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AN IMPROVED FORMULATION FOR OPTIMAL OVERCURRENT RELAY COORDINATION USING LINEAR PROGRAMMING TECHNIQUE

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ABSTRACT

In this paper the problem of directional overcurrent relays coordination in interconnected power networks is presented and solved using the optimization theory. Linear programming with Simplex two-phase method is applied to minimize the operating time of the relays. The insignificance of weighting factors and far-end fault consideration in the problem formulation is proved, through a mathematical example, by simulation, mathematically, graphically and by sensitivity analysis. The current transformer (CT) selection is achieved based on the maximum load and fault currents in order to prevent the miscoordination problem resulting from CT's saturation. A complete algorithm for calculating the optimal operating times is introduced and applied to sample examples.

KEYWORDS

interconnected networks, overcurrent relay, coordination, optimization, and enhanced formulation.

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1. INTRODUCTION

Directional overcurrent relaying, which is simple and economic, is commonly used in power system protection, as a primary protection in distribution and subtransmission systems and as a secondary protection in transmission systems. The main problem that arises with this type of protection, is the difficulty in performing the relays coordination, especially in the multiloop, multisource networks [1]. Since the sixties, a great effort has been devoted for solving this problem by computer. The methods, which are used, for performing this task (relay settings) can be classified into three classes: trial and error method [2], topological analysis method [3,4], and optimization method [5-8]. Traditionally, a trial and error method is applied for relay settings. To make the coordination process faster, Knable [9] innovate the, so-called, break points which represent the relays from which the coordination process will start. The authors of [3,4] have employed topological analysis method (using linear graph theory and functional dependency) for determining the optimal break points. The topological method is the best alternative, but there is no guarantee that it produces optimal relay settings.

In the optimization method, some researchers used nonlinear programming for determining the optimal settings of the pickup current and a linear programming for optmizing the time dial settings of the relays subject to the coordination constraints, and the limits of the relay settings [5,6]. Other researchers [7] applied the linear programming technique only to minimize operating time while the pickup currents are selected based on experience.

Urdenta et al, [5] assumed a middle-line fault in the problem formulation, to reduce the problem dimensionality. The authors of [6] used two constraints for each relay, one for close-in fault and one for far-end fault, and the objective function was considered as the sum of two additive values; the first one is the weighted sum of the operating times of the primary relays for close-in fault, and the second one is the weighted sum of the operating times of the primary relays for far-end fault. In [7], to quote: "the objective function is a weighted sum of operating times of the primary relays for close-in faults, and since the lines are short and approximately of equal length, equal weights (=1) were assigned for the operating times of all the relays". Also, the authors of [8] suggested four constraints for each relay two just as in [6], and two for transient topology changes. In so doing, the problem size based on these formulations increased, which is originally large.

In this paper, the authors suggest a modified formulation to make the coordination process faster, through applying a linear programming technique, and problem dimensionality reduction. In reality, nonlinear programming is a time consuming technique, because for each iteration of the nonlinear programming another linear programming is called for determining the direction search. On the other hand, the main problem is not to determine the optimal pickup settings, but optimal time dial settings. The objective function is stated as a sum of the operating times of all primary relays for maximum close-in faults, and the constraints considered are based on the maximum close-in faults as well. So, the problem dimensionality is reduced to a half and consequently, a faster algorithm, which is more suitable for on line application is obtained.

2. OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS

2.1 Overview

The directional overcurrent relay has two units, an instantaneous unit (time independent), and an inverse overcurrent unit (time dependent). The time dependent unit has two values to be set, the pickup current value (Ipu,) and the time dial setting (TDS), which can be set either according to break point approach [3,4] or according to the concept of optimization theory (linear programming) just as in this paper. The pickup value is the minimum current value for which the relay operates. The time dial setting defines the operating time T of the relay for each current value, and is generally given as a curve, T versus M, where M is a multiple of the pickup current, i.e. $M = \frac{I}{Ipu}$, and I is the relay current (overload and/or fault). In the application reported in this paper, the overcurrent relay is conformed to the following IEC characteristic [11]:

$$T = \frac{k_1 \, .TDS}{[M^{k_2} - 1]} \tag{1}$$

where: k_1, k_2 are constants that depend on the relay characteristic (inverse, very inverse, and extremely inverse). It is worth to mention that directional overcurrent relay allows for continuous time dial setting but discrete pickup current settings.

2.2 Statement of the proposed formulation

The general relay coordination problem can be stated as a parametric optimization problem. The objective function of operating times of the primary relays is optimized subject to keeping the operation of the backup relays coordinated. One possible approach to achieve minimum shock to the system due to faults would be to minimize a sum of the operating times of all primary relays hoping that the operating times of individual primary relays would be close to the minimum individual operating times that might be possible. The problem formulation can be demonstrated with the help of Fig. (1) and by assuming a network consisting of *n* relays, the objective function J to be minimized can be expressed as:

$$J = \sum_{i=1}^{n} T_{ii} \tag{2}$$

where: T_{ii} is the operating time of the primary relay R_i for a close-in fault *i*,

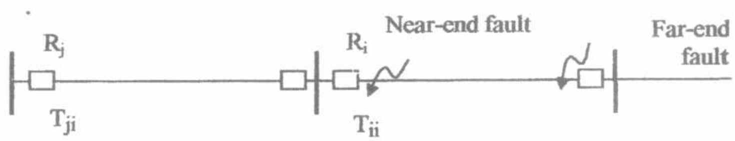

Fig. (1) An illustrative diagram for basic definitions

The operating time of the backup relay must be greater than the sum of the operating time of its primary relay and the coordination margin. This can be expressed as:

$$T_{ji} \geq T_{ii} + CTI \tag{3}$$

where: T_{ji} is the operating time of the backup relay R_j for the same close-in fault at i, and CTI is the coordination time interval.

From equation (1) one can see that the relation between the operating time T of the time overcurrent unit, and the multiple pickup current M, is nonlinear. Since the multiple pickup current of the relays can be predetermined, so for a fixed M, equation (1) becomes linear as follows:

$$T = a \,.\, TDS \tag{4}$$

where:

$$a = \frac{k_1}{M^{k_2} - 1} \tag{5}$$

By substitution in equation (2), the objective function becomes:

$$J = \sum_{i=1}^{n} a_i . TDS_i \tag{6}$$

In equation (6), a_i's haven't any effect on the optimal solution and can be assumed ones, they are predetermined from equation (5) and substituted in (3); values of TDS_i are determined by minimizing J (the objective function) and satisfying the coordination between the primary and backup relays. Equation (6) is optimized using the well-known Simplex two-phase method [10] subject to the condition that the operation of the backup relays remains properly coordinated.

3. JUSTIFICATION OF THE PROPOSED FORMULATION

3.1 The insignificance of weight factors consideration

According to the mathematical formulation of the problem, it can be shown that the objective function has a negative slope and the constraints ($a_i.X-b_i.Y \geq c$) have positive slopes. The optimal solution will not change if the weight factors changed from a zero to infinity. The optimal solution will change only if the weight factors get negative values, but this case is unacceptable because, the weight factors are positive real numbers, and if negative values of the weight factors are accepted, some of the operating times will be maximized rather than minimized.
The following mathematical example will illustrate these facts:

Min $Z = 4X_1 + 3X_2$

Subject to the following constraints:

$X_1 - X_2 \geq 2$ (I)
$2X_1 - 0.5X_2 \geq 2$ (II)

Lower bounds:
$X_1 \geq 0$
$X_2 \geq 0$

By solving this problem graphically, as shown in Fig. (2), mathematically, and by simulation shown in Table (1), the following results are obtained:

$X_1 = 2$, $X_2 = 0$.

Sensitivity analysis [10] means how much change is allowed in the objective coefficients. A change in the objective function coefficients can affect only the slope of the straight-line representing it. The optimum solution depends totally on the slopes of the objective function and constraints. The goal from the standpoint of sensitivity analysis is to determine the range of variation in each of the objective function coefficients that will keep a current optimum solution unchanged.

Tables (1,2) give the optimal solution of the problem and the sensitivity analysis based on TORA program [10]. One can see from Table (2) that by changing the coefficients of the objective function from zero to infinity, the same optimal solution will be obtained.

It is also concluded that only one constraint of the two is active [I] (the constraint with a minimal slope) and will counteract the other constraint effect. The same thing will occur when considering the far-end fault, where the close-in fault constraints will counteract the effect of far-end fault constraint.

Table (1) Optimum solution summary

Variable	Value	Z - Coefficient
X_1	2	4
X_2	0	3

Table (2) Sensitivity analysis of the objective coefficients due to single changes

Variable	Coefficient	MIN Coefficient	MAX Coefficient
X_1	4	0	infinity
X_2	3	-4	Infinity

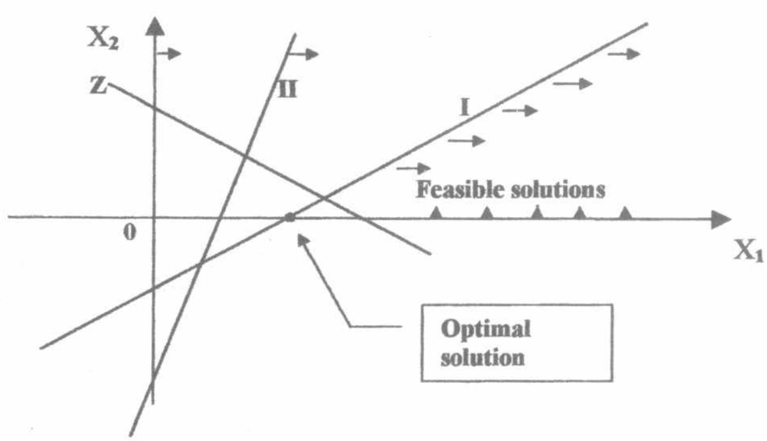

Fig. (2) Problem solution in the two dimensional domain

3.2 The insignificance of far-end fault consideration

The far-end fault consideration will increase the problem dimensionality, and redundant constraints and objective function will be obtained. However, the same optimum solution will result. The authors who considered far-end fault in problem formulation, believed that the operating times of the relays for far-end fault consideration would be minimized. In fact, this consideration hasn't any advantage, because any change in the objective function coefficients such as coefficient increment hasn't any effect on the optimal solution (just as clarified in the previous section). On the other hand, the sums of operating times of the primary relays for different fault locations couldn't be considered as independent objective functions in the optimization problem formulation. The reduction of the operating times for the close-in faults will necessarily lead to the reduction of the operating times for any fault location, just as middle-line and far-end faults, but vice versa is not true. This fact is justified from the inverse overcurrent relay characteristic curves. Moreover, each relay will have two constraints (6,8) but one of them is a redundant, and will be cancelled by the second one of minimum slope just as depicted in the previous mathematical example, Fig. (2). By these facts the problem dimensionality will be reduced to a half, and fast convergence will be occurred (minimum number of iterations), and consequently, fast coordination process which is more suitable for on-line application and the same optimal solution will be obtained.

4. PROPOSED ALGORITHM

Fig. (3) illustrates the flow chart of the proposed program for optimal coordination of the directional overcurrent relays. Each block of the flow chart can be briefly explained as follows:

a- Primary/Backup relay pairs (P/B): Every primary relay has its own backup. These pairs form one of the most important coordination criteria. The coordination time interval (CTI) between the primary and backup relays has been chosen to be 0.2s. A program for calculating the primary/backup relay pairs based on topology tracing, has been developed.

b- Load flow program: Newton-Raphson load flow technique is used in this application to determine the voltages at each bus and the line currents.

c- Fault analysis program: The fault analysis program is developed using the Thevenin's equivalent approach, to simulate a 3-phase fault for each relay location. It is worth to mention that each close-in fault can be considered as a far-end fault for far relay and vice versa.

d- Selection of pickup currents: The pickup current value of the time dependent unit can be determined according to the power system and relay design, and the experience of the protection engineer. In this paper it will be set at 1.5 times the maximum load current, for phase protection. The instantaneous unit can be set at 1.3 times the maximum far-end fault.

e- Optimal selection of TDS: The problem of overcurrent relay coordination is solved by linear programming technique, using the well known Simplex two-phase method [10] subject to the condition that the operation of the backup relays remains properly coordinated. The TDS range is taken between 0.05 to 1.1 according to equation (1).

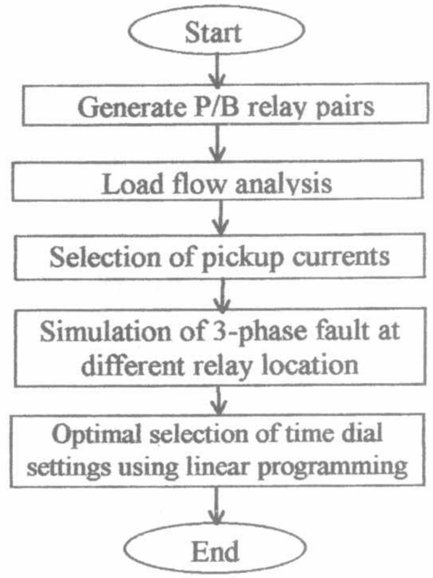

Fig. (3) Flow chart of the proposed program

5 . APPLICATION OF PROPOSED METHODOLOGY

The developed methodology has been applied to a 3-bus test system, which is taken from Ref. [5], for a comparison purpose, and it is shown in Fig. (4), and to IEEE 14-bus test system, which is shown in Fig [5]. Identical directional overcurrent relays with inverse characteristics have been used in these examples, so that k_1=0.14, k_2=0.02.

5.1 Three-bus test system example

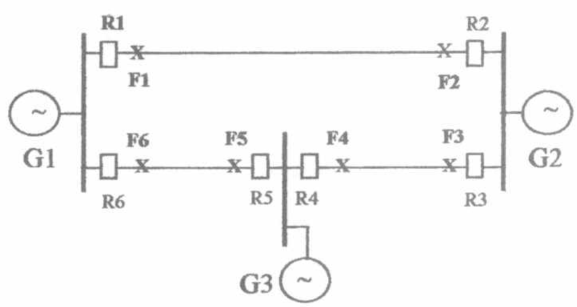

Fig. (4) Three-bus system example

The problem of determining the optimal TDS's and consequently the minimum operating times, for the close-in faults of the relays of this system can be formulated as the following linear programming problem:

$$Min\ J = T_{11}+T_{22}+T_{33}+T_{44}+T_{55}+T_{66} \quad (7)$$

Subject to the following constraints:

$T_{51}-T_{11} \geq 0.2$

$T_{42}-T_{22} \geq 0.2$

$T_{13}-T_{33} \geq 0.2$

$T_{64}-T_{44} \geq 0.2$
$T_{35}-T_{55} \geq 0.2$
$T_{26}-T_{66} \geq 0.2$ (8)

By substituting the values of the short circuit and pickup currents in equations (4,5) then (7,8), yields:

Min

[2.415*TDS1+1.7289*TDS2+2.5488*TDS3+2.5994*TDS4+1.7908*TDS5+2.092*TDS6].

Subject to:

$2.8978*TDS5-2.4150*TDS1 \geq 0.2$
$4.2620*TDS4-1.7289*TDS2 \geq 0.2$
$5.0941*TDS1-2.5488*TDS3 \geq 0.2$
$4.2954*TDS6-2.5994*TDS4 \geq 0.2$
$3.9708*TDS3-1.7908*TDS5 \geq 0.2$
$2.4935*TDS2-2.0922*TDS6 \geq 0.2$

and $1.1 \geq TDS \geq 0.1$

A linear programming technique (Simplex-two-phase method) is used as follows:

In phase I, a feasible solution is obtained and in phase II, the optimal solution is found.

The TDS and operating times of the primary and backup relays for near-end faults are shown in Table (3).

Table (3) Time dial settings and operating times of the 3 – bus test system

No. of iteration = 7		**Objective value (min) = 1.6858**
T11=0.2415	T51=0.4416	TDS1=0.1000
T22=0.3115	T42=0.5114	TDS2=0.1802
T33=0.3035	T13=0.5094	TDS3=0.1191
T44=0.3119	T64=0.5120	TDS4=0.1200
T55=0.2729	T35=0.4729	TDS5=0.1524
T66=0.2492	T26=0.4493	TDS6=0.1192

The authors of Ref. [5] assumed three-phase faults occurred in the middle of the transmission line to reduce the dimensionality of the problem. But, in reality, this assumption is unsuitable and results in miscoordination problem, especially when a near-end fault occur, because the coordination process must be based on the fault just beyond the primary relay, which produces maximum fault current (minimum relay's operating time) in the primary and backup relay.

The time dial settings of the relays according to Ref. [5] and without considering dynamic changes in the network topology are equal to 0.1 and consequently, the operating times of the relays for near end-faults are as shown in Table (4). The cases in which miscoordination occurred are marked with (*).

Table (4) Operating times for near-end fault w.r.t the TDS's formulation of Ref. [5] in seconds

Primary Relays	Backup Relays
T11 0.2415	T51 0.2897*
T22 0.1728	T42 0.4262
T33 0.2548	T13 0.5094
T44 0.2599	T64 0.4295*
T55 0.1790	T35 0.3970
T66 0.2092	T26 0.2493*

(*) Refer to a miscoordination case

A comparison between the operating times of the relays, when a fault occurs in the middle of the line based on the presented formulation and Ref. [5] formulation is shown in Table (5). It is shown that the operating times of Ref. [5] formulation are less than the operating times of the adopted formulation. But, the proposed formulation is more suitable because it satisfies the coordination margin for near-end fault, whereas it is not in [5].

Table (5) A comparison between the results obtained from the suggested formulation and Ref. [5]

Suggested approach	Ref.[5] approach	Suggested approach	Ref.[5] approach
T11 0.3641	0.3641	T51 1.3522	0.8873
T22 0.3773	0.2094	T42 1.0090	0.8409
T33 0.3830	0.3216	T13 0.9633	0.9633
T44 0.4000	0.3390	T64 0.9776	0.8202
T55 0.3534	0.2319	T35 1.2697	1.0661
T66 0.3747	0.3144	T26 1.4131	0.7842

Table (6) shows the sensitivity analysis of the objective function coefficients, from this table one can see that there is no effect of the weights consideration since, if the coefficients change from zero to infinity the same optimal solution will result.

Table (6) Sensitivity analysis of objective coefficients due to single changes

Variable	Coefficient	Min coefficient	Max coefficient
TDS1	2.4150	-2.4498	infinity
TDS2	1.7280	-1.5520	infinity
TDS3	2.5488	0.0000	infinity
TDS4	2.5600	-2.1434	infinity
TDS5	1.7900	-1.1495	infinity
TDS6	2.0920	-2.3212	infinity

5.2 IEEE-14 bus test system example

The results for the IEEE 14-bus test system example are shown in Tables (7,8). Table (7) depicts maximum load current which each relay sees, and choice of the CT's based on both the maximum load and fault currents, pickup settings, and the optimal TDS.

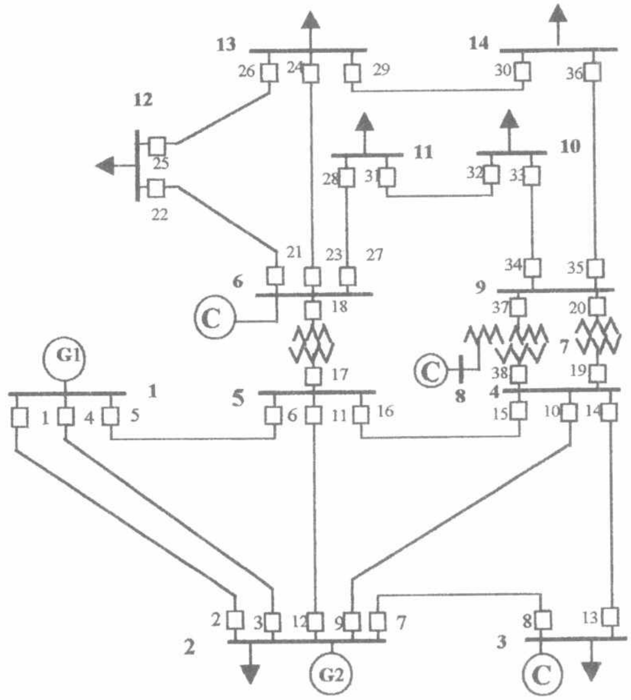

Fig. (5) IEEE 14-bus test system

The dash signal (-) in Table (7) refers that the relay which is insensitive in this direction of the current flow, in case of overload, and the directional unit will restrain the relay operation. This relay will be sensitive if the current inverses its direction, in case of fault current flow. In such a situation, the pickup current value is chosen at a minimum tap available (1 in this example).

5.3 Current transformer selection

The current transformer can be selected according to the maximum load current but it must not saturate at high fault currents. According to Ref. [12] the secondary current value of the CT must not overreach 20 times the selected CT current rating otherwise, the CT will be saturated and consequently, the protective relaying system will not operate, or operate improperly. Many researchers ignored this fact, but in this paper it is considered.

As an example consider relay 19 for which the maximum load current is 69.1 A. Accordingly, one may directly select a CT ratio at 100/5, but this selection is improper, because for a close-in 3-phase fault (3000 A), CT will be saturated and results in either no operation or improper operation of the protective device, so the CT ratio must be chosen at 200/5.

Table (7) Optimal settings of the relays for IEEE 14-bus test system

Relay NO.	Load Current, A	CT Ratio	Pickup (1-12)	TDS (0.05-1.1)
R1	326.3	400/5	6	0.0593
R2	-	200/5	1	0.1732
R3	-	200/5	1	0.1732
R4	326.3	400/5	6	0.0593
R5	312.2	300/5	8	0.0674
R6	-	200/5	1	0.1427
R7	306.6	300/5	8	0.1044
R8	-	100/5	1	0.2343
R9	235.2	300/5	6	0.1067
R10	-	200/5	1	0.1900
R11	-	200/5	1	0.1880
R12	173.7	200/5	7	0.1154
R13	-	100/5	1	0.4232
R14	104.4	200/5	4	0.1497
R15	-	100/5	1	0.4405
R16	272.7	300/5	7	0.1193
R17	196.8	200/5	7	0.1783
R18	-	200/5	1	0.3881
R19	69.1	200/5	2.5	0.2373
R20	-	300/5	1	0.2623
R21	133.6	400/5	2.5	0.3750
R22	-	100/5	1	0.2843
R23	312.8	400/5	6	0.3179
R24	-	100/5	1	0.5147
R25	29.4	200/5	1.2	0.4650
R26	-	300/5	1	0.3189
R27	132.8	400/5	2.5	0.4404
R28	-	200/5	1	0.5058
R29	97.9	300/5	2.5	0.4354
R30	-	200/5	1	0.4768
R31	67.8	200/5	2.5	0.4502
R32	-	300/5	1	0.5653
R33	-	100/5	1	0.5652
R34	112.3	300/5	3	0.5117
R35	167.7	400/5	3	0.3465
R36	-	100/5	1	0.6469
R37	-	200/5	1	0.3220
R38	127.2	200/5	4	0.2149

Table (8) shows the optimal backup/primary operating times of the relays for a close-in three-phase fault at different relay locations. It is good to notice that the maximum operating time of the primary and backup relay is less than 1 and 1.2 second, respectively.

Table (8) Backup/Primary operating times for IEEE 14-bus test system

Backup Relay no.	Time S	Primary Relay no.	Time S	Backup Relay no.	Time S	Primary Relay no.	Time S
3	0.4095	1	0.1900	18	0.7230	11	0.3091
6	0.3900	1	0.1900	5	0.7230	16	0.5230
2	0.4095	4	0.19	12	0.7230	16	0.5230
6	0.3900	4	0.1900	18	0.7230	16	0.5230
2	0.4095	5	0.2095	5	0.7230	17	0.5224
3	0.4095	5	0.2095	12	0.7230	17	0.5224
4	0.5470	2	0.2661	15	0.7224	17	0.5224
8	0.5126	2	0.2661	22	1.0645	18	0.5657
10	0.5470	2	0.2661	24	1.0645	18	0.5657
11	0.5470	2	0.2661	28	1.0110	18	0.5657
1	0.5470	3	0.2661	17	1.0645	21	0.7028
8	0.5126	3	0.2661	24	1.0645	21	0.7028
10	0.5470	3	0.2661	28	1.0110	21	0.7028
11	0.5470	3	0.2661	17	1.0645	27	0.8645
1	0.5470	7	0.3470	22	1.0645	27	0.8645
4	0.5470	7	0.3470	24	1.0645	27	0.8645
10	0.5470	7	0.3470	33	0.9183	20	0.3883
11	0.5470	7	0.3470	36	1.1943	20	0.3883
1	0.5470	9	0.3126	38	1.1943	20	0.3883
4	0.5470	9	0.3126	19	1.1943	34	0.9943
8	0.5126	9	0.3126	36	1.1943	34	0.9943
11	0.5470	9	0.3126	33	0.9183	35	0.7183
1	0.5470	12	0.3052	38	1.1943	34	0.9943
4	0.5470	12	0.3052	19	1.1943	35	0.7183
8	0.5126	12	0.3052	38	1.1943	35	0.7183
10	0.5470	12	0.3052	19	1.1943	37	0.4878
14	0.5722	8	0.3722	33	0.9183	37	0.4878
7	0.8594	13	0.6594	36	1.1943	37	0.4878
13	0.8539	10	0.3148	34	1.0927	32	0.8927
16	0.7104	10	0.3148	31	1.0489	33	0.8489
20	0.8539	10	0.3148	32	1.0318	28	0.8318
37	0.8539	10	0.3148	27	1.0822	31	0.8822
9	0.8539	14	0.3683	26	0.6170	22	0.4170
16	0.7104	14	0.3683	21	0.9747	25	0.7747
20	0.8539	14	0.3683	25	1.0671	24	0.7487
37	0.8539	14	0.3683	30	0.9487	24	0.7487
9	0.8539	15	0.6539	23	1.0671	26	0.4883
13	0.8539	15	0.6539	30	0.9487	26	0.4883
20	0.8539	15	0.6539	23	1.0671	29	0.8671
37	0.8539	15	0.6539	25	1.0671	29	0.8671
9	0.8539	19	0.4714	35	0.9613	30	0.7613
13	0.8539	19	0.4714	29	1.1641	36	0.9641
16	0.7104	19	0.4714	15	0.7224	11	0.3091
37	0.8539	19	0.4714	5	0.7230	11	0.3091
15	0.7224	6	0.2358	15	0.7224	6	0.2358
13	0.8539	38	0.5104	12	0.7230	6	0.2358
20	0.8539	38	0.5104	20	0.8539	38	0.5104

6. CONCLUSION

This paper presented an enhanced formulation of the overcurrent relays coordination. The proposed formulation depends on a predetermination of the pickup currents of the relays and then using the linear programming for optimal operating time determination. The insignificance of weight factors and far-end fault consideration in the problem formulation are proved. For preventing a miscoordination resulting from CT's saturation at high fault currents, CT's have been chosen based on both the maximum load and fault current.

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