

**AUTOMATIC CALCULATION OF RELAY SETTINGS FOR A BLOCKING PILOT SCHEME**

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**SUMMARY**

*An automated procedure provides relay tap settings for phase and ground elements in a directional-comparison blocking scheme. Applied to an actual 161kV line, the algorithms identify the constraints due to infeed on tapped lines and mutual coupling with a parallel 500kV line.*

**INTRODUCTION**

Automated relay setting can improve productivity significantly by applying utility protection rules consistently, simplifying routine data handling and allowing more thorough fault studies than are feasible by hand. Here we are setting the relays at the ends of a transmission line in a directional-comparison blocking pilot scheme.

Relay setting is done within a protection simulation environment, with a system database, a detailed relay library, and a steady-state phasor fault analysis [1]. The database contains the buses, generators, lines, shunts, transformers, the CTs and VTs connecting relays to the network, and detailed relay models. The setting algorithms are encoded precisely in a high-level macro language. A utility can modify the rules or just change specific parameters, according to its own setting criteria.

This algorithm includes an automatic coordination check that applies close-in faults, sliding faults and line-end faults on the protected line, all adjacent lines and on separate coupled

lines, with the generation level given in the database. A table shows the operation or non-operation of the tripping and blocking elements and highlights potential misoperations, allowing an engineer to focus on the most critical cases.

**161kV LINE IN TVA NETWORK**

We use a 161kV line in the Tennessee Valley Authority (TVA) system for demonstration (Figure 1). The blocking scheme is applied between the two source terminals at Montgomery and Springfield, to protect the line and the tapped load branches. The scheme is used with power-line carrier signals and provides dependability, ensuring that a fault will be cleared even if the pilot channel fails [2]. The tradeoff is reduced security, since a loss of blocking signal may cause the line relays to trip for an external fault. Faults on the parallel 500kV line may cause sympathetic tripping through mutual coupling.

We set four elements simultaneously: one TRIP and one BLOCK element at each terminal. The scheme may also include zone-1 elements that can trip directly for close-in faults; those elements are set separately [3].

The TRIP element is a forward overreaching element. It must see faults in the protected line and on the load-tap branches, with a specifiable safety margin. After it operates, and after a coordination time delay, it will trip the local breaker unless a blocking signal has been received from the remote end of the protected line.

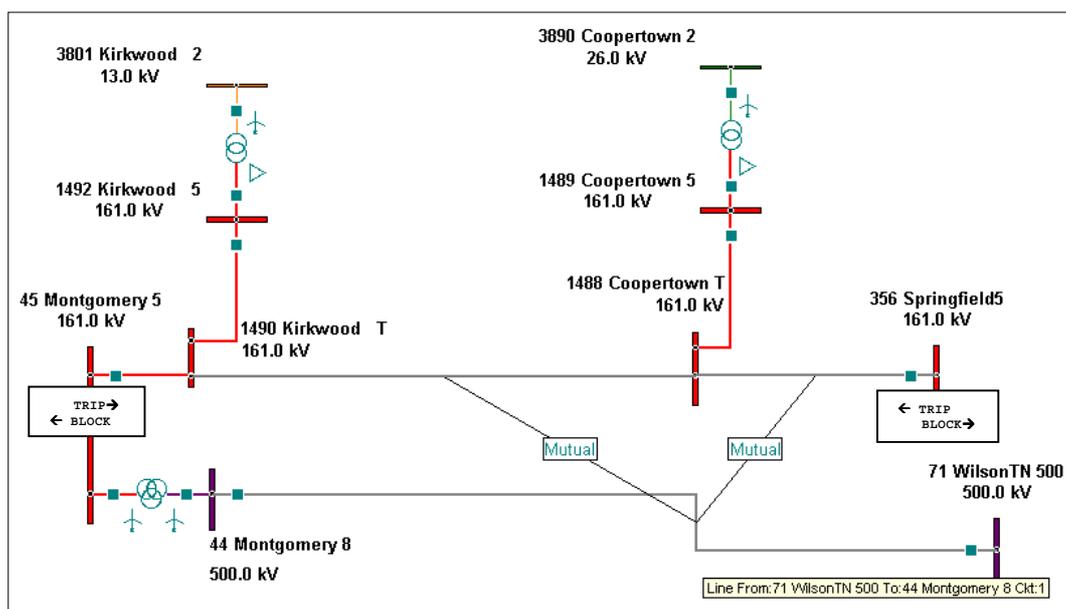


Figure 1 – Protected 161kV line in TVA system

TABLE 1 – Data for Protected Line

	kV	Positive Seq (Ohms)	Zero Seq	Length
Line under study:				
Montgomery - Springfield	161	20 @ 85 deg	66 @ 76 deg	28.6 miles
Coupled line:				
Montgomery - Wilson	500	31 @ 86 deg	117 @ 71 deg	57.5 miles
Load-Tap branches (terminated at delta-wye 161/13 kV transformers):				
Kirkwood	161	0.08 @ 84 deg	0.2 @ 69 deg	0.09 miles
Coopertown	161	2.2 @ 84 deg	7.3 @ 72 deg	3.0 miles
Source-impedance ratio (SIR):		Local SIR		Remote SIR
Montgomery - Springfield	161 kV	0.2 to 0.3		0.4 to 0.6
Montgomery - Wilson	500 kV	0.8 to 1.4		0.6 to 0.8

The BLOCK element is a reverse element, usually connected to the same CT as the local TRIP element. On operation it sends a blocking signal to the remote end of the protected line.

The BLOCK element at bus 45 must see all faults in the overreach region of the TRIP element at bus 356. The BLOCK element at bus 356 must see all faults in the overreach region of the TRIP element at bus 45.

This case uses electromechanical relays: KD distance relays for phase faults and IRC zero-sequence overcurrent relays for ground faults. The line data are in Table 1.

The positive-sequence source-impedance ratios for this line correspond to "long" lines [2] with relatively strong sources. The source impedance for a given fault varies with the fault location in a meshed system and is calculated as

Source impedance for a line at a bus = - (change in bus voltage) / (change in line current) due to the fault.

## PROCEDURE FOR SETTING THE RELAYS

The user chooses the four relays from the system database and selects a distance or ground overcurrent algorithm. Then the algorithm reports the setting calculations. The output module converts the primary pickup or impedance settings to named relay taps for the specific relays installed. The tap settings are now stored in temporary memory for checking, and the user can save them in the database.

## RULES FOR GROUND OVERCURRENT ELEMENTS

For instantaneous ground overcurrent elements, the tripping element should pick up for 40-ohm ground faults all along the protected line. The blocking element at the opposite line end is given 50 percent of this setting.

### Pickup Tap for Tripping Element

The following factors determine the pickup tap setting.

**Fault current for resistive faults with infeed.** The overcurrent elements at buses 45 or 356 are set to detect 40-ohm ground faults all along the protected line. The fault resistance

and other controlling parameters are settable by the user in a single file [3], so it is easy to change a parameter and rerun a particular case. Since we are looking for minimum currents, the fault computations must include possible infeed. However, load currents are ignored for the ground overcurrent settings. The limited sensitivity of the electromechanical relays in this example may produce a pickup higher than desired.

**Tapped Transformers.** The 161kV relays should not trip for faults on the secondary side of load transformers at the line-end buses: the pickup setting should exceed a safety multiple (1.25) of the relay neutral (residual) current. This check is repeated with all infeed branches removed at intermediate buses, for the worst case of high relay current. However, for sensitive pilot protection the tapped transformers may also have relays and carrier equipment so they can send blocking signals for low-side faults. Then the engineer can suppress the check and find more sensitive settings.

**Coupled Lines.** The line is heavily coupled to the first half of the parallel 500kV line from Montgomery (per unit mutual impedance exceeds 50 percent of the 161kV line impedance), so the tripping elements may operate for faults on the 500kV line. The setting algorithm automatically searches for coupled lines and applies bus and line-end ground faults there to find the maximum relay current. The pickup setting must exceed this maximum current by a settable factor.

In this example the relays are insensitive to transformer faults, as the load-tap branches terminate at delta transformer windings and are not sources of neutral current. However, accounting for mutual coupling severely limits the sensitivity. The worst case occurs when the breaker is open at 71. In order to prevent sympathetic tripping, we have to raise the tripping pickup at bus 356 from 560 to 2237 primary A, as the report from the algorithm shows in Table 2 below.

### Pickup Tap for Blocking Element

Next, the block level at bus 356 is set at 50 percent of the trip level at bus 45. This provides a large safety margin: it ensures that the BLOCK element at 356 will pick up for any fault to the right of bus 356 that also operates the TRIP element at 45. If the desired setting is below the minimum available, the minimum will be used. Then the trip element at 45

TABLE 2 – Report from Setting Algorithm

```

Instance name      MAX3IZ
Generic name      MAX_THREEIZPRIM
Location          Branch "356 Springfield5" to "1488 Coopertown T" Ckt 1
Quantity         THREEIZPRIM
Type             MAX
Value            2237.36 @-90.082
Conditions
Midline node on "44 Montgomery 8" to "71 WilsonTN 500" Ckt 1
Distant 0.500 from "44 Montgomery 8"
Open breaker on "71 WilsonTN 500" to "44 Montgomery 8" Ckt 1
at "71 WilsonTN 500"
SINGLE_LINE_GROUND on line side of open breaker at "71 WilsonTN 500"

Local Trip IOC element (Primary A)
Without MUTUALS With MUTUALS
TRIP LEVEL      560.09      2237.36
    
```

TABLE 3 – Trip/Block Coordination Check for Faults on Protected Line

(L) Local Bus: 45 Montgomery 5  
(R) Remote Bus: 356 Springfield5

Faults on relay line 45 1490 1 to 356

Fault	Trip(L)	Block(L)	Trip(R)	Block(R)	Operation
SLG close-in at 45	Y	N	N	N	*Warning*
DLG close-in at 45	Y	N	N	N	*Warning*
SLG on open bkr at 45	N	N	N	N	*Warning*
DLG on open bkr at 45	N	N	N	N	*Warning*
SLG 0.25000 on 45 1490 1 to 356	Y	N	N	N	*Warning*
DLG 0.25000 on 45 1490 1 to 356	Y	N	N	N	*Warning*
SLG 0.50000 on 45 1490 1 to 356	Y	N	Y	N	Ok
DLG 0.50000 on 45 1490 1 to 356	Y	N	N	N	*Warning*
SLG 0.75000 on 45 1490 1 to 356	Y	N	Y	N	Ok
DLG 0.75000 on 45 1490 1 to 356	N	N	Y	N	*Warning*
SLG close-in at 356	Y	N	Y	N	Ok
DLG close-in at 356	N	N	Y	N	*Warning*
SLG on open bkr at 356	Y	N	N	N	Ok
DLG on open bkr at 356	N	N	N	N	*Warning*
Pickup of Trip Element : 2701 IOC	at 45 Montgomery 5		2237.36	Primary A	
Pickup of Block Element: 2702 IOC	at 45 Montgomery 5		1118.68	Primary A	
Pickup of Trip Element : 4688 IOC	at 356 Springfield5		2237.36	Primary A	
Pickup of Block Element: 9044 IOC	at 356 Springfield5		1118.68	Primary A	

will be raised to twice the new blocking pickup. The same rules apply for the tripping element at 356 and the blocking element at 45.

**Coordination Check for Both Pairs of Tripping and Blocking Elements**

Next, the coordination check applies single- and double-line-ground (SLG and DLG) faults and tabulates the operation of all four elements first for faults on the protected line, and then for faults on adjacent and coupled lines. Failure to trip or block when required, or unwanted tripping for external faults, is highlighted (Table 3).

With these warnings for faults on the protected line, the algorithm has found a serious problem: the tripping relay at 356 will see only part of the way along the line to bus 45. The report above shows that its pickup was raised to 2237A to avoid tripping for faults on the 500kV line.

Now the engineer may plot the largest detectable fault resistance against fault location, using the detailed relay models

and including torque control. Figure 2 shows that the line is only partly covered even for solid faults. For Figure 3, the algorithm has been rerun with the settings uncorrected for mutual coupling. The algorithm now chooses the lowest

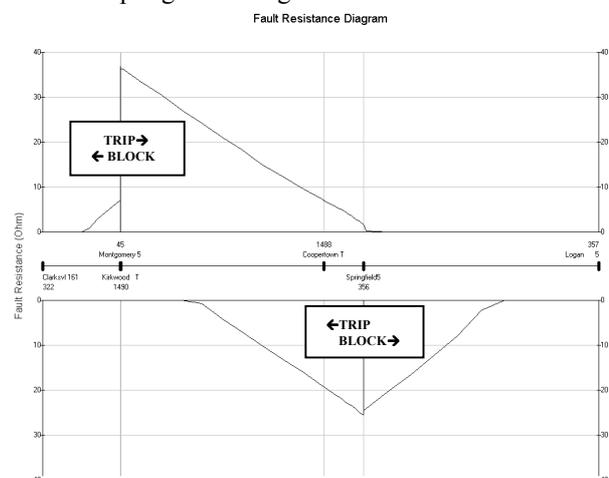


Figure 2 – Threshold fault resistance for single-line-ground faults along protected line. Overcurrent pickup is increased to prevent tripping for faults on coupled line.

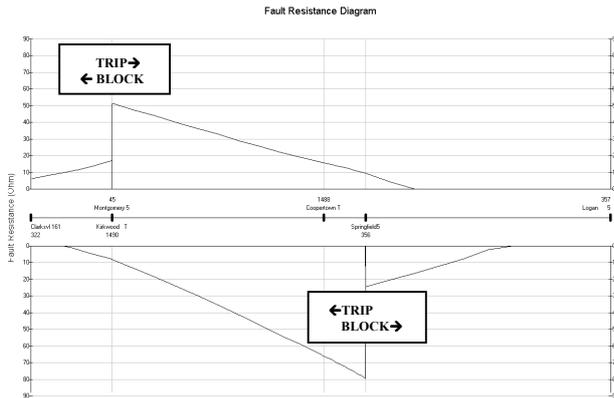


Figure 3 – Threshold fault resistance for single-line-ground faults along protected line; mutual coupling limits ignored; blocking elements set at minimum pickup. These electromechanical relays can detect only 10-ohm remote-bus faults.

available blocking-element taps. In both cases, the blocking elements right of 356 and left of 45 correctly cover the over-reach region (if any) of the tripping elements.

With these settings, however, a ground fault on the 500kV line may trip the 161kV Springfield terminal: the warnings in Table 4 show undesired tripping at the (R) bus and no blocking at the (L) bus when one end of the 500kV line is open. Detailed bus reports for this case show zero-sequence voltage reversal at Montgomery, which prevents the blocking directional element from recognizing the fault as external.

At this point, the user may compromise with the zero-sequence relays available. An alternative is to repeat the

study, using negative-sequence directional elements with negative- or zero-sequence overcurrent elements. The 161kV directional elements must not be allowed to operate for the 500kV faults.

**RULES FOR PHASE DISTANCE ELEMENTS**

For distance elements, the tripping element sees the entire line and the blocking element is set to detect all solid faults on the longest line behind its local bus. The algorithm computes the characteristic reach (e.g. mho circle diameter in primary ohms) from line impedances or apparent impedances as the engineer chooses.

**Reach of Forward Mho Tripping Element**

The macro finds the total line ohms of the protected line or the longest path of a multi-terminal line, and the shortest downstream line at the corresponding line-end bus. A parallel line is treated as a downstream line. The following four factors determine the pilot TRIP setting:

1. Line Ohms: the larger of (a) protected line ohms plus 50 percent of the downstream line ohms and (b) 120 percent of longest protected line path.
2. Apparent Impedances: the larger of (a) apparent impedance for a three-phase or phase B-C fault on the end bus, plus 50 percent of the downstream line ohms, and (b) 120 percent of largest apparent impedance for faults on the end bus. These percentages are user-chosen parameters.

TABLE 4 – Coordination Check for Faults on Coupled Line

(L) Local Bus: 45 Montgomery 5  
 (R) Remote Bus: 356 Springfield5

Faults on coupled line 44 71 1 71

Fault	Trip(L)	Block(L)	Trip(R)	Block(R)	Operation
SLG close-in at 44	N	N	N	N	Ok
DLG close-in at 44	N	N	N	N	Ok
SLG on open bkr at 44	N	<b>N</b>	<b>Y</b>	N	*Warning*
DLG on open bkr at 44	N	<b>N</b>	<b>Y</b>	N	*Warning*
SLG 0.25000 on 44 71 1 to 71	N	Y	Y	N	Ok
DLG 0.25000 on 44 71 1 to 71	N	Y	Y	N	Ok
...					
SLG on open bkr on 71 44 1 to 44	N	Y	Y	N	Ok
DLG on open bkr on 71 44 1 to 44	N	Y	Y	N	Ok

Pickup of Trip Element : 2701 IOC at 45 Montgomery 5 1600 Primary A  
 Pickup of Block Element: 2702 IOC at 45 Montgomery 5 400 Primary A  
 Pickup of Trip Element : 4688 IOC at 356 Springfield5 800 Primary A  
 Pickup of Block Element: 9044 IOC at 356 Springfield5 800 Primary A

TABLE 5 – Automatic Extension of Reach to Encompass Load-Tap Branch

Path 356 1488 Ckt 1 to 45 to 1274 298 Ckt 1  
 Phase Ohms 20.338 @ 85 deg + 0.20000 \* 0.887 @ 83 deg = 20.515 @ 84 deg  
 Phase Zone 2 underreaches farthest zone 1 bus 1492 0.07866  
 Increasing zone 2 to 1.20000 \* 0.07866 pu = 0.09439 24.4677 Ohm

Phase Zone 2 does not reach 1.20000 \* max APP IMP for load-tap branches  
 Increasing zone 2 to 1.20000 \* 0.09767 pu 25.3171 Ohm

Phase Zone 2 / Max impedance to depth 1 124.2 %  
 Phase Zone 2 / Min impedance to depth 2 119.3 %

Warning: Phase Zone 2 overreaches one or more buses at depth 2

Maximum apparent impedances are found with all lines in service, and with infeed removed and with coupled lines out one at a time. The setting is almost independent of the details of the relay comparator if the angle of the apparent impedance is within a few degrees of the relay maximum torque angle (MTA). That is usually the case for solid faults on the line.

The results in Table 5 above show how the reach at bus 356 is increased to cover the more distant tap branch at 1492 (Kirkwood). For a pilot scheme we can ignore the overreach warnings for depth-2 buses, since faults there will be detected by the blocking elements.

3. Load Transformers on Tapped Branches. The relay must not see secondary faults on load transformers along the protected line or at the remote bus. The fractional overlap of the relay into the transformer reactance must be less than a chosen value (e.g. 0.5). This overlap is computed directly from the transformer leakage impedance and corresponds to the worst case with no infeed current between the relay and the transformer.

4. Limits to Avoid Operation for Load Current. The setting is limited to a chosen fraction of the worst-case forward load impedance, using the load current supplied by the user and the bus base kV. A loadability report shows (a) the maximum allowed setting to avoid tripping for a user-specified load and (b) the equivalent load, which is the largest load allowed with the existing setting and safety factor.

### Reach of Reverse Mho Blocking Element

The blocking element at bus 356 must cover the overreach region of the tripping element at bus 45. It is limited to 150 percent of the largest apparent impedance calculated for solid line-end three-phase faults (on the line side of an open breaker) behind the relay; also to 0.67 times the worst-case reverse load impedance. A tripping element (e.g. at bus 45) and its opposite blocking element (at bus 356) are limited by the same maximum load current. These settings allow up to 160 MW load (Springfield to Montgomery) or 189 MW (Montgomery to Springfield) with a 30-degree power factor angle and a 1.5 safety factor.

In the final settings, the tripping reach is reduced slightly to avoid load transformers, and the available taps limit the blocking pilot reach to 128 ohms. Checks for internal and external faults show no violations. Figure 4 shows the tripping and blocking elements as mho characteristics.

### CONCLUSIONS

The algorithms presented here calculate the electrical settings of four overcurrent or four distance elements. Using detailed phasor relay models, the algorithms check the operation for faults both internal and external to the protected line. The computer provides more thorough fault studies than are practicable by hand and finds the limits set by the network, the

maximum load, and the available relay taps.

For the 161kV line studied, the phase distance tripping elements can be set with sufficient reach to detect faults on the load-tap branches, with infeed from the remote source. For the ground overcurrent tripping elements, sensitivity is limited by the minimum available taps, and more severely by the need to avoid tripping for faults on the coupled 500kV line. The algorithm finds these constraints. The engineer can easily repeat the computation to evaluate compromise zero-sequence settings or negative-sequence elements.

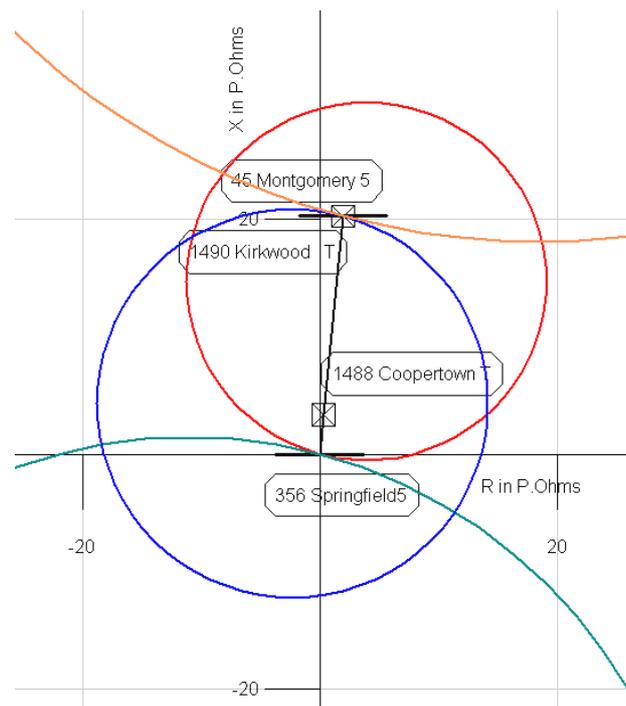


Figure 4 – Phase Distance Characteristics in Line Impedance Plane: Forward Tripping and Reverse Blocking Pilot Elements

### REFERENCES

- [1] Fernando L. Alvarado, Sao Khai Mong, and Mark K. Enns, "A Fault Program with Macros, Monitors, and Direct Compensation in Mutual Groups," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, No. 5, pp. 1109-1120; May 1985.
- [2] "IEEE Guide for Protective Relay Applications to Transmission Lines," *IEEE Standard C37.113-1999*, Institute of Electrical and Electronics Engineers, New York, NY; February 2000.
- [3] Donald M. MacGregor, A. T. ("Tony") Giuliante, and Russell W. Patterson, "Automatic Relay Setting," *56th Annual Georgia Tech Protective Relaying Conference*, Atlanta, Georgia; May 1-3, 2002.