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# Inter-Circuit Faults And Distance Relaying Of Dual Circuit Lines

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**Abstract--** The main sources of error and other difficulties associated with the distance protection of dual circuit transmission lines is well known. However, the design or selection of protection schemes usually fails to consider some of the more extraordinary fault occurrences that do occur.

This paper considers the observed impedances that result from inter-circuit faults on a simulated dual circuit transmission line, where variations in the phasing, and the impedance ratios have been considered. The simulations performed with the Alternate Transients Program show that inter-circuit faults may be undetectable in the instantaneous protection zone depending on the scheme adopted and the impedances of the surrounding network. The observed under-reaching has the potential to lead to a loss of major loads, mal-operation of single pole tripping schemes and even system instabilities based on the critical clearance requirements.

**Index Terms--** Inter-circuit fault, distance protection, dual circuit, distance scheme, phase selectivity, under-reach

## I. INTRODUCTION

The distance protection of dual circuit lines presents various difficulties, which are a result of the well known error sources for multi-circuit lines. These arise from fault resistance, the pre-fault loadflow conditions, the mutual coupling that exists between the circuits and the variety of faults that can occur on such lines.

Mutual coupling is often considered to be the main concern when protecting dual circuit lines with distance relays. The resulting errors are greatly affected by the topology of the line and values of the zero sequence source impedances present at each terminal. This can produce severe under-reaching and over-reaching errors for distance relays. In some cases, distance relays may see less than 50% or far more than 100% of the line, depending on the infeed and coupling conditions experienced [1].

Due to the nature of the zero sequence coupling that exists between the circuits, the status of the parallel line can produce the most noticeable effect. The distance elements will overreach when both lines are in service and under-reach will be experienced if the line is out of service and earthed at either end [1].

The definition of “immunity distance” has been provided in

[2] as a ratio of the terminal zero sequence source impedances. In such a case, the location at which the coupling contributions cancel will be the same for any under-reach or overreach.

It is also well known that the pre-fault load together with any fault impedance can modify the real coverage of a distance element due to the conversion of the fault resistance into an observed reactance [2]. However, on dual circuit lines these effects are generally not as severe as those presented by mutual coupling.

Several solutions are employed to allow for these impedance errors. The Zone 1 and Zone 2 reaches are often reduced and increased respectively in accordance with a set of system studies. This guarantees the correct operation of the relay under all system operation conditions. An alternative approach is to adjust the residual compensation value such that either the under-reaching or overreaching errors are minimized, while experiencing greater over-reach or under-reach respectively [2].

Adaptive zone reaches have also been applied in many references, including [3]. These commonly change a set of basic parameters when the network topology changes, possibly incorporating neural networks. These systems are often very complex and are not presently common in most transmission systems.

An alternative to the above techniques is to adopt new protection philosophies to overcome existing sources of error in protection relaying [4].

The conductor geometry in dual circuit lines makes them prone to multi-circuit faults, of which the earthed cross-country fault is the most common. Nevertheless, unearthed inter-circuit faults create unusual problems for the protection engineer due to the under-reach and the zero sequence currents present in the circuits themselves. These currents do not extend beyond the busbars, and consequently the terminal zero sequence source impedances have little impact [5]. Such faults have a significantly high probability of occurrence, as a result of bushfire activity, conductor galloping or broken conductors on a particular circuit.

The under-reach is created by the apparent transition between a double-phase-to-earth to a single-phase fault as the fault location is varied along the circuits.

Inter-circuit faults and close-in earth faults are also known to result in a loss of phase selectivity for single-pole tripping schemes due to an introduction of zero sequence currents [2,6]. This can be a serious problem on important circuits where system stability is a concern.

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$$Z_S = Z_{AA} - \frac{Z_{AE}Z_{AE}}{Z_{EE}} \quad (5)$$

Similarly, the mutual impedance  $Z_M$  between phases  $A$  and  $B$  under the presence of a single earth wire can be represented by [7]:

$$Z_M = Z_{AB} - \frac{Z_{AE}Z_{BE}}{Z_{EE}} \quad (6)$$

Consequently, there is a reduction in both the self and mutual coupling parameters for the transmission circuit. In the sequence domain, this results in a very small and large reduction in the positive and zero sequence impedances respectively.

Circuit transposition also assists by reducing the overall line impedance as well as the mismatch in the conductor loop impedances. There are generally three transpositions per circuit, which divide the line into sections of equal length. Generally the loop impedance is reduced as the distance between the two conductors decreases, and when the presence of earth is neglected.

Increasing the earth resistivity or the equivalent tower footing resistance results in smaller reductions in the zero sequence impedance of the circuit. Furthermore, a nonhomogeneous tower earthing resistance and variations in the substation earth grid resistances produce a non-uniform zero sequence line impedances.

Table 1 shows three simple dual circuit line configurations of equal length. The line impedances were determined using the Line Constants program within the Alternate Transients Package (ATP), showing that the overall positive sequence loop impedance fluctuates with regard to the phasing and transposition scheme used. It should be noted that only the phase-phase loop impedances have been calculated in this simple case, as a consideration of the zero sequence impedance requires a knowledge of additional variables including the earth resistivity.

TABLE 1  
FAULT LOOP IMPEDANCES FOR VARIOUS CIRCUIT PHASING AND  
TRANSPPOSITION CONFIGURATIONS WITH DUAL CIRCUITS

Loop Impedance	Un-transposed Circuit		Transposed
	Low Reactance Phasing	High Reactance Phasing	Low Reactance Phasing
A-B Fault	59.56∠85.0°	69.20∠85.4°	51.26∠84.9°
A-C Fault	55.35∠84.7°	57.59∠85.0°	51.26∠84.9°
B-C Fault	56.03∠84.6°	58.33∠84.6°	51.26∠84.9°

### III. INTER-CIRCUIT FAULT ANALYSIS

To assess the impact of inter-circuit faults on dual circuit lines, a base scenario was chosen as shown below.

The simulated dual transmission circuits, shown in Fig.2, were 172 km in length and assumed a low reactance construction. This also applied to the conductor geometry and

sizes, resulting in positive sequence line impedances for an un-transposed case of  $58.9\angle 84.9^\circ\Omega$  and a residual compensation factor (RCF) of  $0.735\angle -15.6^\circ$ .

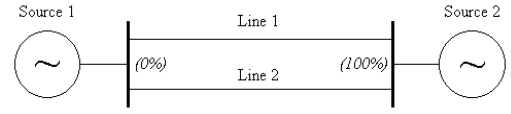


Fig. 2 – Simple dual circuit line topology examined

This scenario was then investigated using ATP with a distributed parameter line model, and a four-wire sequence component equivalent or the source impedances. Defining the Source Ratio (SR) as the ratio of the positive sequence source impedances ( $Z_{1-Source1} / Z_{1-Source2}$ ), 1.15 was initially chosen to identify any resulting dependencies.

The “boundary forward reach setting” has been defined in [5] as the impedance vector normalized against the relay characteristic trip boundary.

All the applied faults have assumed zero fault impedance. Subsequent studies have demonstrated that at EHV transmission voltages the arc impedance between two consecutive conductors results in a minimal variation to the following impedance plots.

For each of the following scenarios the fault position was varied and the boundary forward reach setting was computed for each of the distance elements based on an “ideal” offset mho characteristic with 100% forward reach.

#### A. Variations in Dual Circuits

Applying an  $A$  phase (of line 1) to  $C$  phase (of line 2) inter-circuit fault to this dual circuit line will result in considerable under-reach for the phase elements, as shown in the impedance plot of Fig. 3. This also shows the effects of inter-circuit faults on high and low reactance coupling (*High Z*, and *Low Z*). Such faults are unlikely on high reactance lines due to the conductor geometry, as shown in Fig. 1. However, the calculations have been provided for comparison. The under-reach at the remote busbar for these high reactance circuits is also a result of the coupling between the faulted conductors on one circuit reinforcing the fault loop on the parallel line.

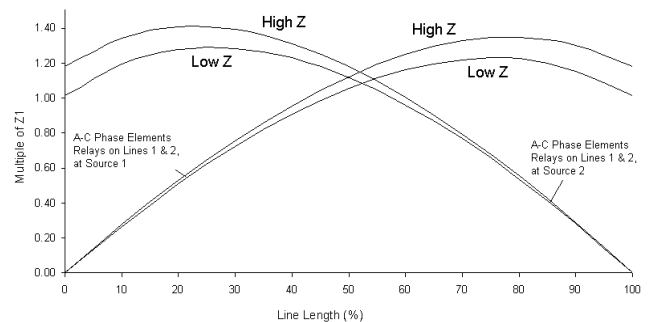


Fig. 3 – Phase element impedance plot for an un-transposed line

Fig. 4 depicts the earth impedances with respect to offset mho earth elements set with a forward at 100% of the line positive sequence impedance ( $Z_1$ ). Nevertheless, with this

characteristic the relay earth elements will also under-reach for these faults. It must also be noted that only one of the two circuits will observe the impedances within the mho characteristic, as shown below.

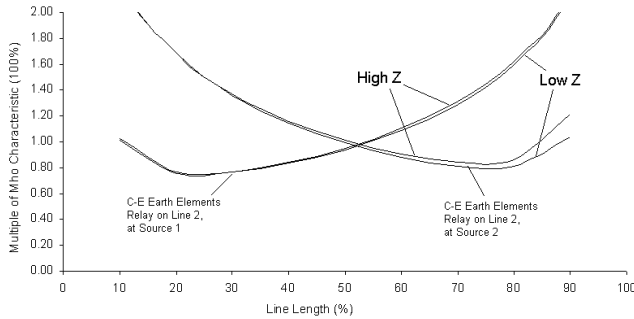


Fig. 4 – Earth element impedance plot for an un-transposed line

The line impedance is reduced when these circuits are transposed, although the only variations when compared to the un-transposed case appear to be fluctuations in loop impedance due to the asymmetrical nature of the faulted sections as shown in Fig.5.

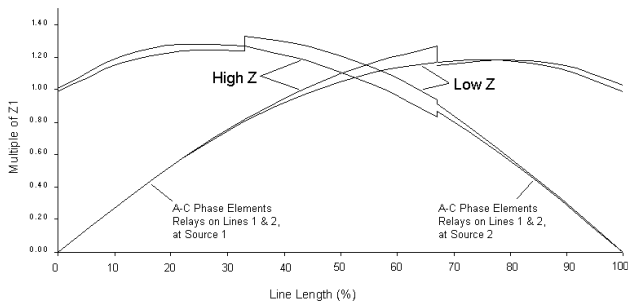


Fig. 5 – Phase element impedance plot for a transposed line

Similarly, the earth impedance with respect to the same offset mho can be seen in Fig. 6. Again the earth elements on only one of the two circuits will observe the impedances shown.

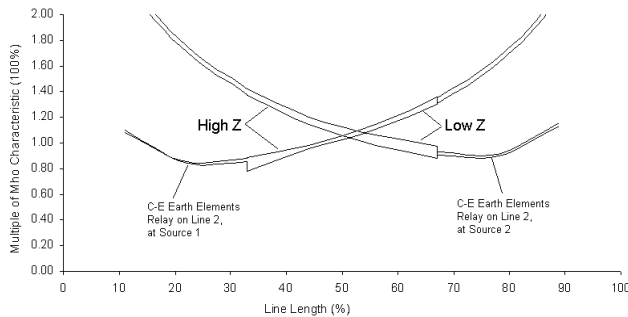


Fig. 6 – Earth element impedance plot for a transposed line

Fig. 7 depicts the phase and earth impedance loci for variations in fault position, against two offset mho characteristics with a forward reach of 100% and 120% respectively. The maximum under-reach experienced by the phase elements occurs at approximately 80% of the line length. The earth elements, however, provide very little extra

coverage when using mho elements.

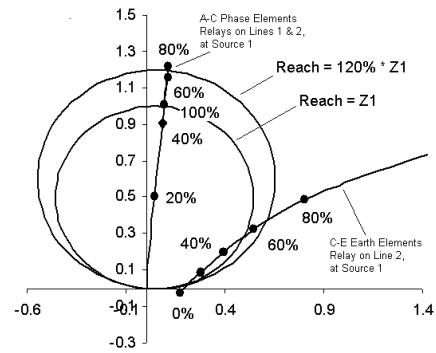


Fig. 7 – Consideration of earth impedance loci

Fault impedance was considered in this analysis. Due to the conductor geometry and the resulting relatively low arc impedances present, no significant change was observed in the impedance plots. However, the earth impedance loci move further away from the trip region of the mho characteristic.

**B. Source Impedance Considerations**

The effects of source impedance variation on the phase elements can be observed as shown in Fig. 8, where the fault position has been varied along the line.

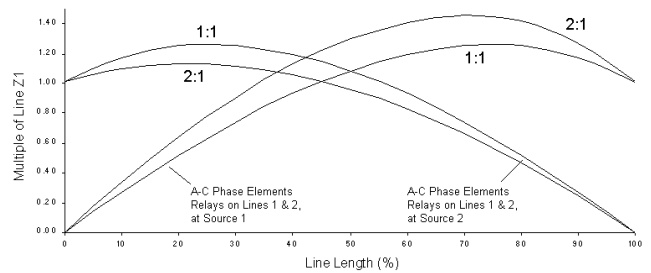


Fig. 8 – Impedances observed by phase elements for source impedance (SR) ratios of 1:1 and 2:1.

Similarly the impedance loci result in greater under-reach at the weaker source terminal for both the phase and earth elements, when the source impedance is increased above unity, as shown in Fig.9.

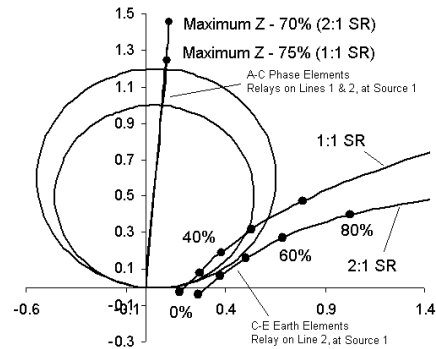


Fig. 9 – Impedance loci observed from the weaker source terminal

However, the opposite occurs for the relaying elements at the terminal with the stronger positive sequence source. The

under-reach magnitude is reduced for the phase elements while the earth elements observe impedances similar to that obtained with a 1:1 SR, as illustrated in Fig.10.

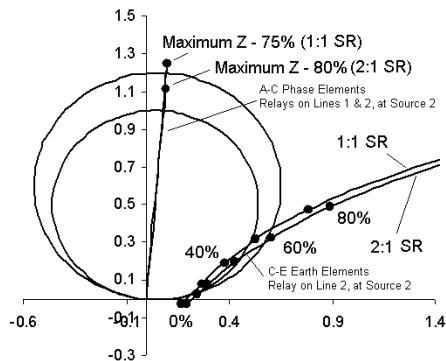


Fig. 10 – Impedance loci observed from the stronger source terminal

This is further portrayed in Fig. 11, which shows the earth impedances normalized against the ideal mho characteristic trip boundary (the element is assumed to have a 100% line forward reach).

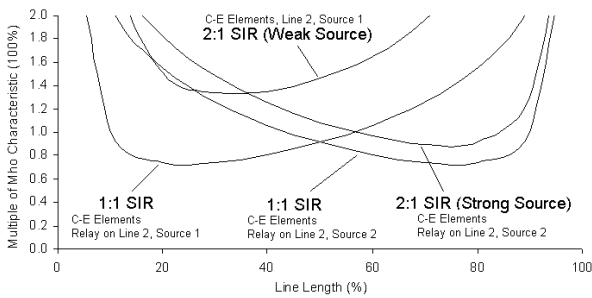


Fig. 11 – Earth element impedance plot for a mho relay with a 100% forward reach.

Similarly, Fig. 12 considers the magnitude of the phase element under-reach for variations in the source impedance ratio. With a large SR, the fault current is supplied predominantly from the strong source, which results in the distance relays observing a double phase to earth fault.

Conversely, the relay at the remote busbar must contend with the fault current infeed from the strong source thus producing a large observed impedance.

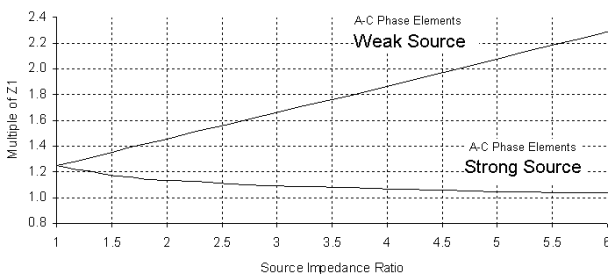


Fig. 12 – Maximum phase element under-reach observed for variations in the source impedance ratio.

**C. Line to Source Impedance Ratios**

In a situation where the line impedance is reduced relative

to the source impedance, the maximum phase element under-reach remains fixed despite the general under-reaching magnitude increasing for other fault locations as shown in Fig.13.

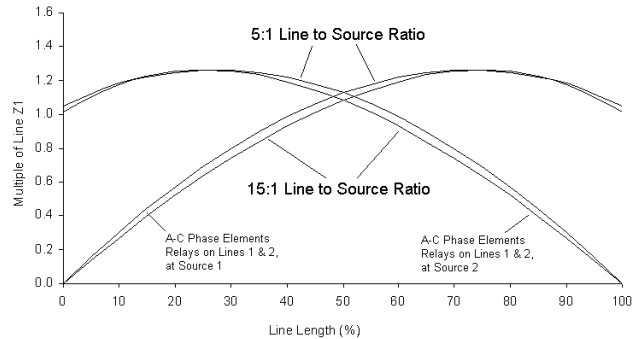


Fig. 13 – Phase element impedance for a 1:1 SR with a variation in the line impedance.

Nevertheless, the earth elements observe fault impedances that are more resistive than those observed on a long line, relative to the line positive sequence impedance, as illustrated in Fig.14.

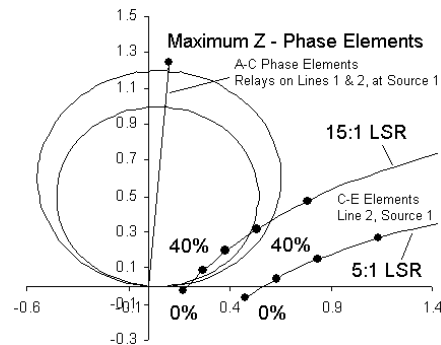


Fig. 14 – Earth element for a 1:1 SR with a variation in the line impedance.

This apparent increase in fault resistance can be offset slightly when using fully cross-polarised mho earth elements. However, the additional resistive reach provided by such polarisation remains smaller than the rate at which the earth impedance appears to move from the origin of the impedance plot.

**D. Uncoupled Topologies**

Assuming a hypothetical case whereby the previous dual circuit with an SR of 1.15 has no mutual coupling between the respective circuits, the magnitude of the under-reach observed by the phase elements is increased greatly as shown in Fig.15.

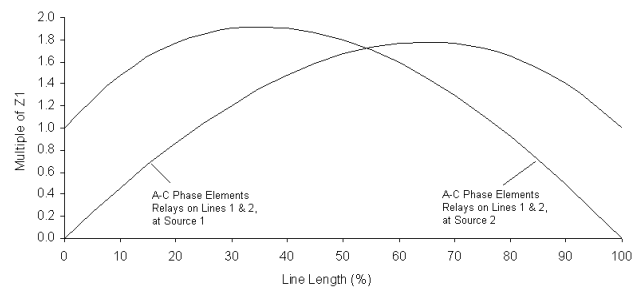


Fig. 15 – Under-reach experienced by a hypothetically uncoupled circuit

This raises questions with regard to some common dual circuit topologies where two predominantly uncoupled circuits are intermittently strung on the same structures. A simple scenario is shown in Fig. 16 where coupled circuits exist for a substantial distance from a busbar, after which different line easements are followed. Such cases may require special protective techniques against inter-circuit faults on the coupled section.

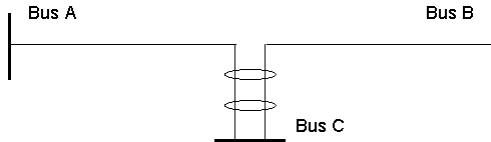


Fig. 16 – Partially uncoupled dual circuit topology

#### IV. PROTECTION CONSIDERATIONS

Detection of these faults using a permissive under-reaching scheme would require the fault to be observed by at least one relay in Zone 1. Consequently at least one of the impedance curves in, say, Fig. 8 must exist below the Zone 1 reach at all locations for the line to be adequately protected. Similarly, neither of the impedance plots may extend beyond the Zone 2 reach.

Zone 1 reaches are usually set to 80% of the lowest impedance that can be observed for faults on the remote busbar. This may occur when the parallel circuit is out of service and earthed at either end, resulting in Zone 1 settings between 60-75% of the line impedance. Consequently, two permissive under-reaching schemes are inadequate for most dual circuit lines, as inter-circuit faults at many locations will not be observed.

Permissive over-reaching or blocking schemes require the fault to be observed within the Zone 2 reach of the relays at each line terminal. These Zone 2 reaches are commonly configured to 120% of the maximum impedance observed to the remote busbar. This may occur when both lines are in service producing overall zone reaches of more than 140% of the line impedance. However, inter-circuit faults on a dual circuit with equal source impedances would require a Zone 2 reach of 150% or more for permissive overreaching or blocking schemes. The required reach also increases as the source impedance ratio shifts from unity.

On long lines, the earth elements may be used for fault detection through the use of quadrilateral relays, however this can only be achieved on circuits where the load current is low. Since the resistive reach of such relays is usually limited to 3.5 times the reactance value [8], this may provide little benefit on shorter circuits as the apparent earth fault impedance is extended further from the origin of the impedance plot.

Generally, protection implementations designed to detect inter-circuit faults should only rely on the observation of the phase impedance due to the absence of any earth return currents. Thus the Zone 2 reaches must consider the prospective worst-case inter-circuit fault impedance, which is a function of the positive sequence source impedance.

Current differential schemes appear to be the only reliable

approach to detecting these faults when appropriate Zone 2 settings cannot be obtained, or when single pole tripping is required. This can be overcome by using at least one current differential scheme in conjunction with logic that will trip the faulted phases only. Otherwise, all six voltage and current signals should be analyzed by a single relay to determine the fault condition, as is proposed in [9].

#### V. CONCLUSIONS

Conventional philosophies directing the use of distance protection schemes for dual circuit lines may not enable the detection of unearthed inter-circuit faults in the instantaneous zone of operation. This is an essential requirement in many cases, including network interconnectors or lines carrying heavy or sensitive loads.

To detect inter-circuit faults, at least one permissive overreach or blocking scheme is required with a Zone 2 reach large enough to extend over the apparent impedances observed from each line terminal.

Current differential protection should be considered on at least one of the circuits in situations where an inter-circuit fault is deemed a credible risk and the source impedance ratio between the line terminations is significantly larger than unity, or if single pole tripping is employed.

#### VI. ACKNOWLEDGMENT

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## BIOGRAPHIES



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