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# Multipole Tripping and Reclosing on Double Circuit HV Lines

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## Abstract

Protection of double circuit mutually coupled lines was always a challenge for protection engineers. Simultaneous faults on both circuits are most complicated cases for protection system. Statistics of faults involving both circuits vary considerably, but are usually in the range of 10 to 20%. These double-circuit lines are usually critical for power system stability and synchronism, therefore it's not desirable to trip both line when synchronism can still be maintained. Mutual coupling creates significant complications for traditionally used distance protection with regards to errors in reach and phase selection for single-pole tripping. Situation worsens when simultaneous faults occur on both circuits. Depending on the faults location, system and line impedances, distance function may misoperate or maloperate.

This paper considers usage of line current differential as a primary protection to maintain system stability, when at least 2 different phases out of 6 poles on double circuit lines remain healthy. Simulations and testing performed with RTDS (Real Time Digital Simulator) support approach and conclusions.

*Index terms*: double-circuit line, cross-country faults, distance protection, line current differential protection, reclosure, protective relaying.

## 1. Arrangement of double-circuit lines

There are known 2 basic arrangements for double circuit lines: Arrangement I and Arrangement II. In its turn, both arrangements have 2 modifications, called "Superbundle" and "Low Reactance".

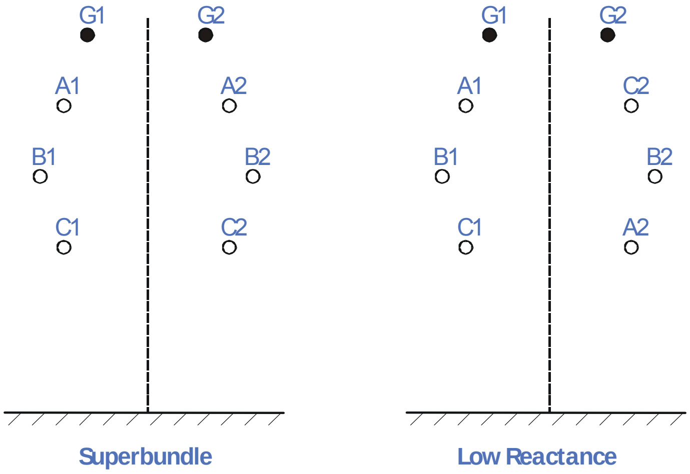


**Figure 1. Double circuit line Arrangement I (vertical)**

Picture above demonstrates Arrangement I geometry of phase conductors, which is physically "vertical" arrangement. This arrangement in North America is used for 345kV to 800kV lines. Number of conductors per phase varies from 1 to 8; ground wires are significantly larger than for single-circuit lines.

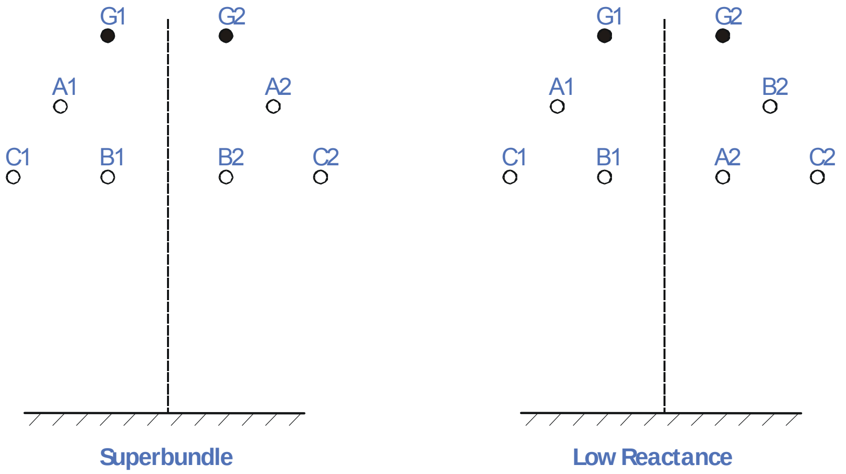


Figure 2. Double circuit line Arrangement II (horizontal)

Arrangement II is used on 362 kV lines only in North America. Impedance and capacitance of line conductors are important for line protections-they vary depending on many factors, including geometry, type/material of conductor, number of conductors in a bundle and spacing, soil resistivity, frequency, and transposition.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} & Z_{Aa} & Z_{Ab} & Z_{Ac} \\ Z_{BA} & Z_{BB} & Z_{BC} & Z_{Ba} & Z_{Bb} & Z_{Bc} \\ Z_{CA} & Z_{CB} & Z_{CC} & Z_{Ca} & Z_{Cb} & Z_{Cc} \\ Z_{aA} & Z_{aB} & Z_{aC} & Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{bA} & Z_{bB} & Z_{bC} & Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{cA} & Z_{cB} & Z_{cC} & Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \bullet \begin{bmatrix} I_A \\ I_B \\ I_C \\ I_a \\ I_b \\ I_c \end{bmatrix}$$

where denomination in capital latter implies 1-st line quantities, while denomination in smaller case implies quantities for the second line. $Z_{XX}$ is self-impedance and $Z_{XY}$ is mutual impedance between corresponding phases.

There are two types of unbalance conditions exist for parallel line double-circuit lines. First there is a through type of unbalance, which is essentially the same as for single-circuit case. This type of unbalance becomes high during fault conditions, but for the balanced load conditions the zero- and negative-sequence unbalance factors are small.

Second type of unbalance is circulating unbalance, which is not affected by loading. In this case current in line #1 induces in both circuits a zero-sequence and negative-sequence potential, which is not equal to potential induced in both circuits by current in line #2. The unbalance potentials cause a circulating current to flow through one circuit.

## 2. Simultaneous faults on double-circuit lines

Although there are 3 different types of the parallel lines connections to the sources, herewith the only type of connection is being discussed: parallel lines with common positive and zero-sequence source at both ends of the lines shown below on the Figures 3 and 4 below. Simultaneous faults on a double circuit line can be divided into 2 categories:

1. Cross country faults where faults are at the different locations of the double circuit lines. Can be caused by lightning strikes in physically different areas or as result of insulation breakthrough due to overvoltage happening shortly after first fault on the parallel line.

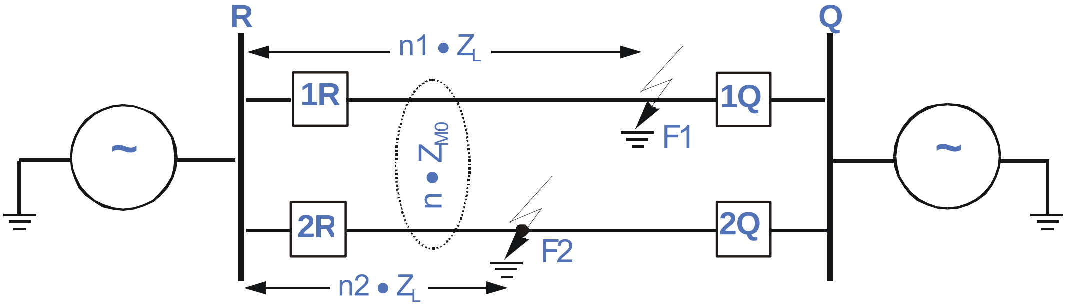


Figure 3. Cross country fault to ground on a double circuit line

2. Flashover faults where faults are at the same location and usually are a result of a lighting stroke to a ground wire or tower, or due to a direct lighting strike to a phase conductor.

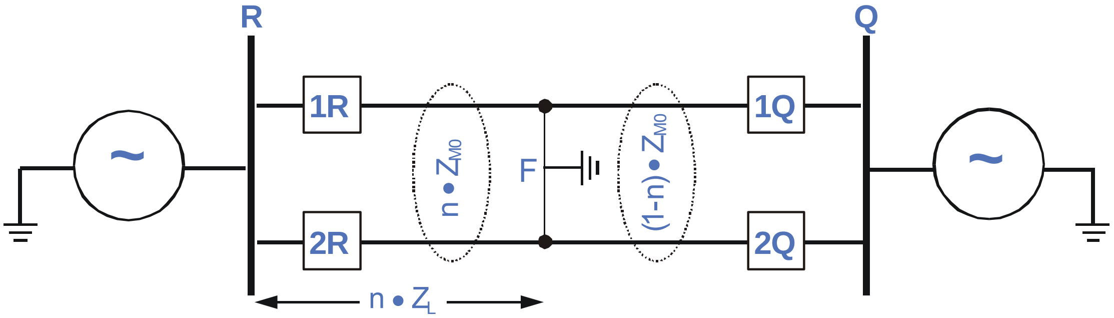


Figure 4. Flashover fault to ground on a double circuit line

As it's well known, mutual coupling doesn't affect phase distance measurements, however for ground distance it contributes to significant measurement errors. Applying parallel line compensation improves measurement for ground distance when single fault exists on one of the circuit. During flashover fault zero-sequence current flows through both circuits-situation complicates.

The sequence networks are connected in such way as to satisfy the system constraints at both fault locations. A direct connection of sequence components is possible at one location, but for magnetic coupling and phase shifting of sequence currents may be required at other location. If 2 or more unbalances occur simultaneously, mutual coupling or connections will happen between the sequence components at each point of unbalance. If unbalances are not symmetrical with respect to the same phase, the connections have to be made through phase-shifting transformers. Various cases of single unbalance can be combined to form proper restraints or terminal connections to represent multiple unbalances. Simultaneous faults that are not symmetrical to the reference phase can be represented by similar connections using ideal transformers or phase shifters to shift the sequence voltages and currents originating in all other unbalances except the first or reference unbalance. The fault, involving phase A is usually taken as the reference and all others are shifted by the proper amount before making the terminal connections to satisfy that particular type of the fault. The positive -, negative-, and zero-sequence shifts, respectively for the unbalance that is symmetrical to phase "A" are 1, 1, and 1; for "B" phase $a^2$, a, and 1; for "C" phase are a, $a^2$, and 1.

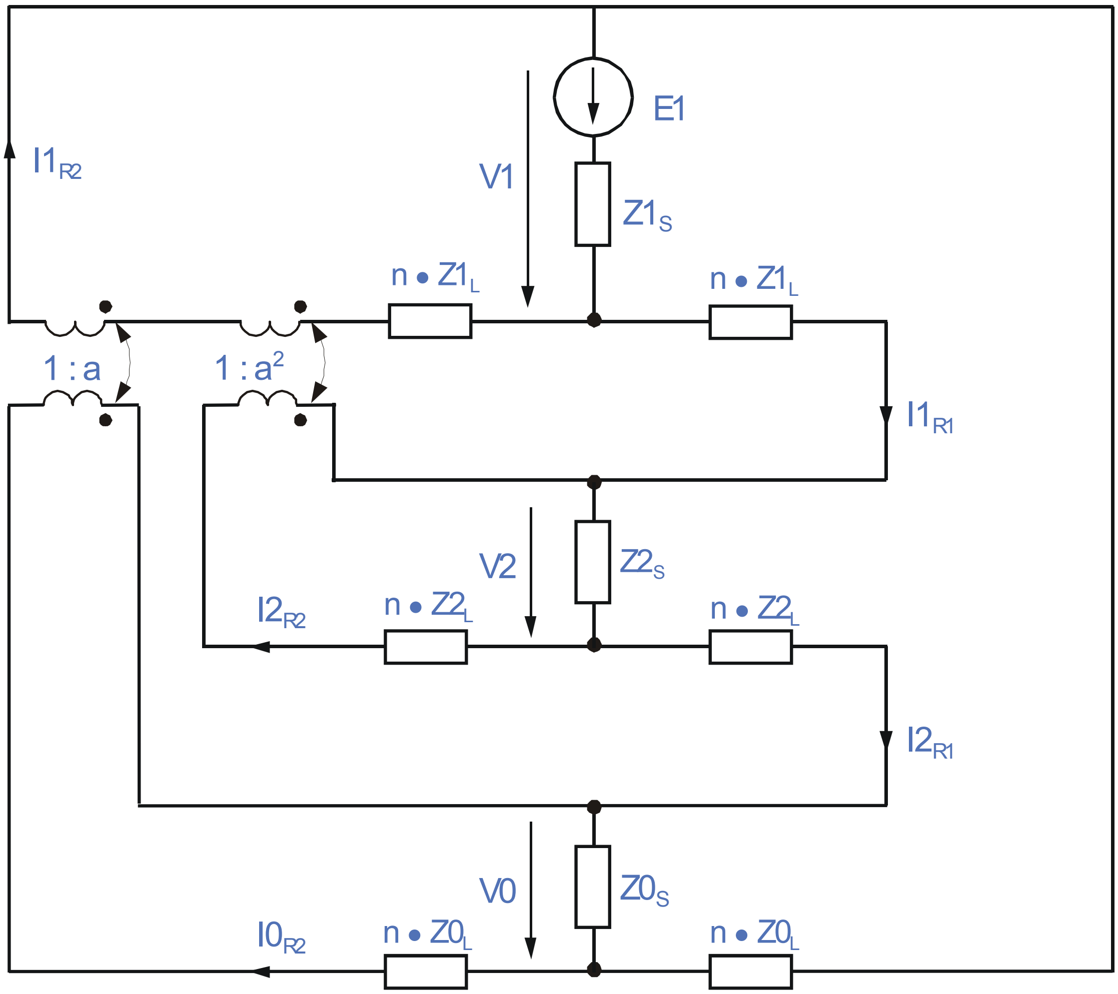


**Figure 5: Symmetrical components network for AG fault on line #1 with BG fault on line #2.**

Figure 5 above shows equivalent circuit for sequence components connections for simple case where double circuit line has system source at one end only and flashover fault AG on line #1 occurs simultaneously with BG fault on line #2.

## 3. Protection consideration

### 3.1. Distance

In many previous publications it was demonstrated that there are certain challenges when applying distance on double circuit lines. Problems described were overreaching, underreaching and loss of phase selectivity. Simulations were run using RTDS digital simulator for the sample double circuit 200km overhead line with following parameters: $Z1L = 3.74 + j \bullet 56.4\Omega$ positive sequence self-impedance, $Z0L = 32.2 + j \bullet 166\Omega$ zero sequence self-impedance, $Z0M = 18.96 + j \bullet 97.64\Omega$ zero-sequence mutual coupling impedance, $Z1C = j \bullet 1179.4\Omega$ positive sequence capacitive reactance and $Z0C = j \bullet 1730.1\Omega$ zero sequence capacitive reactance all values are in primary ohms). In secondary values that yields $zL_1 = 14.13\Omega\angle 86.2^\circ$, $zL_0 = 42.27\Omega\angle 79.0^\circ$ and $zM_0 = 294.8\Omega\angle 90.0^\circ$

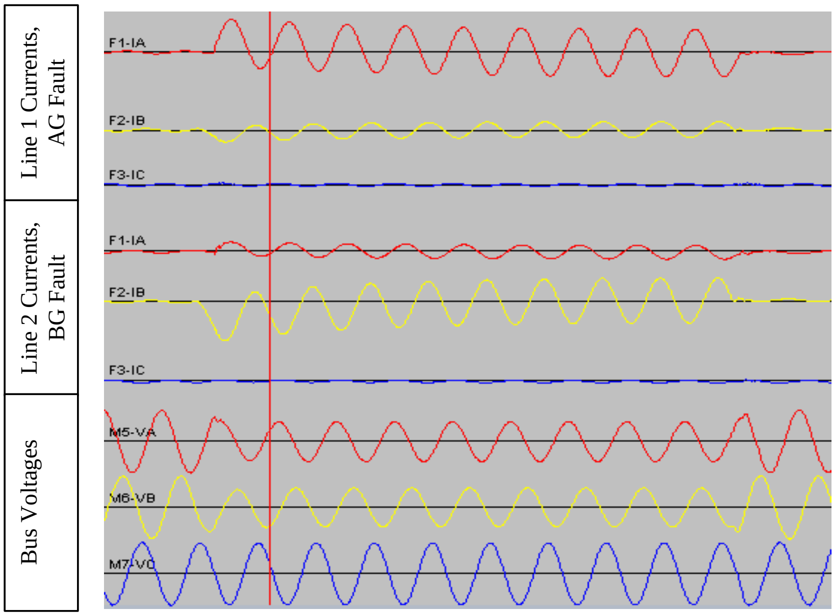


Figure 6. Flashover fault at 60% of the line: currents and voltages

Let us analyze the measurement of ground distance AG loop on line #1 and ground distance BG loop on line #2 with zero fault resistance during flashover fault (all values in secondary quantities).

| **Line #1** | **Line #2** |
|---|---|
| $I_A$ = 4.05A ∠-67.1° | $I_a$= 1.22A ∠-69.0° |
| $I_B$ = 1.33A ∠142.9° | $I_b$ = 3.93A ∠149.6° |
| $I_C$ = 0.26A ∠0.5° | $I_c$ = 0.18A ∠-24.8° |
| $I_0$ = 1.00A ∠-75.2° | $I_0'$ = 0.96A ∠164.5° |
| $I_2$ = 1.3A ∠-48.2° (a) | $I_2'$ = 1.3A∠ 134.3° (b) |
| $V_A$ = 43.7V ∠0.0° | $V_A$ = 43.7V ∠0.0° |
| $V_B$ = 42.1V ∠-105.6° | $V_B$ = 42.1V ∠-105.6° |
| $V_C$ = 66.9V ∠125.2° | $V_C$ = 66.9V ∠125.2° |

Important observations here are as follows:

- Zero-sequence currents flowing through both lines are 120° shifted (lead or lag depending on the phases involved) accordingly sequence components connection diagram. This has a great impact on ground distance mutual impedance compensation functionality, if latest is applied, leading to mis- or maloperation.
- Angle between zero-sequence and negative-sequence currents, which is used to validate fault type, is not close to zero what is normal for single circuit line. This angle is becoming larger as fault is approaching opposite end of the line. Angle between zero-sequence and negative-sequence currents is often used in distance relays for phase selection elements for single-pole tripping and as additional comparator for ground distance elements. Flashover ground faults somewhat beyond 50% of the line might result in phase selection problems.

Assuming that no mutual compensation is applied, relay in line #1 measures apparent impedance as:

$$z_{AG} = \frac{V_A}{I_A + I_0 \bullet \left(\frac{zL_0}{zL_1} - 1\right)} = \frac{43.7V\angle 0.0^\circ}{4.01A\angle -66.8^\circ + 1.0\angle -75.0^\circ \bullet \left(\frac{42.27\Omega\angle 79.0^\circ}{14.13\Omega\angle 86.2^\circ} - 1\right)} = 2.15 + j \bullet 7.03\Omega$$

Conventional distance relay sees this fault at 48 to 52% of line's length depending on source zero-sequence and positive-sequence impedances.

If mutual zero compensation is applied, same line #1 relay measures apparent impedance as;

$$z_{AG} = \frac{V_A}{I_A + I_0 \bullet \left(\frac{zL_0}{zL_1} - 1\right) + I_0' \bullet \left(\frac{zM_0}{zL_1}\right)} = 1.1 - j \bullet 2.68\Omega$$

This is a measurement is completely off the operating zone and would prevent tripping. Therefore, although mutual compensation is very useful for single fault on the dual circuit lines, but it might prevent tripping for internal fault during simultaneous ground faults on parallel lines. This calls for adaptive approach achievable with setting group control: allowing mutual compensation for single fault but disabling during simultaneous faults. However, it is not very easy and customer has to sacrifice with a fault clearance time as distance needs some time for recognition of the condition on the parallel line. Beyond inaccuracy in reach, ground distance relays also have problems with phase selection. Figure 7 depicts flashover fault AG on the line #1 and BG on the line #2 with traditional MHO characteristics drawn for 100% of line impedance. When no mutual impedance compensation is applied, ground distance on both lines performs more or less adequately with some inaccuracies observed up to 10%. There is equivalence between ground distance relays performance on both lines; it was observed that leading phase (phase A) has tendency to overreach while lagging phase to underreach for high source impedance ratios. However, when mutual compensation was applied, relays were completely confused, as shown in the diagram.

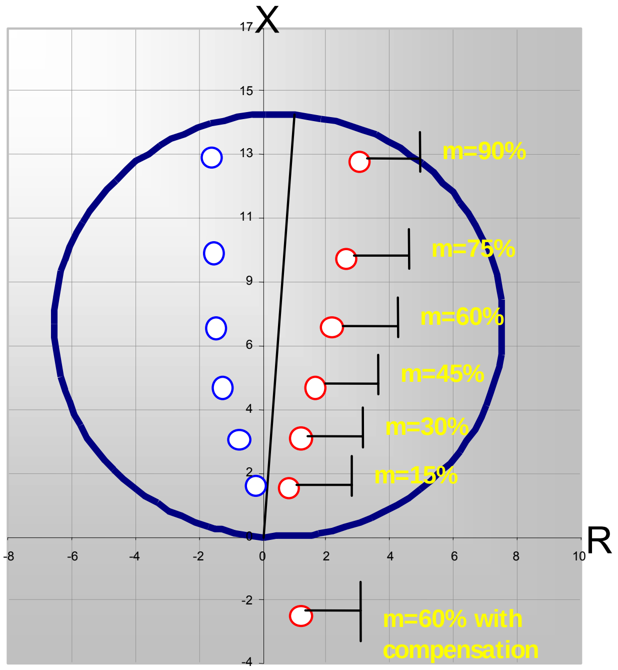


Figure 7. Flashover AG Line #1 (red) and BG Line #2 (blue) faults

Cross-country faults (different fault locations) along both lines showed erratic behavior of ground distance on both lines during testing. Figure 8 gives an indication of difficulty in measuring the correct impedance when BG fault (in blue) was applied at zone 1 reach of 85% on the line #2, while AG fault location varies from 0% to 90% on the line #1 (in red)). It can be seen that conventional MHO characteristics on the line #1 significantly overreaches for fault location below 50% and then slightly overreaches. Impedance measurement is not consistent with a fault location. Line #2 stops seeing fault when faults on the line #1 are beyond 40% of the line's impedance. Mutual compensation again doesn't help for correct measurement.

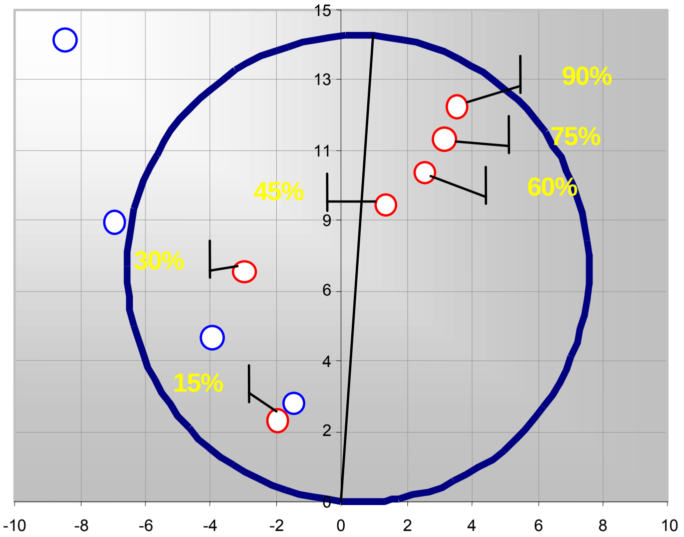


Figure 8. Cross-country AG Line #1 (red) and BG Line #2 (blue) faults

**Cross-country ground faults are the most confusing situation for ground distance comparators.**

Single-pole tripping performance of the distance function on double-circuit lines can be secured in few different ways; a) exchange of the tripping decision between both terminals using pilot channel (preferably 4-bit channel giving essential info on the fault type), b) supervision by phase selector, c) undervoltage supervision, d) monitoring simultaneous fault on the parallel line to turn of mutual impedance compensation. However, all of these methods might lead to delayed trip and still cannot guarantee correct action. Also, as was shown above, significant errors in distance reach are imminent.

### 3.2. Current Differential

In spite of distance, phase segregated line current differential function (87L) is not using sequence components for differential function. Usage of sequence components does not allow 87L function to identify fault type and phases involved.

As per principles of differential protection, 2 quantities are formed in all 3 phases:

$$I_{DIFF\_A} = |IR_A + IQ_A| \quad \text{Eq. 1}$$

$$I_{RESTR\_A} = PKP + K \bullet [IR_A + IQ_A] \quad \text{Eq. 2}$$

Where: $IR_A$ and $IQ_A$ are local and remote currents in phase A
PKP is a pickup setting of differential
K is differential restraint slope setting

The element operates if $I_{DIFF\_A} > I_{RESTR\_A}$

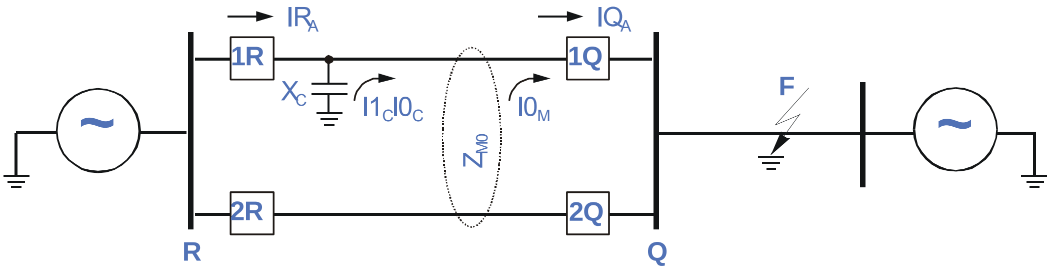


**Figure 9: Leaking differential current during external SLG fault**

However, as it's demonstrated on the figure above, during external AG fault on the adjacent line, there is some leaking differential current on the line 1R-1Q. Phase current measured at terminal 1R will be different from current measured at terminal 1Q by difference in positive sequence and zero-sequence currents at opposite line terminals. This current, which can destabilize the current differential, is sum of 2 components: a) line charging current, b) zero-sequence mutual coupling current. For line differential relays having charging current compensation, 1st component can be neglected, for line differential relays which don't have this functionality, normal practice is to set pickup setting 2.5 times line net charging current. Zero-sequence current induced from parallel line dictates 2nd component, $I0_M$. Therefore minimum pickup for differential protection, which doesn't have charging current compensation, can be calculated as:

$$PKP = 2.5 \bullet \left| \frac{V_{LL}}{\sqrt{3} \bullet Z1_C} \right| + \left| I_0 \bullet \frac{Z0_M}{Z0_L} \right|$$

Where: $V_{LL}$ is system nominal voltage
$Z1_C$ is line positive sequence capacitive reactance
$I_0$ is maximum zero sequence current flowing through parallel line during external fault
$Z0_M$ is lines mutual coupling zero sequence impedance
$Z0_L$ is line zero sequence self impedance

Again, for line differential relays having charging current compensation, 1st term can be neglected. Sensitive differential elements operating on zero-sequence current can be applied with caution taking into account stated above.

## 4. Implementation of multipole tripping/reclosing principles

Normal practice for transmission line protection is to open and then reclose one pole of all breakers on the protected line for SLG fault (Trip 1-pole) and open all 3 poles (Trip 3-pole) for all other types of the fault. This approach is adopted in most relays, sometimes usually hard-coded, used around the world and suites very well into single circuit protection application. Even for LL or LLG faults stability cannot be maintained over remaining one phase assuming that it's possible to trip 2 faulted phases only.

On the double circuit transmission lines, situation is different: even if 2 phases are faulted and tripped on one line, there is high probability that on the parallel line all 3 phases remain in service or if simultaneous fault occurs on both circuits, at least one different phase remains healthy on the parallel line. Actually, one can think that there are 6 poles on the protected line, while still having two sets of 3-phase protective relays. If, at least, 2 different phases remain healthy during disturbance, this would allow maintaining system synchronism and stability. Maintaining maximum power transfer during different types of faults and not allowing unjustified separation of the different parts of the system is vital for system stability. Removing out of service 2 lines interconnecting major generating and consuming centers means major disturbance for the whole system with far going consequences.

It is therefore desirable to develop a protection system which can monitor not only the protected lines, but parallel line as well; as it will be shown later remote breakers status have to be monitored as well to make correct trip/reclose decision. Modern microprocessor based relays allow achieving this goal.

Due to system stability concerns, there are special requirements for 1-pole/3-pole tripping and reclosing relays. Both line #1 and line #2 have at least two protection systems, which must be phase-segregated type relay. Major concern for such applications is ability relays to operate correctly during cross-country fault, which is not uncommon, when both lines conductors are on the same tower. Once any protection system on any line detects the fault, it should share with parallel line protection systems of what fault type is detected and which phases are being tripped. If fault exists on the parallel line as well, depending on which phases are affected on both lines, decision is made what to trip and how to recluse. Thus, coordination for correct tripping is needed not only between at least two protection systems of the protected line, but also between parallel lines protection systems. If at least two different phases out of six phases of the double circuit line remain healthy, these 2 phases shall be not tripped to maintain system synchronism till reclosing.

Another important consideration is reclosing: depending on the fault type, tripped poles and reclosure mode, different reclosure response is required. Relays have to be able to support different reclosure modes: pure 3-pole, 1-pole and 3-pole and at least two multipole modes for double circuit lines. For example, as illustrated in the table below, for case #13, fault AB occurs on line #1 with simultaneous fault AC on the line #2, those affected poles only should be tripped, provided that mode is M2. Accordingly, reclosing should be performed for mode M2. Breakers, which are selected mode M3, should trip 3-pole and then 3P delayed reclosing should be performed.

There are 4 distinctive mode modes of tripping and reclosing operation, which can be chosen with a panel control switches or with relay pushbuttons. Depending on the mode of operation and on the phases tripped on both lines, reclosure has 3 different time dead time delays to close breakers:

1. “1P” initiation, which is high-speed reclosure on order of 0.5 to 0.8 seconds.
2. “M” initiation, which is medium-speed reclosure, performed when multi-pole conditions are satisfied on order of 1 second.
3. “3P” initiation, which is slowest 3-pole reclosure, performed after 3-pole tripping on order of 1.2 to 1.5 seconds.

Additionally, each set of reslosure system performs the following:

- monitors high-speed grounding switch to extinguish arc to allow reclosure,
- monitors status of remote breaker poles on the protected line,
- monitors status of the parallel line breaker poles and controls 2 breakers,
- monitors Leader and Follower selection with selectable sequence of operation,
- monitors breaker fail operation

### Table 1. Tripping and Reclosing Modes of Operation

| Case | Faulted phases | Lines in service | Phases affected | Mode | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 & 3-pole | | 3-pole | | M-pole 2R | | M-pole 3R | |
| | | | | Trip | Reclose | Trip | Reclose | Trip | Reclose | Trip | Reclose |
| 1 | 1 | 1 | L1 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 3P | MP |
| 2 | 2 | 1 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| 3 | 3 | 1 | L1 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| 4 | 1 | 2 | L1 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 3P | MP |
| | | | L2 A B C | - | - | - | - | - | - | - | - |
| 5 | | 2 | L1 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 3P | 3P |
| | | | L2 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 3P | 3P |
| 6 | 2 | 2 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 2P | MP | 2P | MP |
| | | | L2 A B C | - | - | - | - | - | - | - | - |
| 7 | | 2 | L1 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 1P | MP |
| | | | L2 A Ⓑ C | 1P | 1P | 3P | 3P | 1P | MP | 1P | MP |
| 8 | | 2 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 2P | MP | 3P | MP |
| | | | L2 Ⓐ B C | 1P | 1P | 3P | 3P | 1P | MP | 3P | MP |
| 9 | | 2 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| | | | L2 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| 10 | 3 | 2 | L1 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | MP | 3P | MP |
| | | | L2 A B C | - | - | - | - | - | - | - | - |
| 11 | | 2 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 2P | MP | 3P | MP |
| | | | L2 A B Ⓒ | 1P | 1P | 3P | 3P | 1P | MP | 3P | MP |
| 12 | | 2 | L1 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | MP | 3P | 3P |
| | | | L2 A B Ⓒ | 1P | 1P | 3P | 3P | 1P | MP | 3P | 3P |
| 13 | | 2 | L1 Ⓐ Ⓑ C | 3P | 3P | 3P | 3P | 2P | MP | 3P | 3P |
| | | | L2 A Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 2P | MP | 3P | 3P |
| 14 | | 2 | L1 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| | | | L2 A Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| 15 | | 2 | L1 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |
| | | | L2 Ⓐ Ⓑ Ⓒ | 3P | 3P | 3P | 3P | 3P | 3P | 3P | 3P |

It is not necessary to determine which poles are open during the fault. Phase segregated line differential relays or distance relays as a backup operate independently and initiate tripping on its own. It's important, however, to know that trip was initiated by protection and then system has to determine which poles are open. If, per chosen multipole mode, 3-pole tripping is necessary, it will initiate 3-pole tripping later.

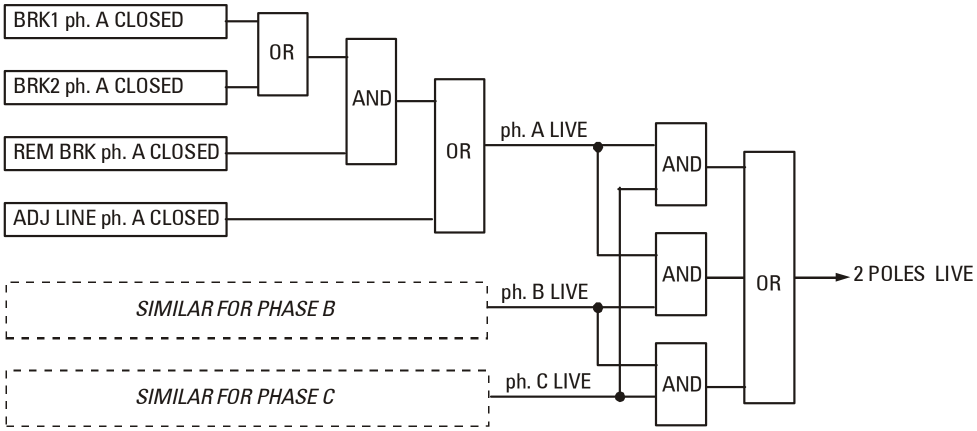
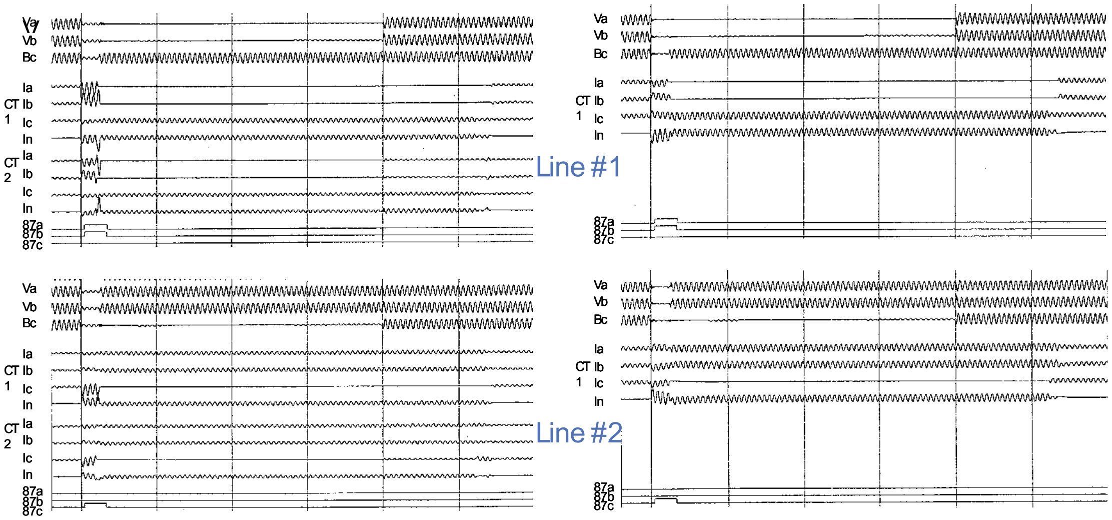


Figure 10. Determination that 2 poles remain live during fault

Reclosure will be performed accordingly mode chosen and determination of what was really tripped during the fault. Multipole tripping/reclosing function resides in the reclosure relay and is independent from phase segregated protective relays.

## 5. Testing

Testing of whole protection system, consisting from line differential relay, distance relay and reclosure relay can be done using RTDS in close loop testing. Four sets of protection system are connected to amplifiers, RTDS breakers simulators etc. Relays are connected to each other via contact inputs/outputs and inputs/outputs over communications.



Simulation of Simultaneous AB Fault on Line #1 with CG Fault on Line #2

The figure above depicts simultaneous faults on double circuit line with 87L operation at all 4 sets of protection and then followed by reclosure without interrupting the power transit. Testing involves different fault types for different operating modes stated above to prove correct operation.

## 6. Conclusions

Using modern protective relays, better performance can be achieved on double-circuit lines. Particularly, during inter-circuit faults, it is possible to prevent tripping of both lines when synchronism still can be maintained. Paper discussed problems and practical solutions of such approach. Protection system described above was fully tested with RTDS simulator and then put in service on 765kV double-circuit line in Korea in cooperation with YPP Company, Seoul, Korea.

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## Biograhpies

**Ilia Voloh** (IEEE member since 99) received his Electrical Engineer degree from Ivanovo State Power University, Soviet Union. He then was for many years with Moldova Power Company in various progressive roles in Protection and Control field. Currently he is an Application Engineer with GE Multilin. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying.

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