OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS CONSIDERING DEFINITE TIME BACKUP RELAYING

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Abstract. **A methodology is presented for the consideration of definite-time backup relays in the optimal coordination of directional overcurrent relays using linear programming. It is shown that the influence of considering second-zone distance relays and breaker failure relays impose important requirements for the determination of the time dial settings of directional overcurrent relays. The paper introduces a revised formulation of the optimization problem. Results are presented for the application of the methodology on a power system with 2 generators, 9 buses, 2 transformers and 7 transmission lines.**

Keywords: Computer Aided Relay Coordination, Optimization Techniques, Power System Protection.

I. INTRODUCTION

The problem of determining the time dial setting of directional overcurrent relays using optimization techniques was first stated in 1987 [1]. It has been shown that the linear programming technique can be successfully applied to this problem, guaranteeing the minimum possible settings of the relays that satisfy the time coordination constraints, i.e., the optimal settings [1-4]. The problem of re-setting the relays after a permanent topology change in the system reducing the number of relays to be reset was presented and solved using the concepts of multiple objective optimization [3]. The consideration of the dynamic changes of the system topology that take place during the fault clearing process using linear programming was also recently addressed [4]. However, the optimization problem has been formulated and solved for systems including only directional overcurrent relays (DOCR) without considering the coordination of DOCR with other relay types.

In many sub-transmission and transmission power systems DOCR are used as secondary protection; the main protection schemes use distance relays (Fig. 1). Distance relay schemes are implemented according to the instantaneous-first-zone and delayed-second-zone scheme. This second zone represents a definite time backup protection, and its operation time is over 300 ms [5]. Additionally, there are systems where local backup relays are used to minimize the dangerous effects of a breaker failure [5,6]. A breaker failure relay basically consists of a definite-time overcurrent unit with a control unit to confirm the breaker failure condition [6]. Fig. 2 shows a typical time-distance coordination scheme for a system with only distance and breaker failure relays (BFR). Notice that the presence of BFR requires that second zone time (t_{Z2}) be greater than for those cases for which BFR are not used. This leads to the fact that second zone operation time must be at least the operation time of the breaker failure relay t_{BF} (typical 0.2...0.3 s.) plus a security margin (sm) which could be about 0.3 s.

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The main goal of this article is to state the optimal coordination problem of directional overcurrent relays (DOCR) including the constraints imposed by distance relays and breaker failure relays.

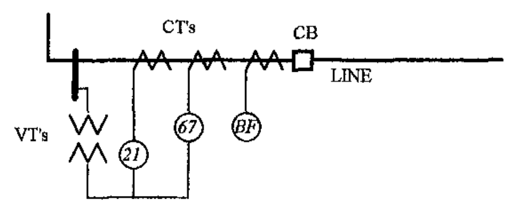


Figure 1. Line protection scheme using distance relays (21), directional overcurrent relays (67) and breaker failure relays (BF).

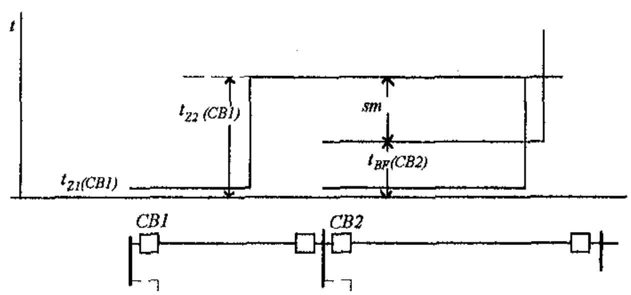


Figure 2. Distance relay and BF timing (DOCR not shown)

II. REVIEW OF THE DOCR COORDINATION PROBLEM USING LINEAR PROGRAMMING (ONLY INVERSE TIME RELAYS INCLUDED)

This section is devoted to the revision of the notation and concepts presented in the past in order to give a better coherency to this paper. In order to achieve the standard formulation of a linear programming problem, it is essential to use the equation for the inverse-type overcurrent relay time curve which separates the time dial setting from the pick-up current settings as follows [4,7]:

$$t_i(Fp) = f_i\,(M_i(Fp))g_i\,(D_i) = e_{ip}x_i \qquad (1)$$

where:

$t_i\,(Fp)$ = operation time of relay i for a given fault Fp.

$M_i(Fp)$ = multiple of the pick-up current of relay i for fault Fp.

D_i = time dial setting of relay i.

$$x_i = g_i(D_i) \qquad (2)$$

$$e_{ip} = f_i\,(M_i(Fp)) \qquad (3)$$

The problem consists of finding the minimum relay time dial settings (D_i), given the current pick-ups, in order to meet the coordination constraints. The relay pick-up currents and the transformer current ratios are previously calculated, therefore, the values of e_{ip} are known. This optimization problem may be stated as follows (see Fig. 3):

$$\min \quad \sum_{i=1}^{r} D_i \qquad (4)$$

Subject to:

$$t_j(F1) - t_i(F1) \geq CI \qquad (5)$$

$$t_j(F2) - t_i(F2) \geq CI \qquad (6)$$

where:

(i,j) = relay coordination pair (main,backup)

$t_j(F1)$ = operating time of relay j for a fault at F1

$t_i(F1)$ = operating time of relay i for a fault at F1

$t_j(F2)$ = operating time of relay j for a fault at F2

$t_i(F2)$ = operating time of relay i for a fault at F2

CI = coordination interval

r = number of relays

F1 and F2 represent the "close-in" and "remote" fault conditions. The calculation is performed considering three-phase faults for phase relays and single phase-to-ground faults for ground relays.

The objective function is taken as the sum of the time dial settings (TDS) of all relays. It has been shown that this leads to minimum relay operation times [1].

Equations (5) and (6) are stated in terms of the relays' operation times, but the variables of interest are the time dial settings (D_i). These equations can be written in terms of new variables x_i, and x_j, which only depend on the TDS of relays i and j (D_i, D_j). Using Eqn. (1), Eqns. (5) and (6) become:

$$e_{i1}x_i - e_{j1}x_j \leq -CI \qquad (7)$$

$$e_{i2}x_i - e_{j2}x_j \leq -CI \qquad (8)$$

Moreover, to minimize the sum of the time dial settings D_i, (Eqn. (1)) is equivalent to minimizing the sum of the x_i. Other constraints, like the maximum and minimum permissible values for the time dial settings, can be treated in the same way. Therefore, the problem can be stated in the standard form, as follows:

$$\text{minimize} \quad \boldsymbol{c}^T\boldsymbol{x} = \sum_{i=1}^{r} c_i\,x_i \qquad (9)$$

$$\text{subject to: } \boldsymbol{Ax} \leq \boldsymbol{b} \qquad (10)$$

This problem is solved by means of a linear programming algorithm, and finally, all the D_i are found by solving the following set of non-linear equations:

$$g_i(D_i) - x_i = 0, \quad i = 1,2,\ldots r \qquad (11)$$

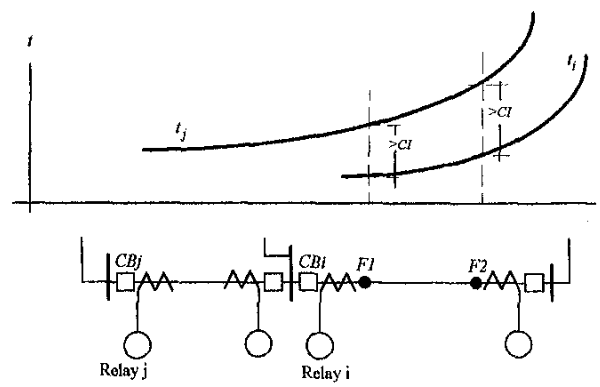


Figure 3. DOCR timing including only the inverse-time time-current curves

III. DOCR COORDINATION INCLUDING INSTANTANEOUS UNITS.

Instantaneous units are often used to improve the speed of system relays. When used, they help to reduce the TDS of the delay units. Normally, the instantaneous settings are calculated prior to the calculation of the TDS, thus they must be considered when stating and solving the optimization problem.

Fig. 4 shows the case of DOCR coordination including instantaneous units. It can be inferred from this figure that the two constraints derived are:

$$t_j(F1) - t_{inst} \geq CI \quad (12)$$

$$t_j(F3) - t_i(F3) \geq CI \quad (13)$$

Where t_{inst} is the operating time of relay i. Again, using Eqn. (1), Eqns. (12) and (13) become:

$$e_{i1}x_i \leq -CI - t_{inst} \quad (14)$$

$$e_{i2}x_i - e_{j2}x_j \leq -CI \quad (15)$$

In practical applications, $CI >> t_{inst}$, thus t_{inst} can be neglected and Eqn. (14) becomes simpler. Notice from Fig. 4 that the second constraint (13) is evaluated at point F3, which corresponds to the point that produces a current contribution at CB_i approximately equal to the primary instantaneous setting of relay i. This implies that an intermediate fault calculation must be performed when computing the elements of matrix A to state the problem as in Eqns. (9) and (10). Equations (14) and (15) can also be used in the case of directional overcurrent relays with hybrid short-time delay units.

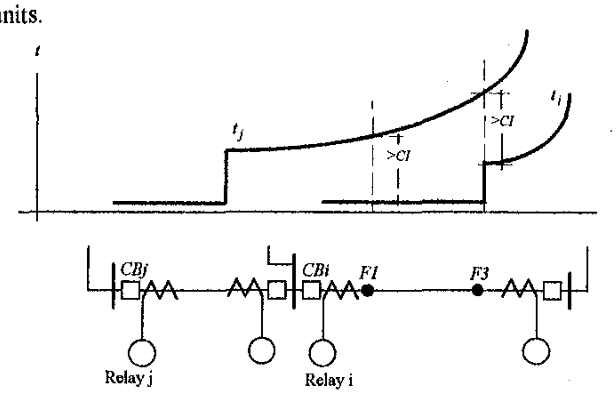


Figure 4. DOCR coordination using time delay and instantaneous units.

IV. CONSIDERATION OF DISTANCE RELAYS

The derivation of the coordination constraints for systems where DOCR and distance relays are used is explained with the aid of Fig. 5. In the scope of this work, it is assumed that the ohmic reach of each distance relay has been properly set prior to the time coordination process. There are two important types of constraints:

a. Second zone distance relay associated with *CBj* must be slower than the DOCR associated with *CBi*; which can be stated as follows:

$$t_{Z2j} - t_i(F1) - tinst \geq CI \quad (16)$$

b) DOCR relay associated with *CBj* must be slower than the second zone distance relay associated with *CBi*:

$$t_j(F2) - t_{z2i} \geq CI \quad (17)$$

As t_{z2} is given, constraints (16) and (17) become:

$$-e_{i1}x_i \leq -CI + t_{Z2j} \quad (18)$$

$$e_{j2}x_j \leq -CI - t_{z2i} \quad (19)$$

Notice that these two equations represent a severe restriction for the DOCR.

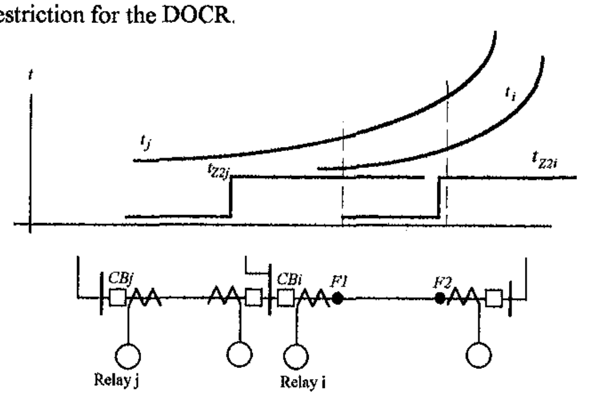


Figure 5. DOCR coordination with distance relays

V. CONSIDERATION OF BREAKER FAILURE RELAYS

As indicated in Figure (2) the presence of BFR makes the distance relay second zone time to be relatively large. If DOCR, distance relays, and BFR are present in the system, the simplified time diagram is shown in Figure (6). Notice that the constraints are the same as the equations (18) and (19). This is the most frequent case. If there was a case where distance relays are not present, the coordination constraints are similar to (14) and (15) but using t_{BF} instead of t_{inst}.

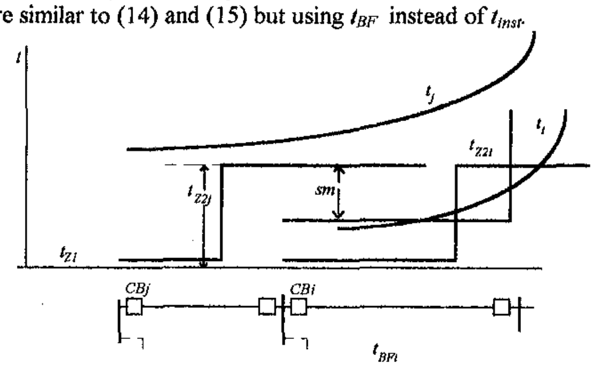
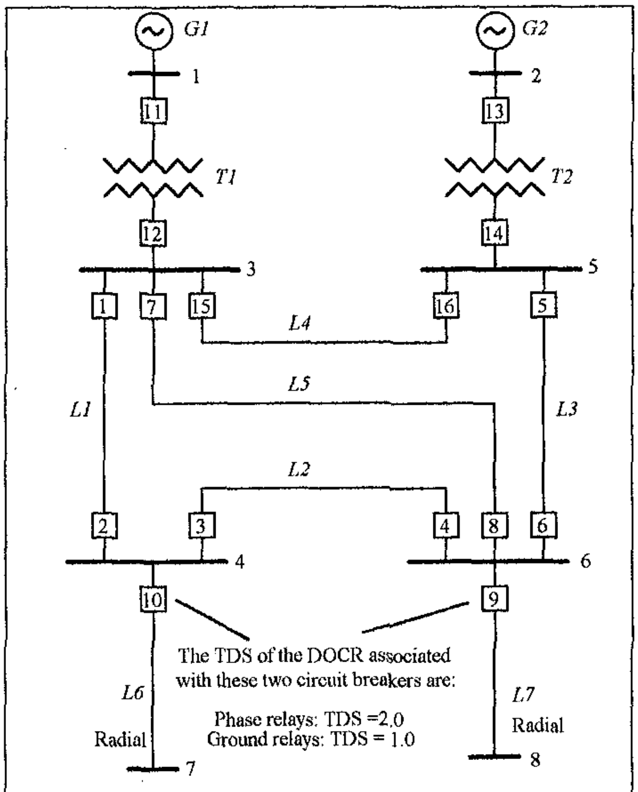


Figure 6. Coordination of DOCR with distance relays when BFR are present.

VI. TEST CASE

The methodology explained in the paper was applied to the system shown in Figure 7. This is a system consisting of 2 generators, 2 *Y-Y* power transformers, 9 buses and 7 lines. The pick-up current settings (*Ip*) and the current transformer ratios (*CTR*) are given in Table I (all relays have minimum TDS of 0.5 and maximum TDS of 11). Three cases are analyzed: 1) DOCR with only time delay units (similar to IBC51 type); 2) DOCR with time delay and instantaneous units ($t_{inst} = 0$); and 3) DOCR with time delay and instantaneous units as the secondary protection, distance relays (DR) as the main protection, and breaker failure relays (BFR) as local backup.



System Characteristics:
G1 and G2: 12 kV, 25 MVA, $X^+ = X^- = 15\%$; $X^0 = 8\%$
T1 and T2: 30 MVA, 69/12 kV, $X = 9\%$, $X/R = 10$
Line impedances:
$z_1 = 0.19 + 0.461j \quad \Omega/km$
$z_0 = 0.65 + 1.254j \quad \Omega/km$
Lines' lengths (km):
L1=10, L2=20, L3=12, L4=10, L5=20, L6=10, L7=10.

Figure 7. Test case

TABLE I.
DOCR Relay basic data

CB	CTR	Phase relays	Ground relays
		Ip (A)	*Ip (A)*
1	600/5	5.0	1.0
2	400/5	5.0	1.0
3	200/5	5.0	1.0
4	200/5	5.0	1.0
5	600/5	5.0	1.0
6	400/5	5.0	1.0
7	400/5	5.0	1.0
8	400/5	5.0	1.0
9	400/5	5.0	1.0
10	300/5	5.0	1.0
11	1600/5	5.0	1.0
12	100/5	5.0	1.0
13	1600/5	5.0	1.0
14	100/5	5.0	1.0
15	400/5	5.0	1.0
16	400/5	5.0	1.0

Tables II to V show the results obtained with the application of the proposed linear programming technique for the DOCR's time dial settings for the three different cases using a coordination time interval $CI = 0.3$ *sec*. Instantaneous units must be directional [5] and their settings were previously calculated. From Tables II and III it can be concluded that the instantaneous units definitely help to improve the relay times. In both cases the linear programming technique works very well. The TDS were treated as continuous variables. It is understood that they have to be fixed according to the resolution allowed by the relays being used.

TABLE II.
Test case (1) results. Only time-delay DOCR

CB	DOCR (67)				DR	BFR
	Phase relays		Ground relays		(21)	(50BF)
	TDS	*Inst.(A)*	*TDS*	*Inst.(A)*	$t_{Z2}(s)$	$t_{BF}(s)$
1	1.211	---	3.041	---	---	---
2	0.500	---	3.269	---	---	---
3	1.175	---	2.858	---	---	---
4	2.663	---	4.094	---	---	---
5	0.830	---	3.420	---	---	---
6	0.500	---	2.422	---	---	---
7	0.500	---	3.259	---	---	---
8	0.500	---	1.652	---	---	---
9	2.000	---	1.000	---	---	---
10	2.000	---	1.000	---	---	---
11	2.068	---	4.285	---	---	---
12	0.500	---	0.500	---	---	---
13	1.770	---	4.5814	---	---	---
14	0.500	---	0.500	---	---	---
15	0.696	---	3.322	---	---	---
16	0.857	---	3.080	---	---	---

TABLE III.
Test case (2) results
Only time-delay and instantaneous DOCR

CB	DOCR (67)				DR	BFR
	Phase relays		Ground relays		(21)	(50BF)
	TDS	*Inst.(A)*	*TDS*	*Inst.(A)*	$t_{Z2}(s)$	$t_{BF}(s)$
1	0.500	13	1.653	13	---	---
2	0.500	---	0.500	--	---	---
3	0.720	12	1.691	12	---	---
4	1.410	17	2.079	17	---	---
5	0.500	10	1.538	10	---	---
6	0.500	---	0.657	---	---	---
7	0.500	9	1.492	9	---	---
8	0.500	---	0.500	---	---	---
9	2.000	21	1.000	18	---	---
10	2.000	27	1.000	23	---	---
11	0.731	24	3.517	30	---	---
12	0.500	46	0.500	31	---	---
13	0.705	24	3.510	30	---	---
14	0.500	46	0.500	31	---	---
15	0.500	11	1.355	11	---	---
16	0.500	11	1.521	11	---	---

TABLE IV.
Test case (3) results
DOCR (including instantaneous units),
Distance relays (DR) (t_{z2} =*0.6 sec.*) and
Breaker failure relays (BFR) (t_{BF} =*0.3 sec.*)

CB	DOCR (67)				DR	BFR
	Phase relays(*)		Ground relays		(21)	(50BF)
	TDS(*)	*Inst.(A)*	*TDS*	*Inst.(A)*	$t_{Z2}(s)$	$t_{BF}(s)$
1		13	3.176	13	0.6	0.3
2		---	0.500	--	0.6	0.3
3		12	3.110	12	0.6	0.3
4		17	3.565	17	0.6	0.3
5		10	2.991	10	0.6	0.3
6		---	1.176	---	0.6	0.3
7		9	2.917	9	0.6	0.3
8		---	0.654	---	0.6	0.3
9		21	1.000	18	0.6	0.3
10		27	1.000	23	0.6	0.3
11		24	5.076	30	---	0.3
12		46	0.500	31	---	0.3
13		24	5.054	30	---	0.3
14		46	0.500	31	---	0.3
15		11	2.100	11	0.6	0.3
16		11	2.369	11	0.6	0.3

(*) Not feasible

Tables IV and V help to understand how important it is to consider the definite time backup protection in the coordination process. Notice that the optimization problem is not feasible for the case of phase relays (*) when t_{Z2} = *0.6 sec.*

Table V shows the results for the same case, but with a higher second zone operation time of the phase distance relays (t_{Z2} = *0.8 s*). In this case, the non-feasibility trouble was overcome and the desired optimal solution was reached. This fact is explained by reviewing the constraints stated in Eqns. (16) and (18); which clearly imply that the second zone time must be large enough such that the backup circuit breaker tripped by the distance relay is slower than the main circuit breaker tripped by the DOCR.

TABLE V.
Test case (3) results
DOCR (including instantaneous units),
Distance relays (DR) (t_{z2} =*0.8 sec.* for phase relays, t_{z2} =*0.6 sec.* for ground relays) and
Breaker failure relays (BFR) (t_{BF} =*0.3 sec.*)

CB	DOCR (67)				DR (phase)	DR (grnd.)
	Phase relays		Ground relays		(21)	(21)
	TDS	*Inst.(A)*	*TDS*	*Inst.(A)*	$t_{Z2}(s)$	$t_{Z2}(s)$
1	0.634	13	3.176	13	0.8	0.6
2	0.500	---	0.500	--	0.8	0.6
3	0.720	12	3.110	12	0.8	0.6
4	1.636	17	3.565	17	0.8	0.6
5	0.500	10	2.991	10	0.8	0.6
6	0.500	---	1.176	---	0.8	0.6
7	0.500	9	2.917	9	0.8	0.6
8	0.500	---	0.654	---	0.8	0.6
9	2.000	21	1.000	18	0.8	0.6
10	2.000	27	1.000	23	0.8	0.6
11	1.106	24	5.076	30	0.8	0.6
12	0.500	46	0.500	31	0.8	0.6
13	1.106	24	5.054	30	0.8	0.6
14	0.500	46	0.500	31	0.8	0.6
15	0.500	11	2.100	11	0.8	0.6
16	0.500	11	2.369	11	0.8	0.6

VII. CONCLUSIONS

The operation time coordination problem of directional overcurrent relays considering the operation times of the instantaneous units and the definite time backup units (second zone of distance relays and breaker failure relays) can be stated as an optimization problem and solved using linear programming techniques. The resultant time dial settings not only assure coordinated operation of the relays but also guarantee the minimum possible operation times.

The presence of instantaneous units and definite time backup relays affects the mathematical formulation of the linear programming problem by generating additional linear restrictions which have to be included in the constraint set.

The particular characteristics of these linear equations that have to be added to the optimization problem are described in the article for the case of instantaneous units, distance relays and breaker failure relays.

It was shown, with the aid of the test case, that the presence of instantaneous units is translated into smaller time dial settings, and therefore into faster operation times of the time-delay directional overcurrent units.

The presence of the breaker failure relays from a mathematical point of view is reflected in the inclusion of additional lower bounds for the operation times of certain relays. Sometimes these bounds are not active.

Distance relays, however, introduce two types of constraints: lower limits as well as upper limits on the operation times of the directional overcurrent relays. The lower limit constraints, if they are active, may push the operation times of the directional overcurrent relays to higher values. However, the upper limit constraints may turn the problem into a nonfeasible problem, with no feasible solution. In this case, the possibility exists of increasing the second zone operation time of the critical distance relays, until a feasible solution is found, and the coordination of the protective system is achieved. If the resulting second zone operation time is out of the limits imposed by system requirements (stability, thermal damage, etc.)[8] the coordination criteria or the protection scheme wold have to be modified.[9]

The application of linear programming techniques for the time coordination of directional overcurrent relays considering definite time backup relaying proved to be a very useful tool for detecting and solving specific problems in realistic power systems with combined protection schemes.

VIII. ACKNOWLEDGEMENTS

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X. BIOGRAPHIES

Luis G. Pérez (SM), was born in Valle de la Pascua, Venezuela, in 1957. He received the Electrical Engineer degree from Universidad Simón Bolívar in 1979, the M. Sc. in E.E. from the Universidad Central de Venezuela in 1982 and the Ph. D. from Washington State University in 1994. He is a relay specialist who has been involved in many industrial and research projects in the field since 1979. He currently is an Associate Professor at Universidad Simón Bolívar, where he continues his work in Power System Protection, High Voltage Substation Design and System Dynamics.

Alberto J. Urdaneta (SM), was born in Maracaibo, Venezuela, in 1957. He received the Ph. D. degree and the M. Sc. in Electrical Engineering and Applied Physics from Case Western Reserve University, Cleveland, Ohio, in 1986 and 1983 respectively. He received the Electrical Engineer degree with honors from Universidad Simón Bolívar in 1979. Former Dean of Professional Studies, he presently is a Professor of Electrical Engineering, the Head of the Department of Energy Conversion and Delivery at Universidad Simón Bolívar and the Chairman of the IEEE Venezuelan Section. His interests are in the areas of Power System Analysis and Optimization.

Discussion

CHARLES F. HENVILLE (BC Hydro, Burnaby, BC, Canada). The authors present an interesting means of optimizing the settings of inverse time directional overcurrent relays with definite time distance relays and breaker failure relays. Two issues which affect the coordination process come to mind.

First, why is it deemed necessary to increase the settings of zone 2 timers to accommodate the time for breaker failure relays to operate? This discusser believes it is not generally necessary to accommodate breaker failure times in zone 2 settings, and is in fact often undesirable. Given that line faults occur many times more frequently than breaker failures, and the fact that zone 2 elements typically only reach a short distance past a remote substation, it would seem advisable to accept the rare possibility of overtripping of a line for a case of breaker failure at a remote substation to gain an advantage of substantially decreased clearing times for the much more frequent line faults. Further, there is often little or no adverse consequence to tripping a remote line terminal for a breaker failure situation. Certainly with the substation arrangements of figure 7 of the paper, there is no penalty caused by tripping the remote line terminals for a breaker failure. For instance, if breaker 10 fails to clear a fault on line L6, there is no negative impact if breakers 4 and 1 open, since breakers 2 and 3 will also have to be opened by the breaker failure protection of breaker 10. It would be appreciated if the authors would explain why they feel it is always, or even usually, necessary to increase zone 2 tripping times to accommodate breaker failure protection timers.

Secondly the coordination problem appears to have been simplified to a level that makes the results questionable. It does not seem reasonable to consider only single fault current pairs for faults at locations F1, F2 and F3 as described in the paper. Distance relays are capable of detecting faults with significant amounts of resistance at locations within their reach. The amount of fault resistance that can be sensed by a distance relay depends on its polarization methods and the system topology (which affects the source impedance behind the relay). Therefore faults with resistance which brings the impedance to just within the relay characteristic would also seem to be important, since such faults present significantly less current to the overcurrent relays. However, the amount of fault resistance to be considered varies with the system topology, and even with fixed topology, would be non trivial to calculate. Note that even a small amount of fault resistance can be quite significant to decrease the current presented to protective relays, especially when remote infeed is considered. Further, the apparent resistance can change dramatically when the remote terminal opens, as may be expected with sequential clearing. Even without fault resistance, the currents presented to the overcurrent relays will change significantly in the case of sequential clearing, especially for single line to ground faults, but also for multiphase faults. This means that in selecting the fault current pairs, the presence or absence of infeed from the remote terminal during the whole fault clearing time should be considered.

Considering only three phase faults for phase relays is also questionable, since two phase faults may present significantly less current to the overcurrent relays than three phase faults at the same locations.

Given the possible variations in current pairs for faults at the same locations, it appears that the quantities M_i and M_j are quite variable and may even be indeterminate in some cases. The author's comments on the need for detailed investigation of the appropriate current pairs used for coordination would be appreciated.

The above noted difficulties in determining the current pairs to be used for coordination studies should encourage those presented with the problem of coordinating distance relays with overcurrent relays to take more fundamental approaches to overcoming the problem. One such approach would be to use protection systems with similar operating principles to coordinate with each other. That is, either the distance relays should be replaced with overcurrent relays or vice versa. Another approach would be to add communications assistance to the distance protection systems and remove the direct tripping timed zone 2 functions. That is, have the overreaching distance functions trip only with communications assistance. This discusser believes that even with the most sophisticated coordination analysis techniques, there is often a danger of miscoordination between protection systems using different operating principles.

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Luis G. Pérez and **Alberto J. Urdaneta (Universidad Simón Bolívar).** The authors are grateful to the discusser for his interest in the article. The issues will be addressed in the same order they were stated.

Zone 2 and BF coordination

The disccuser's question is more related to the use of breaker failure relays than to the general methodology presented in the paper. In fact, breaker failure relays must be used for those substation bus arrangements where the operation of local back up circuit breakers could avoid a major outage due to the operation of zone 2 remote relays (reference [5] of the paper). The discusser's comment is correct regarding the example used in the paper (Figure 7), this particular case is not one of those systems where BF relays are a good solution. The example presented in the paper is more oriented towards the validation/verification of the applicability of the methodology rather to the study of the protection schemes by themselves. Figure C.1. shows two examples where it is more convenient to have local back-up circuit breaker tripping. In these cases, for a line fault close to the substation, the failure of breaker F will be better overcome by tripping breakers 1,2,3, instead of tripping breakers 4,5,6. The outage of these last three breakers could lead to a major stress to the system, since the post-fault network topology could imply a larger lost of service and probably a "less stable" power system. Thus, second zone of distance relays is left as a second back-up for these kinds of faults and for these kinds of systems, and therefore, it would be recommendable to have a time security margin between zone 2 and breaker failure relays, being the BF time as low as possible, to accomplish the condition of minimum clearing times. Of course, there could be better back-up schemes using communication means, but this is not a very common practice.

Fault location, fault impedance and pre-fault topology
Fault locations F1, F2 and F3 are convenient when there are only directional overcurrent relays (DOCR) involved. When distance relays and DOCR are together, the coordination between the second zone of distance relays and the DOCR must be performed by computing the current at a fourth point, which is the point on the line where the second zone reach. As indicated in Figure C.2, this point (F4) must be determined for each coordination pair and then the DOCR current is calculated. A routine to make this procedure was included in the program, assuming forward polarization for the distance relays. The results, for the particular example of Figure 7, did not change. This routine represents a simple extension to the original program, since the computer code is structured such that it allows modifications to be included easily (no external short-circuit program is used).

With regard to the well known problem of the presence of an undetermined fault impedance, it is a conventional and extensively used practice to assume solid faults for the relay setting calculation. The authors are aware that the use of this assumption could cause selectivity problems for some special cases.

The consideration of the changes in the pre-fault system topology is non trivial. In a preventive operation scheme, presently adopted by some protection engineers, the calculation of the appropriate relay settings is performed considering the constraints associated to the relevant configurations. In a corrective operation mode, adaptive relays can be used to accommodate the settings for each of the relevant system topologies[A]. Regardless of the adopted scheme, the proposed optimization methodology can be used to calculate the relays settings.

Indeterminate Mi and Mj
Regarding the discusser's issue about possible variations in the current "pairs", it must be cleared that the methodology permits the consideration of different fault types and locations as well as the presence of a predetermined value of fault impedance. In general, there could be more that two coordination constraints for each relay coordination pair. The computer program checks out when the DOCR currents fall below their pick-up. If that is the case (undetermined M), the corresponding coordination constraint is not included in the linear programming problem statement.

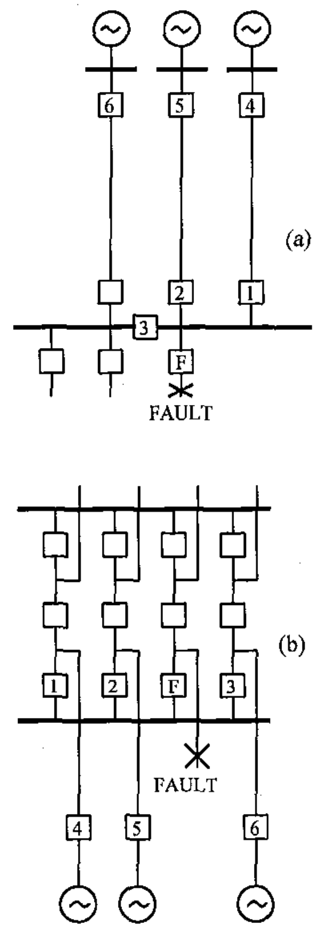

Figure C.1. Two examples where local back-up is better than remote back-up

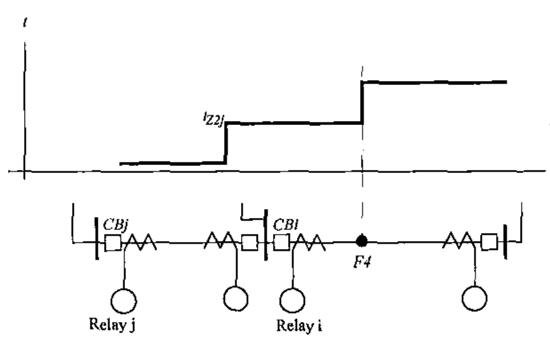

Figure C.2. F4 represents the relay j second zone reach, considering the infeed effect.

Protection schemes with similar principle

It is not an unusual practice to use a back-up relaying system with different protection principle than the main protection. The authors agree with the discusser in the fact that in some cases it is not convenient to combine DOCR with distance relays. The methodology presented in the paper could assist the protection engineer to make decisions on this matter. In fact, when the resulting second zone time of distance relays violates the transient stability requirement, the scheme is not recommendable. This is commented in the conclusion of the paper.

The authors would like to call the attention about a typo in Fig. 7 of the paper. The correct line lengths (*km*) are: *L1=10, L2=10, L3=20, L4=12, L5=20; L6=20, L7=20.*

[A] Ramaswami, R., Damborg, M., Venkata, S., Jampala, A., Postfoorosh, J. "Enhanced Algorithms for Transmission Protective Relay Coordination." *IEEE Trans. on Power Delivery.* Vol. PWRD-1, No. 1, January 1986, pp. 280-287.