Development of Three Zone Quadrilateral Adaptive Distance Relay for the Protection of Parallel Transmission line

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***Abstract*--This paper describes the development of adaptive distance relay for the protection of parallel transmission line with mutual coupling. The quadrilateral trip characteristic with directionality feature is developed for three zone protection. The relay automatically adjusts its operation based on the availability of the input signals. Zero sequence current, if available from the parallel transmission line, is used to fully compensate the mutual coupling effect. When the parallel line's zero sequence current is not available, the line operating status is used to select the proper zero sequence current compensation factor in impedance calculation. If both the signals mentioned above are not available, default compensation factor is used. The performance of adaptive relay is tested through steady state and dynamic test. The comparative evaluation of test results presented shows the efficacy of the proposed adaptive distance relay over the conventional distance relay.**

I. Introduction

Parallel transmission lines have been extensively utilized in modern power system to enhance the reliability and security for the transmission of electrical energy. The different possible configuration of parallel lines combined with the effect of mutual coupling make their protection a challenging problem.

Mutual coupling can cause incorrect (non-)tripping of distance relays. In particular, overreach can cause sympathy trips, which can lead to major power system disturbances. They should whenever possible be avoided and it is therefore important to make the relays as accurate as possible.

Mutual coupling effect between the parallel lines varies with the line operating condition and bus configuration. The relays must be selected to avoid overreach/underreach operation under the worst case scenarios. This results in sub-optimal performance of a relay under other operating conditions. We find some proposed solutions in [1]-[5]. An adaptive distance scheme was suggested in [1], in which the impedance calculation is done using a correction factor, based on the information of the surrounding system of the protected line under different operating status. In [2], an adaptive distance protection scheme is proposed which accesses multiple locally available signals and automatically adapts its operation to the signal availability. In [3], a traveling-wave based parallel line protection scheme was investigated. In [4], phase current comparison between two circuits and positive sequence current level detection were used in conjunction with parallel line's zero sequence current compensated impedance calculation. In [5], the suggested technique is based on the comparison of the measured impedance of the corresponding phases. However, the implementation of the adaptive distance relaying scheme and its extensive evaluation is yet a challenge in the field.

In this paper, development of an adaptive distance relay and its evaluation is presented elaborately. In order to minimize the required communication, local measurements are used to estimate the entire power system condition. The proposed adaptive distance protection scheme accesses multiple locally available signals and automatically adapts its operation to the signal availability.

The proposed relay uses the best available signals for optimal performance at all the moments. The quadrilateral trip characteristic with directionality feature is developed for three-zone protection.

The performance evaluation of developed adaptive distance relay is done extensively under different faults and power system conditions by simulating a realistic parallel line transmission system in PSCAD. The comparative analysis is made extensively with that of conventional distance relay and the results are tabulated and graphs are shown for some sample cases.

Generally, the mutual coupling effects between parallel lines caused by positive and negative sequence currents are very small and are considered to be negligible. However, the mutual coupling effects of zero sequence currents between parallel lines could be significant [2].

When there is a phase to ground fault on a single line, the measured phase impedance seen by the conventional distance relay by using conventional zero sequence current compensation method with fault impedance zero is given by (1)

$$Z_{m\_a} = \frac{V_{sfa}}{I_{sfa} + k_0 I_{sf0}} = mZ_{L1} \tag{1}$$

$$K_0 = \frac{Z_{L0} - Z_{L1}}{Z_{L1}} \quad (2)$$

Where,

K_0 The line zero sequence current compensation factor.

Z_{L0} & Z_{L1} Zero sequence and positive sequence impedance of the line.

V_{sfa} & I_{sfa} The post-fault phase voltage and current at the relay location,

m The per-unit distance between the relay and the fault location

I_{sf0} The post-fault zero sequence current at the relay location.

Fig. 1 indicates the conventional distance relay as applied to protect a parallel line with the mutual coupling.

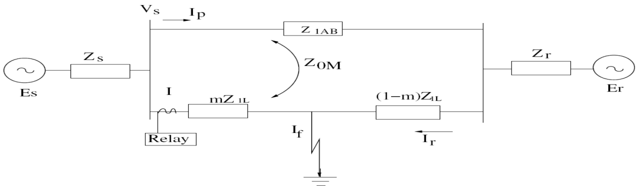

Fig. 1. Parallel Transmission Line

The measured fault impedance of a distance relay using conventional zero sequence current compensation will contain errors [2] since

$$Z'_{m\_a} = \frac{V_{sfa}}{I_{sfa} + k_0 I_{sf0}} = mZ_{L1} + \delta Z_{L1} \quad (3)$$

Where, the per unit error δ in terms of Z_{L1} is [2]

$$\delta = \frac{m(Z_{0M} / Z_{L1}) I_{Psf0}}{I_{sfa} + k_0 I_{sf0}} \quad (4)$$

Z_{0M} The total zero sequence mutual coupling line impedance

I_{Psf0} The parallel line's zero sequence current.

The error may cause the relay either to overreach or underreach depending upon the relative direction of the parallel line's zero sequence current I_{Psf0} verses the compensated current, $I_{sfa} + K_0 I_{sf0}$ .The above overreach or underreach effect of conventional distance relays caused by the mutual coupling may be compensated by selecting proper relay settings provided the bus configuration, system impedance and line operating condition of a parallel line do not change during the normal operation.

Due to various reasons like load dispatch, forced outage, scheduled maintenance, etc. operating condition of a parallel line could change from one to the other during the normal operations. Fig. 2(a) and 2(b) show such two typical operating conditions of a double-circuit line.

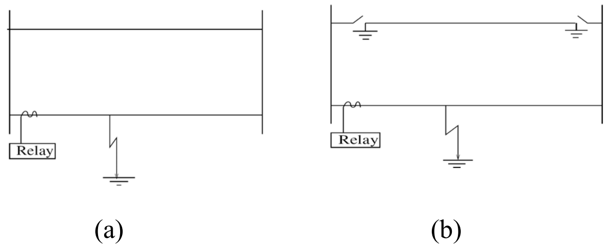

Fig. 2. Parallel-Line Typical Operating Modes. (a).Both Lines Are in Operation. (b).One Line switched off and Grounded at Both Ends.

Generally, the line operating condition shown in Fig.2(a) will cause conventional distance relay to underreach and the line operating condition shown in Fig. 2(b) will cause conventional distance relay to overreach for remote end faults [2]. Also the other line operating conditions and/or the bus configurations combinations may further complicate the problem.

Generally in parallel line distance protection the settings are chosen such that they can cover the worst-case situation [1] [2]. Even though the Safety margins are used to ensure correct operation in as many situations as possible, the result is that the relays operate incorrect or delayed. Sympathy trips due to unexpected overreach can be particularly disastrous [1].

Hence to minimize the effect of incorrect settings the system calls for the Adaptive protection which covers the wide range of power system condition thus increasing the accuracy and selectivity of the protection system.

II. Development of Adaptive Distance Relay

The adaptive scheme for the proposed relay on each protected line accesses the three-phase voltage and current signals of the protected line. In addition, the zero sequence current and line operating status of the paralleled lines at the substation where the distance relay is located will be used by the scheme. The parallel line's zero sequence current could be obtained either through additional cabling, direct communication link between relays, or substation local networks. The parallel line's operating status could be obtained by accessing the circuit breaker's auxiliary contacts and/or parallel line's voltage/current level detection or substation PLC (programmable logic controller). The scheme automatically adapts its operation based on the signal availability from the parallel lines to achieve an optimal performance by using the best available signals.

If the parallel line's zero sequence current is available the scheme uses it first to compensate the mutual coupling effect in impedance measurement on faulted line. For a phase-a -to-ground fault on the protected line, the correct fault impedance on the faulted line is given by (5)

$$Z_{m\_a} = \frac{Va}{I_a + K_0 I_0 + k_{0M} I_{0p}} = mZ_{1L} \quad (5)$$

Where

$$K_{0M} = \frac{Z_{0M}}{Z_{1L}}$$

Thus the error in distance measurement caused by the mutual coupling effect of I_{0p} is fully compensated. Fig.3 illustrates the adaptive scheme [2] implemented in the proposed new relay.

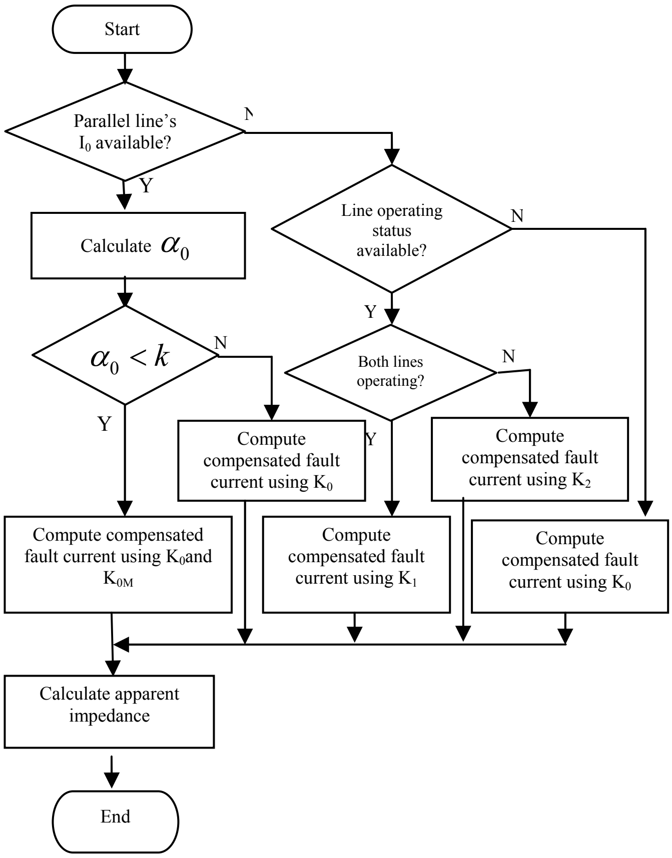

Fig . 3 Flowchart for Adaptive Distance Protection Scheme.

When Parallel line's zero sequence current compensation is applied on both faulted line and healthy line in the impedance computation, the relay placed in healthy line will also operate with the relay placed in faulted line. To avoid such possible false operation, the compensation should be adapted to the line fault status. In the proposed scheme it is achieved by using a zero sequence current ratio criterion, defined as a magnitude ratio of paralleled line's zero sequence current over the zero sequence current measured on the protected line [2].

$$\alpha_0 = \frac{|I_{0p}|}{|I_0|} \tag{6}$$

By setting a proper threshold, selected, so that the relay false operation on the healthy line for close-in faults on an adjacent parallel line could be effectively prevented.

When the parallel line's zero sequence current is not available due to local technical problems to the relay for various reasons[2] ,the proposed adaptive scheme adopts to use parallel line's operating status signal, for an improved performance. A relay could make proper zone setting and/or zero sequence compensation factor adjustment to take into account of the mutual coupling effect corresponding to each line operating status.

The sequence network in Fig. 4 corresponds to the line operating condition as in Fig. 2(a).

In Fig. 4, $Z_{AB0} = Z_{L0}$ is assumed, the accurate zero sequence compensation factor in (1) at m the fault location under this condition is,

$$K_1(m) = K_0\left(1 + \frac{Z_{0M}}{Z_{0L} - Z_{1L}} \cdot \frac{mZ_{0R} - (1-m)Z_{0S}}{(2-m)Z_{R0} + (1-m)(Z_{0S} + Z_{0L} + Z_{0M})}\right) \tag{7}$$

which is a function of the fault location, system, and line impedance.

Similarly, the zero sequence current compensation factor for one parallel line switched off and grounded at both ends could be derived. The zero sequence network [2] for one parallel line switched off and grounded at both ends is shown in Fig. 5. If $Z_{0L} = Z_{0AB}$ is assumed, the accurate zero sequence compensation factor in (1) at the fault location m under this condition is

$$K_2(m) = K_0\left\{1 + \frac{Z_{0M}}{Z_{0L} - Z_{1L}} \cdot \frac{Z_{0M}[(1-m)Z_{0S} - mZ_{0R}]}{Z_{0L}[(1-m)Z_{0L} + Z_{0R}] - (1-m)Z_{0M}^2}\right\} \tag{8}$$

which is also a function of the fault location, system, and line impedance

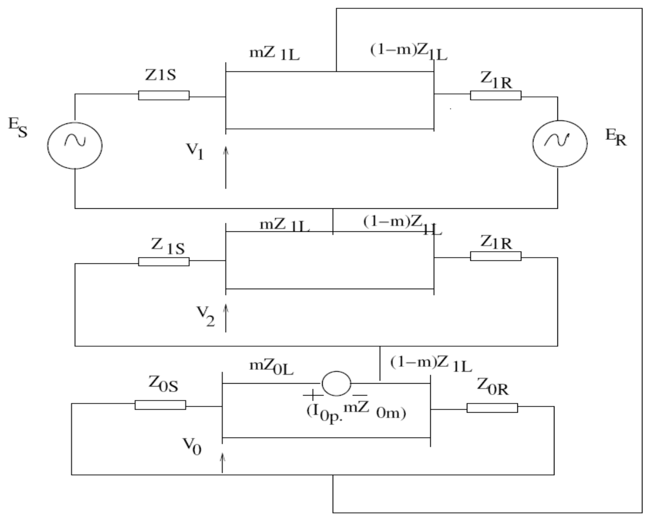

Fig . 4. Sequence network for both the lines in operation condition in a single line to ground fault.

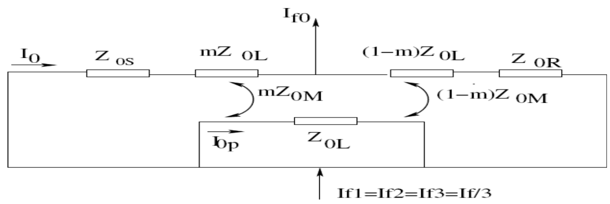

Fig. 5. Zero Sequence network Connection for One Line Switched Off and Grounded Condition in a single line to ground Fault.

The value for zone 1 should also be determined at the zone setting boundary (80%) using (7) and(8) for more accurate compensation of the mutual coupling effect taking into account of system parameter variations, plus certain margins to avoid overreach operations.

In the case that both parallel line's zero sequence current and line operating status signals are not accessible, a default zero sequence compensation factor (K_0), based on the worst-case scenario, will be used by the new adaptive relay to ensure a reliable operation of the relay This operation mode achieves the same performance level.

III. Development of Quadrilateral Relay Logic With Directionality Feature

To develop the quadrilateral characteristic [6] shown in Fig. 6. requires reactance test (top line), Positive and negative resistance tests (sides) and Directional test (bottom line).

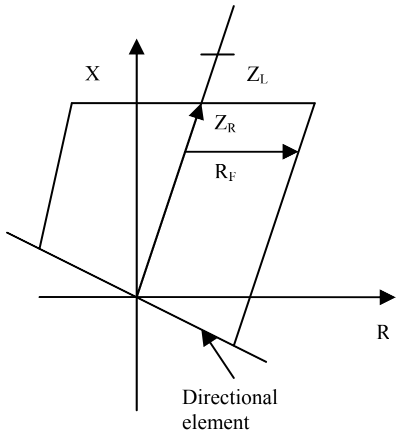

Fig . 6. Quadrilateral Characteristics

Where, Z_L is transmission line impedance,

Z_R is distance element reach,

R_F is resistance reach setting.

We can find different directional elements in [7], In the proposed adaptive relay negative sequence polarized directional element is considered as it has its own advantages for mutually coupled circuits.

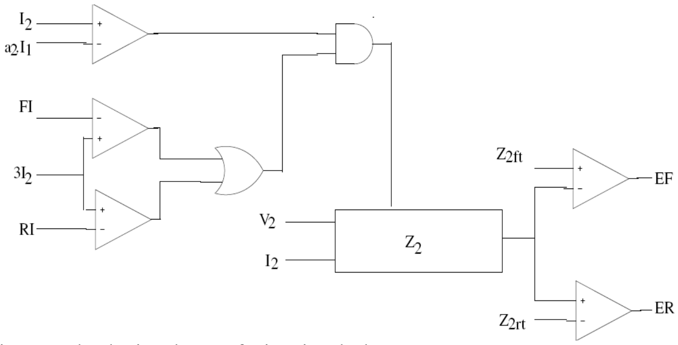

Fig. 7 Relay logic scheme of Directional Element

Fig: 7 show the simplified block diagram of the relay logic scheme for negative-sequence voltage polarized directional element.

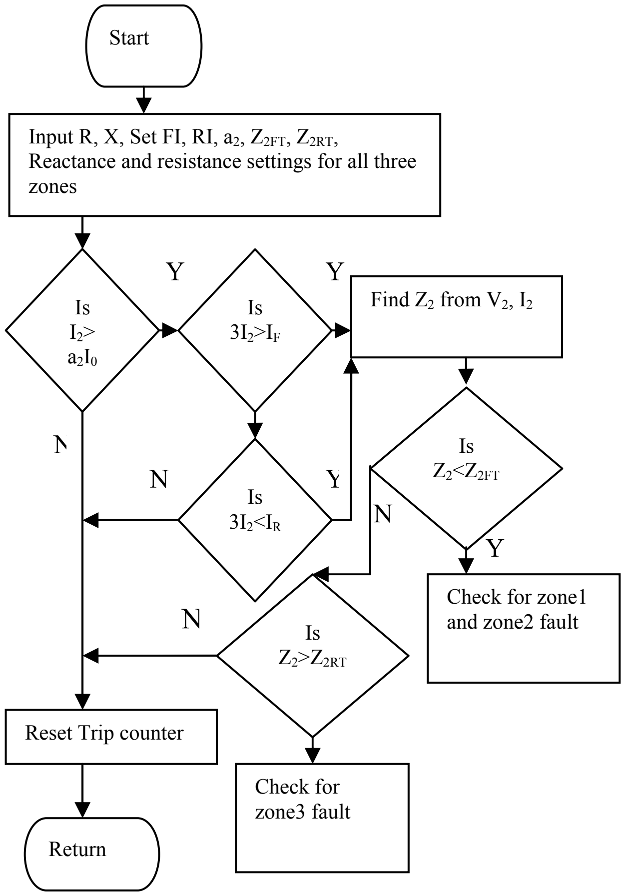

Fig: 8: Flowchart for Determining the Directionality of three quadrilateral relay.

The flowchart of Fig. 8 shows the development of three zone quadrilateral trip characteristic with directionality feature. The Relay logic is developed for three zone distance protection. Zone1 and zone2 covers 80% and 120% of the line from relay location in forward direction, and zone3 covers 20% of the line in reverse direction from the relay location.

The negative sequence impedance is given by

$$Z_2 = \frac{\mathrm{Re}\left[V_2\left(1\angle\theta_{L2}.I_2\right)\right]}{\left|I_2\right|^2} \tag{9}$$

Where, θ_2 Line negative-sequence impedance angle.

V_2 negative-sequence voltage,

I_2 negative-sequence current,

The directional element Enable bit, asserts when all of the following conditions are true.

1) $I_2 > a_2 I_1$

Where, I_1 is positive sequence current,

$a_2 = \frac{\min I_2}{I_1}$, generally this factor varies between 0.07-0.1.

2) $3I_2$ is greater than forward and reverse negative-sequence current threshold (FI&RI).

This setting is above normal load unbalance and below the lowest expected negative-sequence current magnitude for unbalanced faults.

Forward threshold impedance, Z_{2FT} can be set for ½ the positive sequence impedance of the line and Reverse threshold impedance, Z_{2RT} can be set equal to Z_{2FT} + 1 ohm. Any measured negative sequence impedance which is less than the Z_{2FT} setting is declared as a forward fault and any measured negative sequence impedance which is more than Z_{2RT} is considered a reverse fault.

The evaluation of the simulated new adaptive distance relay is carried out by comparing its performance with conventional distance relay. The quadrilateral characteristic is developed by static test with the settings

X=24.7 Ω; R=2.4 Ω; and step angle= 5^0

For the dynamic test, a typical parallel transmission system as shown in Fig. 9 which is of 400KV, 200km long, is simulated using EMTDC/PSCAD software package with frequency dependent phase model to obtain the fault transients.

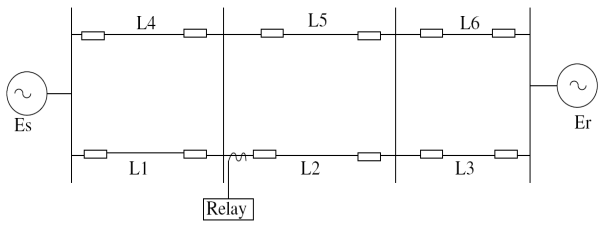

Fig . 9. Single Line Diagram of Parallel Transmission System

The length of line sections

L_1, L_4 =80 km; L_2, L_5 = 80 km; L_3, L_6 = 40 km.

The system parameters are

<u>Equivalent System Impedance:</u>

$$Z_{S0} = 23.459 + 108.31i\ \Omega$$
$$Z_{S1} = 8.561 + 20.241i\ \Omega$$
$$Z_{R0} = 17.53 + 70.795i\ \Omega$$
$$Z_{R1} = 8.36 + 15.57i\ \Omega$$

<u>Line Impedance</u>:

$$Z_{0L} = 0.297 + 1.1842i\ \Omega / km$$
$$Z_{1L} = Z_{L2} = 0.0352 + 0.4028i\ \Omega / km$$
$$Z_{0M} = 0.262 + 0.7814i\ \Omega / km$$

The adaptive relay is developed for three zone protection. Zone1 covers the 80% of the line 2, zone 2 covers 120% of the line 2, and zone 3 covers 20% of the line 1 in reverse direction (20% of L1 before relay location). The quadrilateral trip characteristic will change automatically obtaining the parallel line's operating status through substation PLC.

Following two configurations of parallel transmission line are considered for relay performance evaluation

1) One Line is Switched Off and grounded at Both Sides,

2) Two Parallel Lines are in Operation.

The test signals are obtained for fault location like

10% inside the zone1, 10% outside the zone2, and 10% before the relay location.

The developed adaptive relay is tested for all types of ground faults for each configuration mentioned above and results are shown in respective Tables given below. Finally the adaptive relay performance is compared with the performance of the conventional relay for different cases.

The Table I shows the performance of the developed adaptive relay for different fault conditions considered in circuit configuration, *One Line is switched Off and grounded at Both Sides.* The different fault conditions are given case reference numbers which are shown in table inside brackets. In subsequent discussion these case numbers are used for referring to each case.

Table II, illustrates the results obtained for the circuit configuration *Two Parallel Lines are in Operation,* when the zero sequence current of adjacent parallel line is available. Similarly Table III illustrates the results obtained when the zero sequence current of adjacent parallel line is not available. Table IV, gives the comparative analysis of adaptive and conventional distance relay for some sample cases with respective R-X plots.

Observing the operating times obtained after extensive tests, we observed that the operating time of the adaptive relay is almost same whether zero sequence current of adjacent parallel line is available or not. This gives the advantage of stable operation of the relay with adaptability.

TABLE I

ONE LINE SWITCHED OFF AND GROUNDED AT BOTH ENDS

Type of fault	Location of fault w.r.t.	Load applied	Inception of fault at voltage	Relay operating time(ms)
AG	10% inside the zone 1 end	10% FL	Zero**(a.1)**	**27ms**
			Peak**(a.2)**	**33ms**
		90% FL	Zero**(a.3)**	**26ms**
			Peak**(a.4)**	**40ms**
	10% outside the zone1 end	10% FL	Zero**(a.5)**	**404ms**
			Peak**(a.6)**	**404ms**
		90% FL	Zero**(a.7)**	**404ms**
			Peak**(a.8)**	**404ms**
	10% before the relay location	10% FL	Zero**(a.9)**	**503ms**
		90% FL	Zero**(a.10)**	**503ms**
BCG	10% inside	10% FL	Zero**(a.11)**	**30ms**
	10% outside	90% FL	Peak**(a.12)**	**404ms**

TABLE II
TWO LINES ARE IN OPERATION WITH THE AVAILABILITY OF PARALLEL LINE ZERO SEQUENCE CURRENT

Type of fault	Location of fault w.r. t.	Load applied	Inception of fault at voltage (Case no.)	Relay operating time(ms)
AG	10% inside the zone 1 end	10% FL	Zero(**b.1**)	**25ms**
			Peak(**b.2**)	**28ms**
		90% FL	Zero(**b.3**)	**24ms**
			Peak(**b.4**)	**21ms**
	10% outside the zone1 end	10% FL	Zero(**b.5**)	**402ms**
			Peak(**b.6**)	**402ms**
		90% FL	Zero(**b.7**)	**402ms**
			Peak(**b.8**)	**402ms**
	10% before the relay location	10% FL	Zero(**b.9**)	**503ms**
			Peak(**b.10**)	**508ms**
		90% FL	Zero(**b.11**)	**503ms**
			Peak(**b.12**)	**508ms**
BCG	10% inside	10% FL	Zero(**b.13**)	**24ms**
	10% outside	90% FL	Peak(**b.14**)	**402ms**

TABLE III
TWO LINES ARE IN OPERATION WITH OUT THE AVAILABILITY OF PARALLEL'S LINE ZERO SEQUENCE CURRENT.

Type of fault	Location of fault w.r. t.	Load applied	Inception of fault at voltage	Relay operating time(ms)
AG	10% inside the zone 1 end	10% FL	Zero(**c.1**)	**24ms**
			Peak(**c.2**)	**28ms**
		90% FL	Zero(**c.3**)	**24ms**
			Peak(**c.4**)	**21ms**
	10% outside the zone1 end	10% FL	Zero(**c.5**)	**402ms**
			Peak(**c.6**)	**402ms**
		90% FL	Zero(**c.7**)	**402ms**
			Peak(**c.8**)	**402ms**

TABLE IV
COMPARISON BETWEEN ADAPTIVE AND CONVENTIONAL DISTANCE RELAY

Fault condition (fault location)	**R-X plot (Fig)**	**Operating Time**		**Operating Status** × mal operation ✓ Correct operation	
		Conv.Relay (Tripped in)	**Adaptive Relay**	**Conv. Relay**	**Adapt. Relay**
a.1 (Zone 1)	10	27ms, (Zone 1)	28ms	✓	✓
a.6 (Zone 2)	11	25ms, (Zone 1)	Zone 2	×	✓
b.2 (Zone 1)	12	(Zone 2)	28ms	×	✓
b.4 (Zone 1)	13	21ms	21ms	✓	✓
a.7 (Zone 2)	---	26ms, (Zone 1)	Zone 2	×	✓

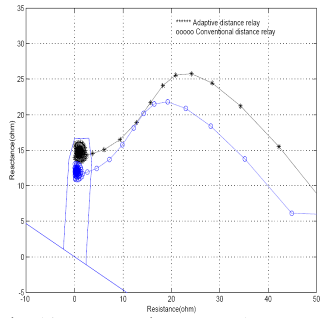

Fig. 10 R-X plot - case a1

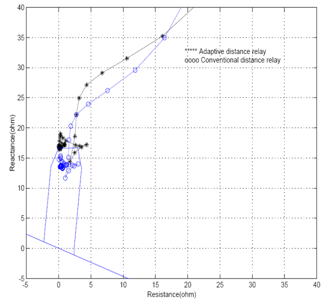

Fig.11. R-X plot- case a6

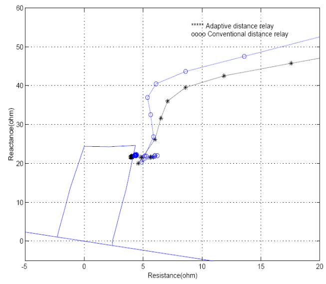

Fig.12 R-X plot - case b2

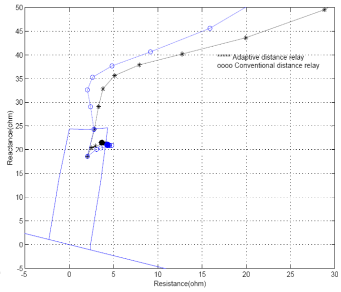

Fig.13.R-X plot- case b4

IV. CONCLUSIONS

1. The new adaptive distance relay described and evaluated, provides an enhanced distance protection for parallel lines with mutual coupling.
2. No remote signals are required for the adaptive scheme incorporated in the proposed relay.
3. The adaptation to the signal availability provides a built-in fallback scheme, which ensures the reliable operation under all conditions.
4. The developed quadrilateral trip characteristic with directionality feature is successfully tested for the three zone protection.
5. The results of extensive comparative evaluation prove the efficacy of the new adaptive relay.

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