# Protection of Double Circuit Transmission Lines

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## I. INTRODUCTION

Parallel transmission lines have been extensively utilized in modern power systems to enhance the reliability and security for the transmission of electrical energy. The different possible configurations of parallel lines combined with the effect of mutual coupling make their protection a challenging problem. Different types of protection and algorithms have been proposed in the past to overcome some of the performance related issues. In addition to the effect of mutual coupling, fault resistance and pre-fault loading consideration, as well as cross-country faults have to be considered in order to determine the protection response. In the case of distance relays, the determination of the final fault impedance is therefore not that straight forward as a number of system conditions affect it:

1. The dynamic changes of the characteristics of the power system, such as in generation capacity, load and in the network topology
2. Inaccuracies in the measuring instruments, relay measuring inputs, line parameters and protection algorithms

The effect of the dynamic characteristics of the system on protection is normally dealt with by traditionally determining the relay settings according to worst-case scenario studies. Inaccuracies in the electric power system need to be considered in the process. For example, a sequence components based model for a protection coordination study of a transmission line that is not completely transposed, will result in a difference between the results from the simulation and real fault conditions.

Inaccuracies in the image of the primary system conditions seen by the protective relays due to the errors in the measuring circuit can be limited by using properly selected current and voltage transformers and more advanced relay input modules.

To compensate for the above described effects, the relay settings require large safety margins. A typical Zone 1 distance setting is 80% of the line impedance. These settings have to be appropriate for extremely weak system conditions, as well as in the cases where over or under tripping could further weaken the system and lead to stability problems.

Since distance relay settings may therefore not be appropriate for all system conditions in terms of security and dependability, adaptive protection based on different setting group selection are often considered in practice.

Consideration of different types of protection for double circuit lines is important in order to achieve improved performance of the protection system and reduction in the effect of the fault on power system stability and sensitive loads. The issues with the limitations in the performance of distance relays on parallel lines can be easily overcome by the use of modern line differential protection relays based on digital communications technologies. Line differential schemes using GPS for data synchronization are a very secure and dependable solution for such applications in case when a communications channel is available. They offer significant benefits, but have an important deficiency – lack of remote backup functionality and dependence on the state of the communications channel. However, modern relays have increased processing power that allows them to run dual high-performance schemes based on distance and line differential protection respectively thus giving the users the benefit of both technologies in a single relay hardware.

This paper describes different cases of parallel transmission lines and analyzes some well known application problems associated with their protection. Distance protection performance problems are in the focus due to the fact that they are the most commonly used protection type for parallel transmission lines. The behavior of ground overcurrent protection on double circuit applications is also discussed in the paper. Finally, some advanced features of communications assisted schemes, non-communications protection schemes and fault location for double circuit lines are discussed.

## II. DOUBLE CIRCUIT LINE PROTECTION APPLICATION CONSIDERATIONS

Mutual coupling and the possibility of the occurrence of cross country faults are possibly the main sources of problems and complexity when faults in multi-circuit lines are to be studied. Different double line topologies have to be considered for various fault conditions and the recommended solutions that are available for these scenarios are often not implemented in practice. The use of single line settings are often only considered without analyzing the mutual coupling effects. Also, cross-country faults may be deemed a low risk, but in the event of such a fault may cause incorrect tripping operation which could lead to stability problems on already weak-end networks.

### *A. Mutual Coupling Effects*

Double circuit lines on the same towers (Figure 1) or on the same right-of-way are very common.

**Fig. 1 Double circuit line**

They can have many different configurations based on the system topology and how they are connected at the two ends of the double circuit line. For example:

- they are not connected to the same bus at either end of the line
- they are connected to the same bus at only one end of the line
- they are connected to the same bus at each end of the line

Figure 2 shows the last case that will be the focus of the analysis in the paper.

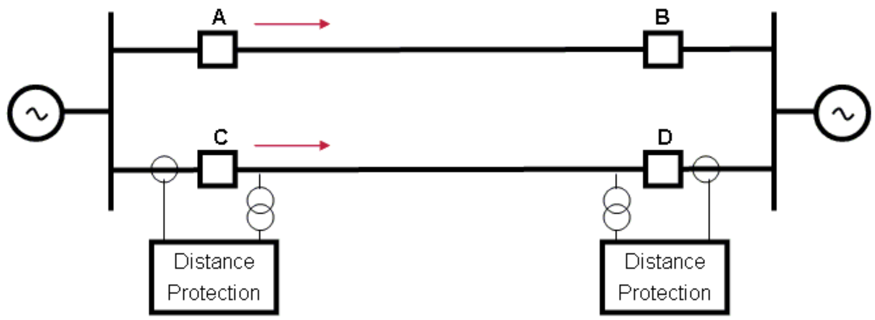


**Fig. 2 Example parallel line system**

The parallel line configuration is further complicated when the two (or more) lines on the same tower or right-of-way are at different voltages. Again there are several possible scenarios:

- they are connected to the same substation at either end of the line
- they are connected to the same substation at one end of the line
- they are not connected to the same substation at either end of the line

The main difference between a single transmission line and a transmission line on the same tower or parallel along the same right-of-way with one or more other lines is the mutual coupling (Figure 3). Since typically the behavior of protection relays is analyzed in terms of sequence components, following is some discussion of the effect of mutual coupling on the different sequence systems.

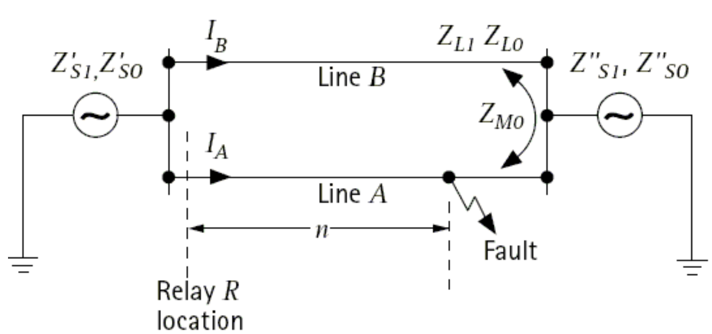


**Fig. 3 Mutual coupling on double circuit line**

The positive and negative sequence coupling between parallel feeders for symmetrical lines are usually small and therefore can be neglected.

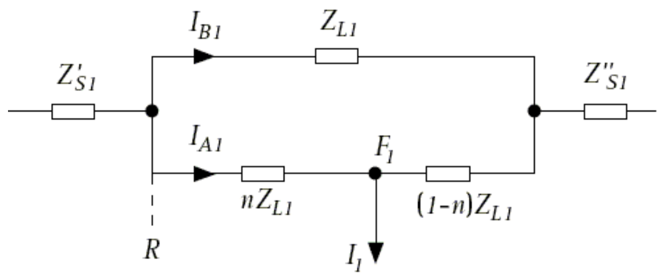


**Fig. 4 Positive sequence diagram**

That is not the case with the zero sequence mutual coupling. It can be considerable, since it is up to 50 to 70% of the self impedance $Z_{L0}$ of the line.

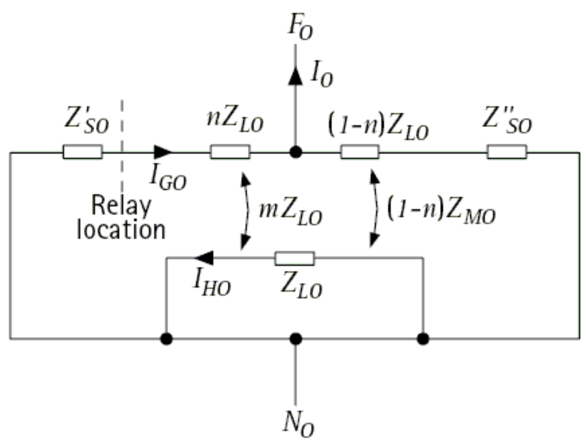


**Fig. 5 Zero sequence diagram**

When a ground fault occurs in the system, the voltage applied in one circuit includes an induced voltage proportional to the zero sequence current in the other circuit. In the case of an impedance measurement, the current measured does not reflect the effect of mutual coupling and the relay's measured impedance could underreach or overreach depending on the direction of the current flow in the healthy circuit.

**1. Parallel line in service with faults on the protected line or adjacent line**

Consider the system in Figure 6 with a ground fault F1 towards end B. The zero sequence current $I_{L0C}$ in the healthy line CD, is in the same direction as the fault current $I_{L0A}$ and $I_{L0B}$ is in the opposite direction.

The zero sequence current in the healthy line induces a zero sequence voltage in the faulty line resulting in a higher voltage at A. Thus the apparent impedance seen by the relay at A increases. At end B, the zero sequence voltage induced opposes the voltage at B, resulting in a reduced voltage and hence a reduced apparent impedance. The current magnitudes depend on the source impedances. The relay tends to underreach with a strong source and overreach for a weak source end. It should be noted that the relay at the opposite end tends to overreach when the local relay underreaches.

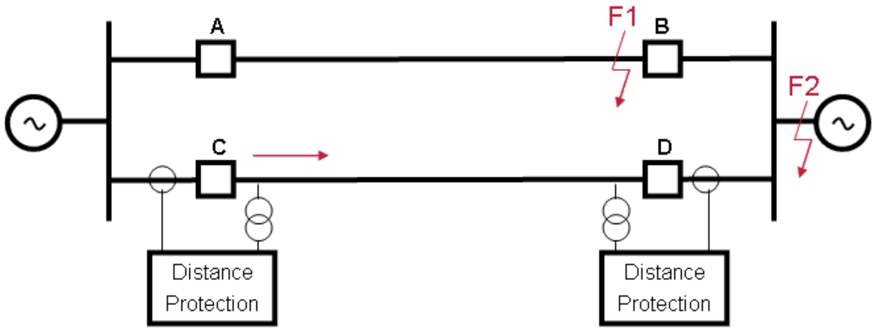


**Fig. 6 Double circuit line with faults**

It can be shown that the overreach effect at the one end will extend the protection coverage without causing the relay to operate beyond the remote busbar. The Zone 1 characteristic will overlap in this case for ground faults on the line so a permissive underreach scheme will provide adequate high speed operation for the line.

Families of reach curves can be calculated and plotted [1] as shown in Figure 7. In the figure n' is the effective per unit reach of a distance relay set to protect 80 % of the line.

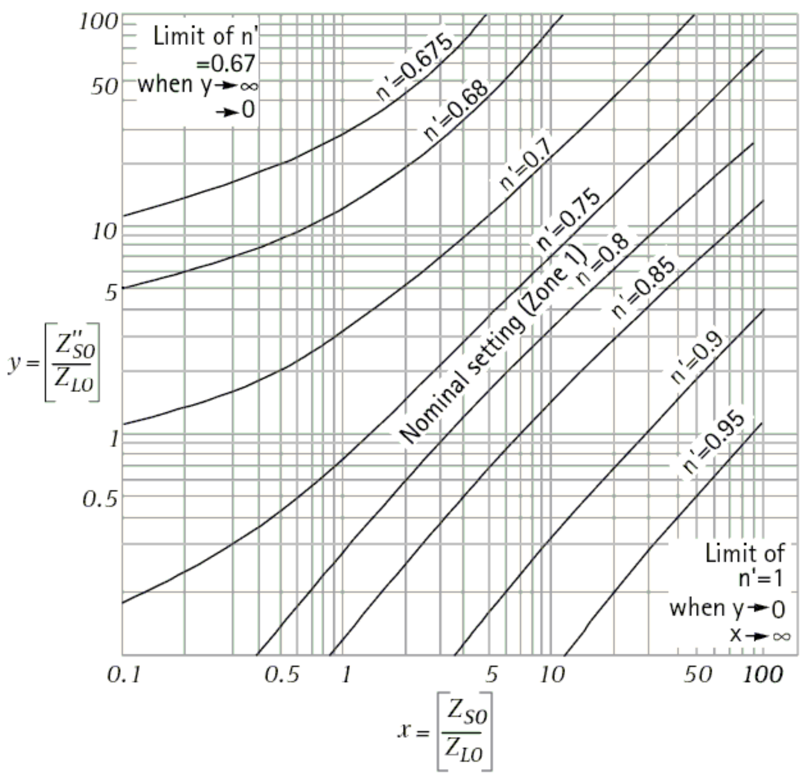


**Fig. 7 Family of reach curves with mutual coupling effect**

The accuracy of measurement can be improved by using mutual compensation whereby the parallel zero sequence current is included in the relay current measurement. In this case only the current has to be compensated as the voltage measurement already includes the effects of mutual coupling. Thus the values fed into the relay can be derived as follows [1]:

Vr=Vg and Ir= Ifault + $K_R.I_0$ + $M.I_0$ par.

Where

Vg = voltage at relay point
Ifault = fault current on the protected line
$K_R$ = residual compensation factor
$I_0$ = zero sequence current on protected line
$I_0$par. = zero sequence current on parallel line
M = mutual compensation factor = $Z_{M0}/Z_{L1}$

Mutual compensation has to be approached with caution however, as it may give improved accuracy on the protected line but may operate incorrectly for close in faults on the adjacent feeder. This is overcome by limiting the amount of compensation to typically $1.5.K_R.3I_0$ which can be shown not to affect performance for faults on the protected line.

**2. Parallel line in service with faults on the remote line**

In cases where parallel lines have similar parameters, the effects of mutual coupling are effectively cancelled as both lines will usually share the zero sequence currents due to the remote ground fault F2 in Figure 6. If a fault occurs on a line that lies beyond the remote terminal end of a parallel line circuit, the distance relay will still however under-reach for those zones set to reach into the affected line. Analysis shows that under these conditions, because the relay sees only 50% (for two parallel circuits) of the total fault current for a fault in the remote line section, the relay sees the impedance of the affected section as twice the correct value. This may have to be allowed for in the settings of Zones 2 and 3 of conventionally set distance relays. Since the requirement for the minimum reach of Zone 2 is to the end of the protected line section and the under-reach effect only occurs for faults in the following line section(s), it is not usually necessary to adjust Zone 2 impedance settings to compensate. However, Zone 3 elements are intended to provide backup protection to adjacent line sections and hence the under-reaching effect must be allowed for in the impedance calculations.

**3. Parallel line out of service with faults on the protected line or remote line**

The other situation that requires mutual effects to be taken into account is when there is an earth fault on a feeder when the parallel feeder is out of service and earthed at both ends. An earth fault in the feeder that is in service can induce current in the earth loop of the earthed feeder, causing a misleading mutual compensation signal.

In the case where both ends of the parallel line are open and grounded (Figure 8), the relay will not measure correctly the impedance.

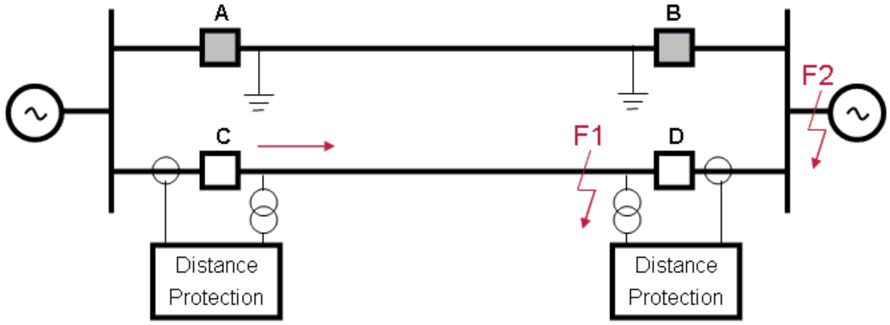


**Fig. 8 Parallel line open and grounded at both ends**

The apparent impedance seen by the relay in this case is

$$Z_R = Z_{L1} - \frac{I_{A0} Z_{M0}^2}{I_R Z_{L0}}$$

$$I_R = I_A + K_R I_{A0}$$

Figure 9 shows the zero sequence network under these conditions.

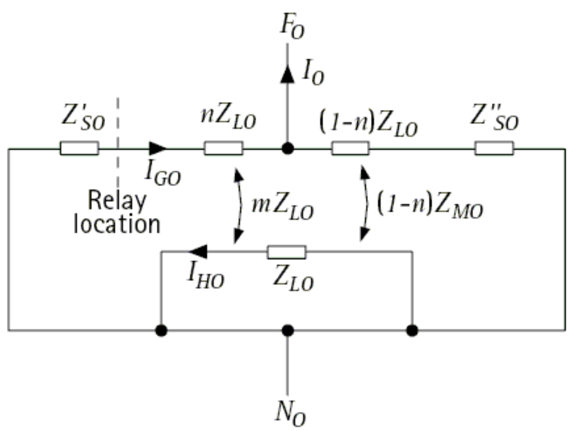


**Fig. 9 Zero sequence network with one line open and grounded at both ends**

It can be shown that the worse case is when the system is grounded behind the relay with no generation at that end and the apparent impedance presented to the relay is then given by:

$$Z_R = Z_{L1}\,(1 - Z^2_{M0}/Z^2_{L0})$$

This shows the tendency of the relay is to overreach which is especially a problem for remote faults. Although mutual compensation may have been applied to the relay on the protected line, it will have no effect on accuracy in this case as the grounding takes place on the line side of the CT's thus preventing any possible zero sequence current measurements from taking place.

The way to overcome this is to have reduced ground fault reach settings during the parallel line maintenance period and in modern relays this is easily done using a different settings group. The question of security also comes into play as the associated risk of a close in remote line fault may be seen as a low risk during the line outage and thus many utilities' practice is not to adjust settings.

Another solution offered by relay manufacturers to the above problem is to implement an adaptive zero sequence compensating factor depending on the line status. For example, when the adjacent line is open but not grounded, a zero sequence compensating factor applicable to a single line scenario is selected based on the line status information. When the adjacent line is in service, a mutual compensating factor is used taking into account the effects of mutual coupling as discussed previously. Lastly, when the adjacent line is out of service and grounded, a modified compensating factor is used relevant for this scenario. Thus appropriately selected zone reach settings and zero sequence current compensation factors allow a distance relay to provide a better zone coverage and prevent possible overreach or underreach effects due to double line operating conditions.

### *B. Cross country faults*

These types of faults are more likely to occur on double circuit lines located on the same tower structures and may result due to bush fires under the lines, lightning, as well as broken conductors. Cross country faults result in unusual current distributions that compromise the seen impedance by units not directly involved in the fault loop, giving fault selector problems for close-in faults.

#### 1. Distance Relay Performance

These types of faults are difficult to distinguish for a distance relay and undesired three pole tripping may occur during simultaneous line to ground faults on two different phases of a double circuit line. The most frequent inter-circuit fault is the double ground fault.

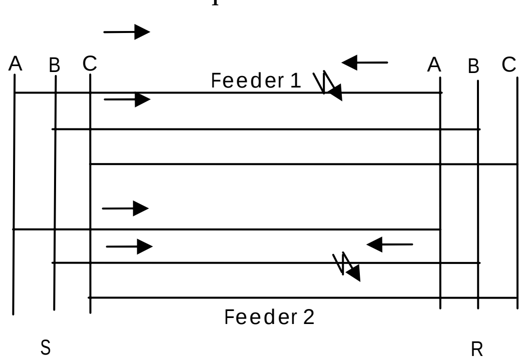


**Fig. 10. A-B-G cross country fault**

Figure 10 illustrates the problem. For an A-G fault on feeder 1 and a B-G on feeder 2, the relays at end R will correctly measure that it is a single phase fault. Relays at end S could determine an A-B-G fault and would issue a three pole trip if the zone 2 element is for instance picked-up whilst receiving a permissive trip from the remote end. This is normally the case for faults towards the remote end. A permissive scheme using phase segregated permissive signals from the remote end will provide selectivity.

Phase-to-phase cross country faults also need to be considered. The phase-to-phase inter-circuit fault causes the presence of zero-sequence current, that normal ground distance units may detect. For example, for an inter-circuit A-B fault, not only could the A-B phase distance elements of both lines pick-up, but A-G on both lines as well as C-A elements may also pick-up for different fault locations on the lines. Correct phase selection is therefore a problem and in applications where the risk of such a fault is considerable, careful evaluation and selection of the distance relay is essential. Modern relay algorithms are designed with advanced phase selection techniques and take into account such onerous conditions.

**2. Ground overcurrent protection**

These relays are often applied as back-up protection on transmission lines and offer good coverage for high impedance faults when applied as a directional comparison scheme. As discussed previously, a ground fault on one line will induce a zero sequence voltage in the adjacent line causing current to flow in the healthy line. For faults towards the remote end of the line, mutual coupling may cause a reduction in the available zero-sequence current in both lines. This will have an effect on the sensitivity of the ground element and pick-up settings may have to be adjusted.

On the other hand, sequential tripping on a faulted line may cause operation of the healthy line protection. For a phase to ground fault close to a line end, that end may trip first and the remote relay sequentially. This may induce a large zero sequence current in the healthy line during the transition period where only one end is open and the fault current maintained through the remote end. This may cause the ground element to operate and therefore ground overcurrent settings has to consider both scenarios carefully.

The effect of a parallel circuit open and grounded at both ends will result at the largest current for remote end faults and needs to be considered when determining the settings of the ground overcurrent protection relays.

***C. Sequential Tripping and Current reversal***

When a fault is cleared sequentially on one circuit of a double circuit line with generation sources at both ends of the circuit, the current in the healthy line can reverse for a period of time. Unwanted tripping of circuit breakers on the healthy line can then occur if Permissive Overreach or Blocking type communications aided distance schemes are used. Figures 11a and 11b show how the situation can arise.

Figure 11a shows the initial fault F1 close to circuit breaker B.

The protection at circuit breaker *B* clears the fault faster than the relay at circuit breaker *A*. Before circuit breaker *B* opens, the Zone 2 elements at *C* may see the fault and operate, sending a trip signal to the relay for circuit breaker *D*. The reverse looking element of the relay at circuit breaker *D* also sees the fault and inhibits tripping of circuit breakers *C* and *D*.

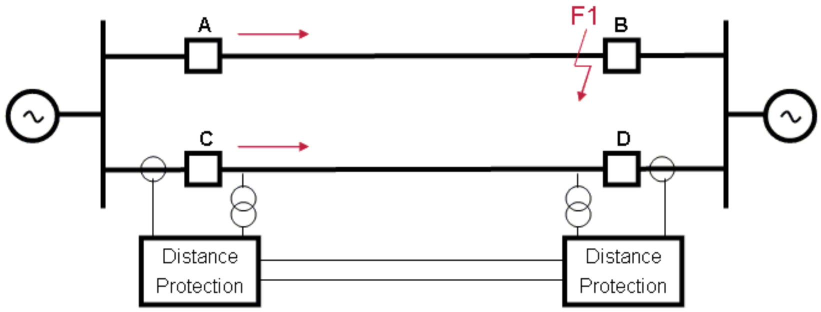


**Fig.11a. Current reversal considerations**

However, once circuit breaker *B* opens, the relay element at *C* starts to reset, while the forward looking elements at *D* pick up (due to current reversal) (Figure 11b) and initiate tripping. If the reset times of the forward-looking elements of the relay at *C* are longer than the operating time of the forward looking elements at *D*, the relays will trip the healthy line. The solution is to incorporate a blocking time delay that prevents the tripping of the forward-looking elements of the relays and is initiated by the reverse looking element which also inhibits the relay's permissive trip logic and signal send logic at substation D. The time delay must be longer than the reset times of the relay elements at *C*. This timer is the so called current reversal guard timer.

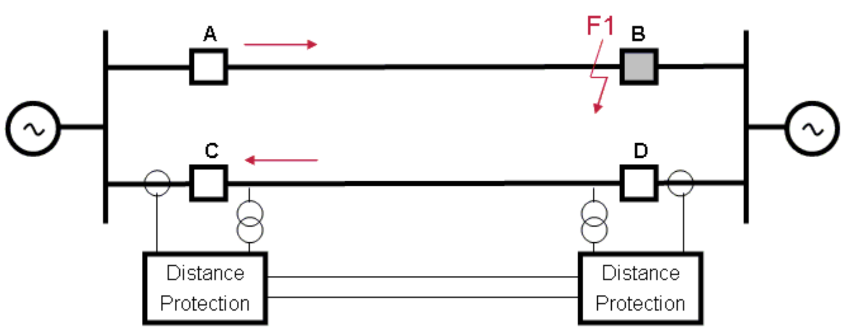


**Fig.11b. Current reversal considerations**

## III. IMPROVED RELAY FEATURES FOR DOUBLE CIRCUIT PROTECTION

To overcome some of the problems associated with double line protection, various modern day improvements are available such as improved distance protection schemes, distance protection accuracy, unit type protection and back-up protection. These are discussed below:

### A. Improved communicating protection schemes for double circuit lines

Possible problems with applying permissive type schemes on double circuit lines have been discussed. The critical communication requirements for such applications need to consider aspects of security, speed and reliability. Relay to relay communications via direct fiber optic implementation or using IEEE C37.94 meet all of the above requirements.

In a direct fiber application, the relays have fiber optic ports and may be connected directly via 1300nm fiber optic for example, or though a multiplexed communications network. Speeds of 56k/64kBit/s are achievable giving high-speed teleprotection for distance aided schemes with a typical end-end delay of 5ms for Permissive/Blocking signals and around 6 ms for Inter-tripping. This minimal difference in times is largely due to the security requirements for the types of aided scheme eg. for a direct inter-trip scheme two complete messages to confirm the remote command offers far superior security than waiting for a single message to execute a command. With modem based solutions, this is even more important in the presence of noise and it is highly recommended to have this level of security in the inter-relay communications protocol.

The inter-relay commands allow easy implementation of a phase segregated permissive scheme for correct cross-country fault phase selection. For example, although a single phase fault on a line may be seen as a Ph-Ph-G fault due to a cross-country fault condition, three pole tripping is prevented unless a minimum of two phase permissive trip signals are received.

### B. Non-Communications based protection schemes for parallel lines

Line differential protection remains the most selective form of protection for multiple circuit line protection as it is immune to phenomena such as mutual coupling. Communications requirements may be cost prohibitive and a solution with similar advantages as line differential protection but without the communications requirements are advantageous. The cross-differential scheme principle (Figure 12) is illustrated below.

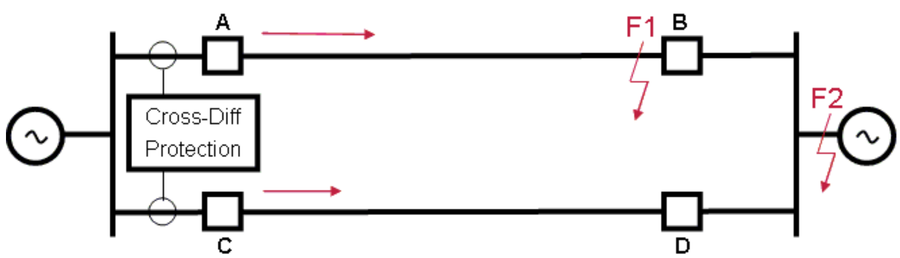


**Fig. 12 Cross-differential protection on double circuit line**

The basic principle of the cross differential directional element is based on the calculation of the amplitude of the differential current between the two lines to determine whether a fault is internal or external and select the faulted line.

$$|I_1| - |I_2| > I_{op} \rightarrow \text{Trip Line1}$$

$$|I_2| - |I_1| > I_{op} \rightarrow \text{Trip Line2}$$

The logic diagram is shown in Figure 13. Where $I_1$ and $I_2$ are currents of the two lines; $I_{op}$ is the operating value; $U_{\phi\phi}$ is the phase-phase voltage; $\theta_{\min}$ and $\theta_{\max}$ are the operating ranges.

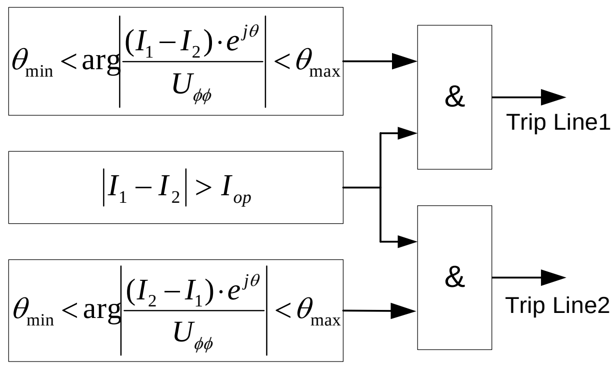


**Fig. 13 Logic diagram of cross differential directional element**

As can be seen from Figure 14 under load conditions (same will be the case with external fault conditions) the difference between the currents in both circuits will be minimal, while after a fault occurs on one of the lines there will be a difference between the currents in the faulted and the healthy circuit.

This technique offers a considerable benefit since it allows in most cases fast fault clearing for faults on any of the lines. The instantaneous tripping zone covers a large section of protected line with the remainder of the line covered by sequential tripping which is faster than the Zone 2 distance operation.

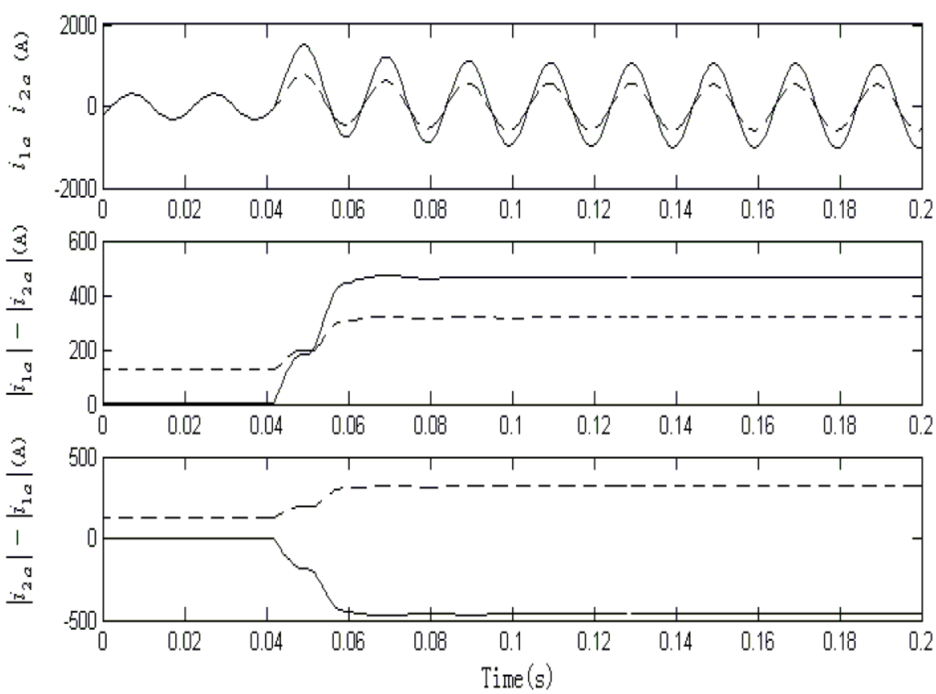


**Fig. 14 Operation of cross-differential protection for a fault in the middle of the line**

When the difference between the sources at the two ends of the lines is very large, the current amplitudes of both lines on the weak source end are similar, and cross differential relay can not operate to clear the fault. To solve the above-mentioned problem, a superimposed currents based method is used to improve the performance of the cross differential protection [5].

When a fault occurs, a superimposed current will be produced, which can be defined as the difference between the short circuit current and the pre-fault load current.

The top diagram in the Figure 14 shows the currents of the double lines. The solid curve is the phase current of the faulted line and the dash curve is the phase current of the healthy line. The middle and bottom diagrams in the figure show the differential currents of the double lines.

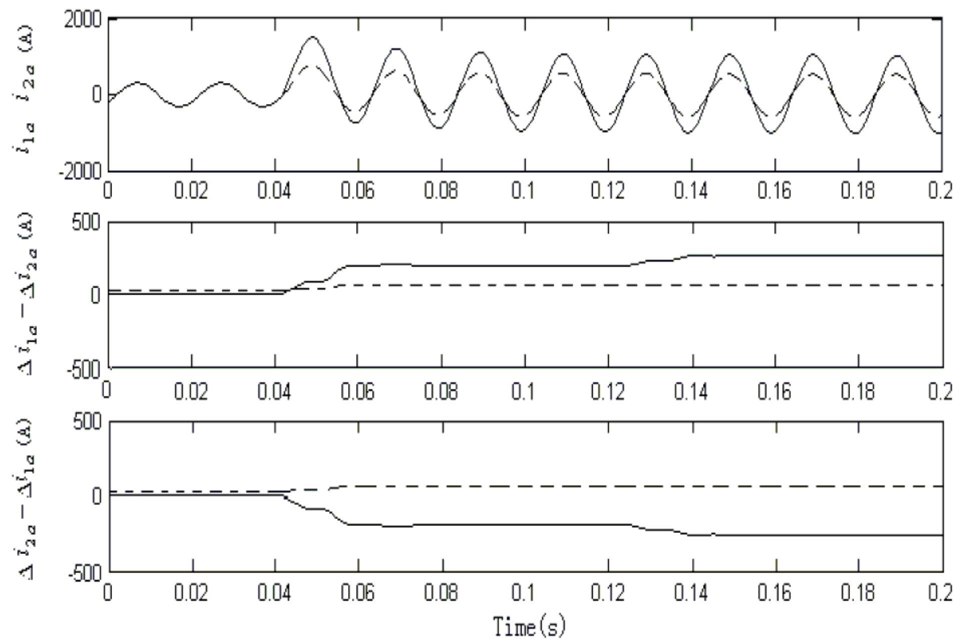


**Fig. 15 Operation of superimposed cross-differential protection for a fault in the middle of the line**

The middle and bottom diagrams in Figure 15 show the superimposed differential currents of the two lines. The solid curve is differential current and the dash curve is the bias current. The relay will operate when the amplitude of the differential current is higher then that of the bias current.

## IV. TESTING THE PROTECTION OF DOUBLE CIRCUIT LINES

From the discussions in the previous sections of the paper it is clear that the protection of double circuit or other parallel line configurations need to be able to operate under different system conditions, evolving and cross-country faults, sequential tripping conditions and under the influence of mutual coupling. All of the above needs to be considered in the testing of such protection relays or communications based schemes.

The testing requires the use of advanced test tools and software that can simulate the different system conditions and status of primary substation equipment, the mutual coupling between the parallel lines and the signals from other multifunctional IEDs protecting the parallel lines.

As can be seen from Figure 17, the test system should be able to replay COMTRADE files from disturbance recorders or produced from electromagnetic transient analysis programs. In the case of a disturbance record there are two possible cases. If the waveform record is available from a relay protecting one of the parallel circuits, it will include typically one set of three phase currents and one set of three phase voltages seen and recorded by the relay. The problem with such records is that it does not provide any information on the currents in the parallel line that can be used to analyze their impact and the effect of the mutual coupling on the behavior of the relay that provided the record. It will be better to use for the analysis a waveform record from a device that records the bus voltage at the relay location and the three phase currents on both parallel lines.

If the COMTRADE file is provided by a transient simulation program, it is important to properly model not only the impedances of the two circuits, but also the mutual coupling between them. Generic programs such as EMTP or ATP can be used to produce such files. They require good knowledge of the software and proper configuration of the model and simulation.

Specialized testing tools make this easier by providing a template for the transient simulation of different fault conditions on mutually coupled double circuit line (Figure 17).

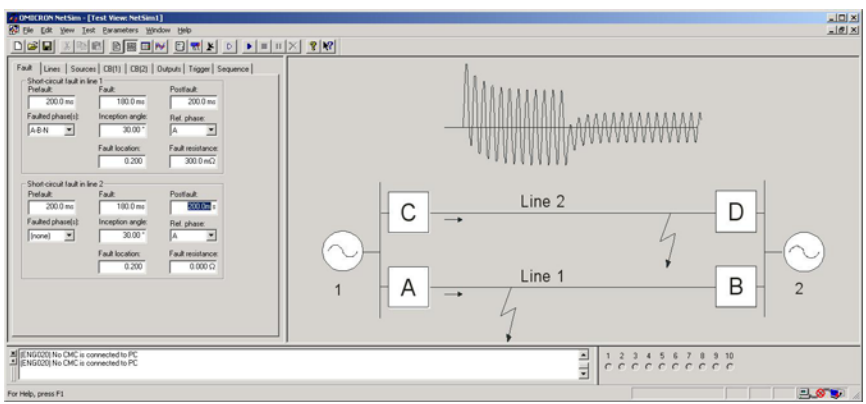


**Fig. 17 Double circuit line transient simulation configuration**

The user just needs to enter the source and line impedances and the mutual coupling impedance. The duration of the different steps in the transient simulation, type and time of one or two faults and the switching of breakers needs to be entered as well. The last step in the simulation configuration is the selection of the outputs that will depend on the relays being tested. If a distance relay with no mutual compensation is being tested the output of the bus voltages and the three phase line current is going to be sufficient. If a cross-differential protection or a relay with mutual compensation is being tested, then the output file should include the three phase bus voltage and the three phase currents of both parallel transmission lines (Figure 18).

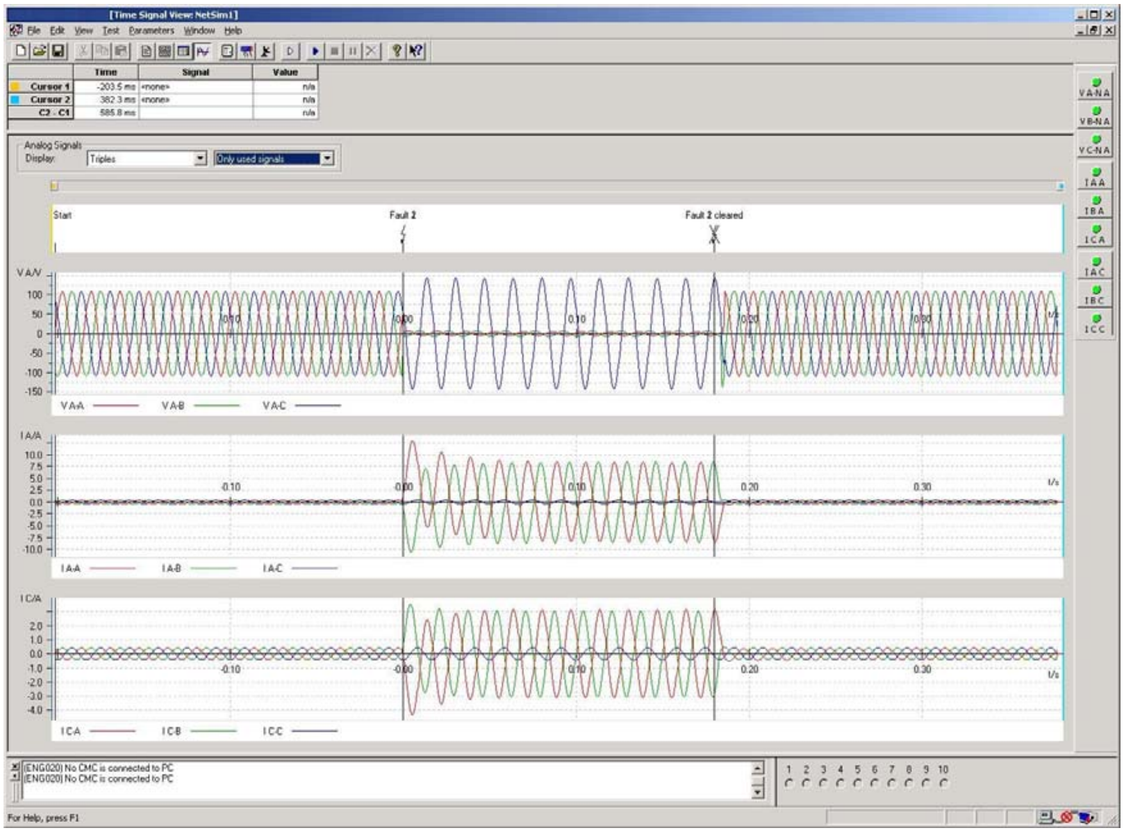


**Fig. 18 Double circuit line transient simulation output**

Another way of performing the testing is based on a sequence of steps programmed in the testing software based on the calculated voltage and current phasors for the simulated fault conditions. In this case any steady state fault analysis program can be used, as long as it takes into consideration the mutual coupling between the parallel circuits for the phasors calculation. This approach still has some disadvantages compared to the transient simulation due to the fact that the model used for the calculation is based on the sequence components and thus does not take into account the unbalance caused by untransposed transmission lines.

From the above discussions it is clear that the test system should be able to apply to the tested relay or relays the three voltages and six currents described. It should also be able to replay COMTRADE files or apply user defined current and voltage signals with settable phase angles, as well as execute a sequence of pre-defined pre-fault, fault and post-fault steps.

The testing of the different protection elements – distance, directional, overcurrent, etc. and end with the most complex cases of cross-country faults and current reversal for communications based schemes such as Permissive Overreaching or Directional Comparison used for the protection of the parallel circuits.  Protective relays with such schemes operate based on the state of multiple monitored signals such as permissive signals, breaker status signals, and relay status signals. Time coordination of these signals and synchronization with the pre-fault and fault analog signals is required in order to perform adequate testing of these types of schemes on double circuit lines.

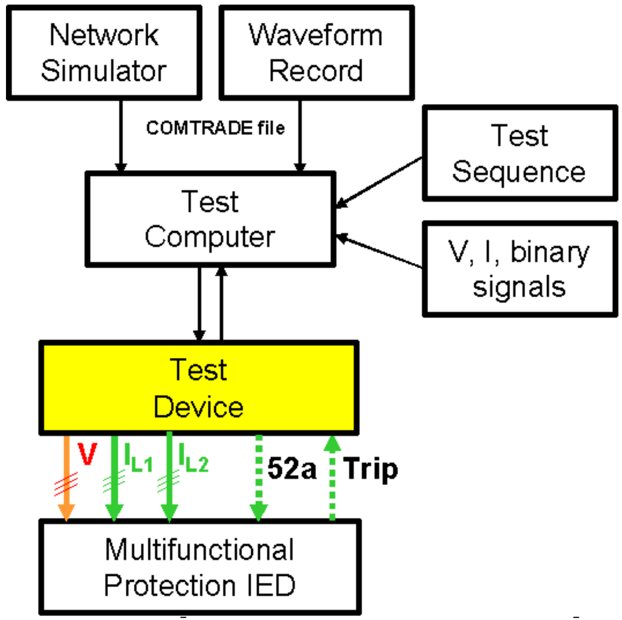


**Fig. 19 Test system block diagram**

## V. CONCLUSIONS

The application of protection systems to double circuit lines requires careful consideration of fault scenarios under various network topology conditions. Complex analysis is required for phenomena such as mutual coupling, untransposed lines and cross-country faults as it may have adverse effects on relay performance.

Line differential protection is obviously the first choice, since it provides instantaneous operation for faults anywhere on the protected line. However, it requires high-speed communications that are not always available. Unit protection schemes also do not provide remote backup which is typically required. That is why the effects of double circuit lines on non-communications based protection relays or systems are analyzed in the paper.

Distance protection performance is especially affected by the state of the parallel circuit and the mutual coupling. The application of adaptive protection principles is useful to improve the relay performance.

Back-up ground overcurrent relays are also affected under the zero sequence coupling conditions and the pick-up settings have to be calculated considering different operating conditions. Adaptive settings also provide advantages compared to fixed settings.

Various methodologies have been implemented in modern relays to assist the user in dealing with the uncertainties in double circuit applications. Advanced functions include mutual compensation, multiple setting group selection, high-performance communications based protection schemes and improved back-up protection functionality.

Cross-differential protection is non-communications based alternative that provides better sensitivity and faster fault clearing times for more faults compared to other non-communications protection functions.

Testing of protection relays or schemes for double circuit or other parallel line configurations requires proper transient or steady-state simulation of the fault conditions that takes into consideration the mutual coupling effects. The test system needs to be able to apply to the tested relays the three phase bus voltage and the three phase currents of both parallel transmission lines.

## VI. REFERENCES


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