays can operate, travelling wave relay provides primary protection and Mho relay provides backup protection.

4.6 Comparison of operation of relay

Table 2: Relay Tripping

	Х	Trave wave	elling relay	Impedance wave relay		
Type of Fault		Usin g prop osed meth od	By Ref. pape r	Using propo sed metho d	By Ref pap er	
3-ph to grou nd	525	Yes	No	No	No	
B-g	25	No	No	Yes	Yes	
A-g	220	Yes	No	Yes	Yes	
C-g	195	Yes	No	Yes	Yes	

- 525, 220 and 195 are the cases where travelling wave relay provides protection to the transmission line according to the proposed methodology while it does not operate according to the technique shown in Ref. paper. Hence proposed method helps in reducing limitations of the correlation technique shown in reference paper [1].
- Also proposed method obtains trip signal components of a hybrid relay in

terms of travelling wave and distance relay components.

5 CONCLUSION

The methodology based on travelling wave for EHV transmission line protection was developed. Proposed methodology was tested on 500 kV transmission line system.

Post-fault voltages and currents, travelling wave components and fault location were calculated. Relaying signals were obtained. Comparison of proposed method was done with correlation technique shown in Ref. paper [1] for 500 kV test system. Post-fault voltages, post-fault currents and relaying signals were compared with the Ref. paper [1]. The proposed method has also offered hybrid relay tripping signals.

Proposed method based on travelling wave can be used for protection of EHV transmission line using travelling wave relay and/or mho relay as faster protection scheme compared to available protection scheme. Travelling wave components and steady state components of post fault quantities can be used for tripping hybrid relay (combination of Travelling wave relay and Mho relay) which gives faster as well as more reliable protection scheme.

References

- [1] Vajira Pathirana, "A power system protection scheme combining impedance measurement & travelling waves: software & hardware implementation", Ph.D. Thesis, University of Manitoba, Canada, April 2004.
- [2] Harjinder Singh Sidhu, "High speed digital protection of EHV transmission lines using travelling waves", Thesis, University of Saskatchewan, Canada, April 2004.
- [3] H. Hizam and P.A.Crossley, "Single ended fault location technique on a radial distribution network using fault generated current signals", submitted to Power Engineering Society, 2002.
- [4] Magnus Ohrstrom, Martin Geidl, Lennart Soder and Goran Andersson, "Evaluation of travelling wave based protection schemes for implementation

in medium voltage distribution systems", 18th international conference on electricity distribution, CIRED, Session No.3, Turin, 6-9 June 2005.

- [5] Abdelsalam Mohamed Flhaffar, "Power transmission line fault location based on current travelling wave", Ph.D. Thesis, Helsinki University of technology, Finland, March 2008.
- [6] Francisco Salgado Carvalho & Sandoval Carneiro, "Detection of fault induced transients in EHV transmission lines for the development of a fault locator system", International Conference on power systems transients-IPST, USA, 2003.
- [7] E.H.Shehab-Eldin and P.G.McLaren, "Travelling Wave Distance Protection – Problem Areas and Solutions", IEEE Transaction on Power Delivery, Vol.3, No.3, July 1988, pp.894-902.
- [8] Zeng Xiangjun, Zhou Yanling, Liu Zhengyi and Lin Gan, "The Sensor of Travelling-Wave for Fault Location in Power Systems", International Conference on Power System Technology–POWERCON 2004, Singapore, 21-24 November 2004, pp. 1518-1521.
- [9] Zhang Xiaoli, Zeng Xiangjun, Li Zewen, Deng Feng, "Travelling Wave fault location of transmission line using Hilbert-Huang Transform", the third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT 2008), 6-9 April, 2008, China.
- [10] David W.P.Thomas, Ricardo J.O Carvalho & Elisete T. Pereira, "Fault location in distribution system based on travelling waves", IEEE Bologna Power Tech Conference, Italy, June 23rd-26th 2003.
- [11] Kit Po Wong and Kelvin Lee, "Visualizing Wavelet Transformed Travelling waves on Power Transmission Line using JAVA", the 5th International Conference on Advances in Power System Control, Operation and Management, APSCOM

2000, Hong Kong, October 2000, pp.349-353.

- [12] V.Pathirana and P.G. McLaren, "Improving Relay Reach and Speed Through a Hybrid Algorithm", IEEE Bologna Power Tech Conference, Italy, June 23rd-26th 2003.
- [13] P.G. McLaren and V.Pathirana, "A Hybrid Algorithm for High Speed Transmission Line Protection", IEEE Transaction on Power Delivery, Vol.20, No.4, Oct.2005, pp.2422-2428.
- [14] T I A H Mustafa, D W P Thomas, C Christopoulos and A Raizer, "Comparison of Simulated and Recorded Transients for Travelling Wave Fault Location", IEEE Bologna Power Tech Conference, Italy, June 23rd-26th 2003.
- [15] Mahmoud I. Gilany, El Sayed M. Tag Eldin, Mohamed Mamdouh Abdel Aziz, and Doaa K. Ibrahim, "Travelling Wave-Based Fault Location Scheme for Aged Underground Cable Combined with Overhead Line", International Journal of Emerging Electric Power Systems", Volume 2, Issue 2, Article 1032, 2005.
- [16] Vajira Pathirana, Mark Mihalchuk, Ralph Kurth and Mansour Jalali, "Design, Implementation and Commissioning of a Hybrid Substation Automation System Using IEC 61850" Western Power Delivery Automation Conference Spokane, Washington, April 8-10, 2008.
- [17] Ravindra P. Singh, "Digital Power System Protection", Prentice-Hall of India private Limited, New Delhi, 2007.
- [18] Arun G. Phadke & James S. Thorp, "Computer relaying for power systems", John Wiley & Sons Inc., New York, 1988.
- [19] I.J.Nagrath & D.P.Kothari, "Modern power system analysis", Tata McGraw-Hill publishing company ltd, New Delhi, 1980.
- [20] William D. Stevenson, "Elements of power system analysis", McGraw-Hill, Third Edition.