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Optimal Coordination of Directional Overcurrent Relays Using Charalambous Least *p*th Algorithm

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In this paper, a new method for optimum coordination of directional overcurrent relays in interconnected multi-loop power systems is proposed. The method is based on Charalambous Least pth Algorithm. Normally the optimal directional overcurrent relay coordination problem is solved by using the Simplex Method of Linear Programming, which is a computationally intensive method. Considerable computational effort can be saved by using the proposed method. The method has been applied to solve the optimal coordination problem of IEEE 14-bus power system and IEEE 57-bus power system. A comparison of the Simplex Method and the Charalambous Method has been carried out for the determination of optimal settings of the relays of the systems under study.

1.0 INTRODUCTION

The role of directional overcurrent relays in a power system is to detect abnormalities by monitoring current flow in different parts of the system and to give commands to circuit breakers to isolate swiftly only the faulty components from the healthy system. A reliable protection scheme is vital to the stable operation of the system and the assurance of the customers' supply security. To safeguard against possible failures of the primary directional overcurrent relays, backup protection is required to prevent the system from suffering catastrophic consequences.

The directional overcurrent relays are placed strategically throughout a power transmission system. These relays operate in a coordinated manner. The relays have three settings, namely the Instantaneous Time Setting, the Time Multiplier Setting (TMS) and the Pick-up Current Settings (I_p). The instantaneous time setting of relays does not come into picture in the coordination process. The coordination of these relays is the process of determining the TMS and the I_p that provide an orderly shut-down, in case of a fault. In performing coordination, both the settings of all relays are found such that all Backup/Primary (B/P) relay pairs operate in a predefined manner. While obtaining the coordinated settings, the problem is formulated as a linear programming problem. The Simplex Method is used to solve for the optimal TMS for all relays. Considerable computational effort is involved in determining the optimal values of TMS. The paper reports the use of Charalambous Least *p*th Algorithm for obtaining the optimal values of TMS thereby saving considerable time and effort.

2.0 REVIEW OF OPTIMISATION METHODS

This section is devoted to the revision of concepts presented in the past on the subject of

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optimal relay coordination. An objective function is a necessary requirement for linear optimal coordination of directional overcurrent relays. The objective function can be the sum of the operating times of the relays for specified short circuit faults. Some of the objective functions previously used are given below [1]:

$$\text{Min } F1 = \sum_{i=1}^{N} \alpha_i T_{pi} \quad (1)$$

Where α_i is a positive coefficient and T_{pi} represents the time of operation of a primary relay.

$$\text{Min } F2 = \sum_{i=1}^{Nc} \alpha_i T_{pci} + \sum_{j=1}^{Nf} \beta_j T_{pfj} \quad (2)$$

Where T_{pci} is the time of operation of relay i when responding to a close-in fault; T_{pfj} is the time of operation of relay j when responding to a far-bus fault; α_i and β_j are the corresponding positive weights that reflect the priority of operation of a relay.

For determining B/P relay pairs, LINKNET, which is a linked list type of data structure, is used [2]. It stores information about nodes, branches and their directions in the network. The aim is to minimise the relevant objective function. Minimisation of the objective function is made by optimisation technique within some limitations called restrictions. Constraints are normally boundaries of currents and time settings, time interval between backup and primary relays, etc.

The operating time of the time-delay unit of a directional overcurrent relay is non-linear function of the relay settings and the current seen by the relay. Therefore, the optimal coordination problem is a non-linear optimisation problem. The relay pick-up currents are assumed to be previously defined.

3.0 THE PROBLEM FORMULATION

The optimal coordination problem can be stated so as to minimise a performance function subject to coordination criteria and limit on problem variables.

The performance function, F, is the summation of the primary operating times of the relays that would respond to the close-in fault currents and the summation of the primary operating times of the relays that would respond to the far-bus fault currents, i.e.:

$$F = \sum_{i=1}^{Nc} \alpha_i T_{pci} + \sum_{j=1}^{Nf} \beta_j T_{pfj} \quad (3)$$

The performance function is minimised subject to the following constraints:

$$T_{backup} - T_{primary} \geq CTI \quad (4)$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \quad (5)$$

CTI is the coordination time interval. It is the time lag in operation between a primary and its backup relay. The limits on TMS are also included as constraints.

The directional overcurrent is mathematically represented as:

$$T = K1 \ (TMS) \ / \ [(M)^{K2} + K3] \quad (6)$$

T is the time of operation of the relay, M is the multiple of pick-up current (I/I_p), I is the current seen by the relay and K1, K2, K3 are the constants of the relay.

For known values of I_p, equation (6) is written as:

$$T = K \ (TMS) \quad (7)$$

Equation (3) is written as:

$$F = \sum_{i=1}^{Nc} K_i \ (TMS_i) + \sum_{j=1}^{Nf} K_j (\ TMS_j) \quad (8)$$

Observation of equation (8) reveals that it would be a linear function in terms of TMS. Hence, this problem could be solved as a linear optimisation problem, subject to linear constraints. Therefore, the Simplex Method would be easily applicable.

4.0 THE PROPOSED METHOD

It has been observed that a major portion of the computational effort in solving the coordination problem of directional overcurrent relays of power networks is consumed by the optimal selection of TMS [2]. The optimal values of TMS are calculated by solving the linear programming problem using the Simplex Method. The problem can also be solved by using Charalambous least *p*th algorithm. Basically this algorithm is a part of the software package FLOPT5 which has been developed by Bandler and Sinha [3]. FLOPT5 was developed to solve minimax optimisation problems using the accelerated least *p*th algorithm. The main features of FLOPT5 include the following:

1. Fletcher's Quasi-Newton Algorithm
2. Least *p*th Objective Formulation Algorithm
3. Charalambous Least *p*th Algorithm

With appropriate utilisation of these features, the program can solve a wide variety of optimisation problems. These may range from unconstrained problems, problems subject to inequality/equality constraints to minimax problems in general. The same package has been utilised to solve the linear programming problem for determining the optimal values of TMS.

The operating time of relays is minimised by constituting the objective function, subject to the coordination criteria. The coordination criteria implement the coordination rules in the form of constraints. The coordination criteria depend upon the time lag in operation between the primary relay and its backup relays. A primary relay may have many backup relays in a multi-looped or meshed power system. A backup relay may also have many primary relays. In a medium sized interconnected power system, there may be thousands of Backup/Primary (B/P) relationships and all have to be satisfied. The proposed method is capable of satisfying all interdependent relationships and limits on directional overcurrent relay settings of individual relays irrespective of their role in the coordination strategy.

Formulation of the coordination problem as an optimisation problem suggests that the coordination criteria are supplied in the form of a constraint list. The generation of this constraint list depends upon the list of the Backup/Primary (B/P) relay pairs and the corresponding fault current pairs for every fault location. The Backup/Primary relay pairs are generated in any manner one likes. There is no need to have a specific order in which these could be generated. We can start from anywhere and there is no need to have a list of the starting relays. The reason is that, the coordination of the direction relays in an interconnected power system is achieved by simultaneously satisfying all the constraints. When all the constraints are treated simultaneously, the idea to go from one relay to another relay in order to coordinate them becomes unnecessary. Thus an elaborate and complex topological analysis is not required [4].

No database management packages are needed to manage huge data generated by the program. The method uses an efficient technique to generate, store and retrieve the data as per the requirements of the coordination [4]. Data generation, updating, retrieval and use are all combined in the same package.

The overall organisation of the FLOPT5 software package is depicted in Fig. 1.

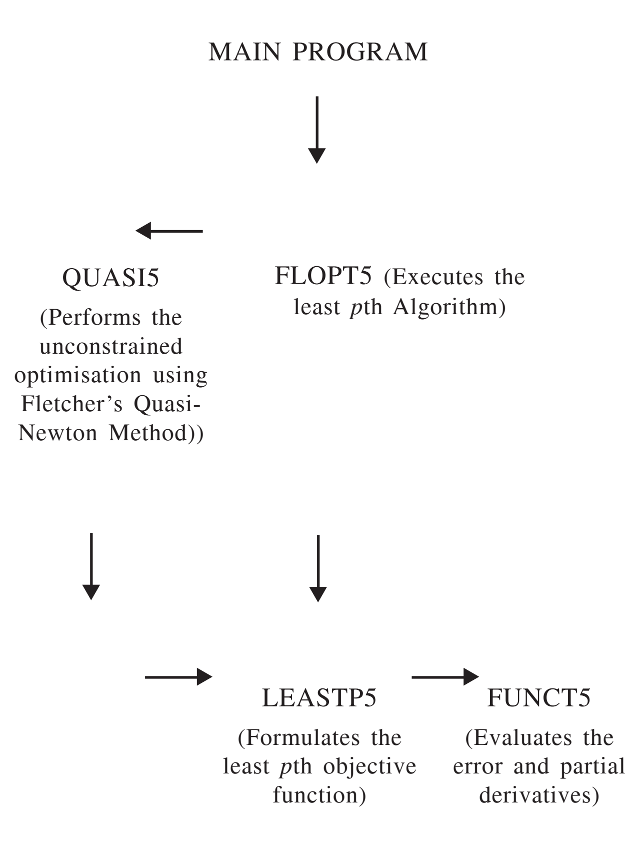

FIG. 1 OVERALL ORGANISATION OF FLOPT5 SOFTWARE PACKAGE

5.0 APPLICATION AND RESULTS

The algorithm explained in the paper was applied to determine the optimal TMS of relays of the systems namely; IEEE 14-bus power system (Fig. 2) and IEEE 57-bus power system (Fig. 3)

Both systems are complex and have interconnected loops. This multi-loop system generates many Backup/Primary relationships between its directional overcurrent relays. As is evident from the system data, the B/P relationships go into hundreds. Every relationship must be an active one. This ensures that the relays trip as planned for any fault in the system. The relay directionality will be a problem which cannot be tackled by this algorithm.

Table 1 depicts the relevant data about the systems studied.

TABLE 1

RELEVANT DATA

	IEEE 14-bus	IEEE 57-bus
No. of relays	40	156
Total No. of B/P relay pairs	184	680
Actual B/P pairs to be coordinated	149	593
Constraints for optimal determination of TMSs	229	905

K1 = 0.14, K2 = 0.02, K3 = –1.0 for an IDMT Relay Coordination Time Interval (CTI) = 0.3 sec

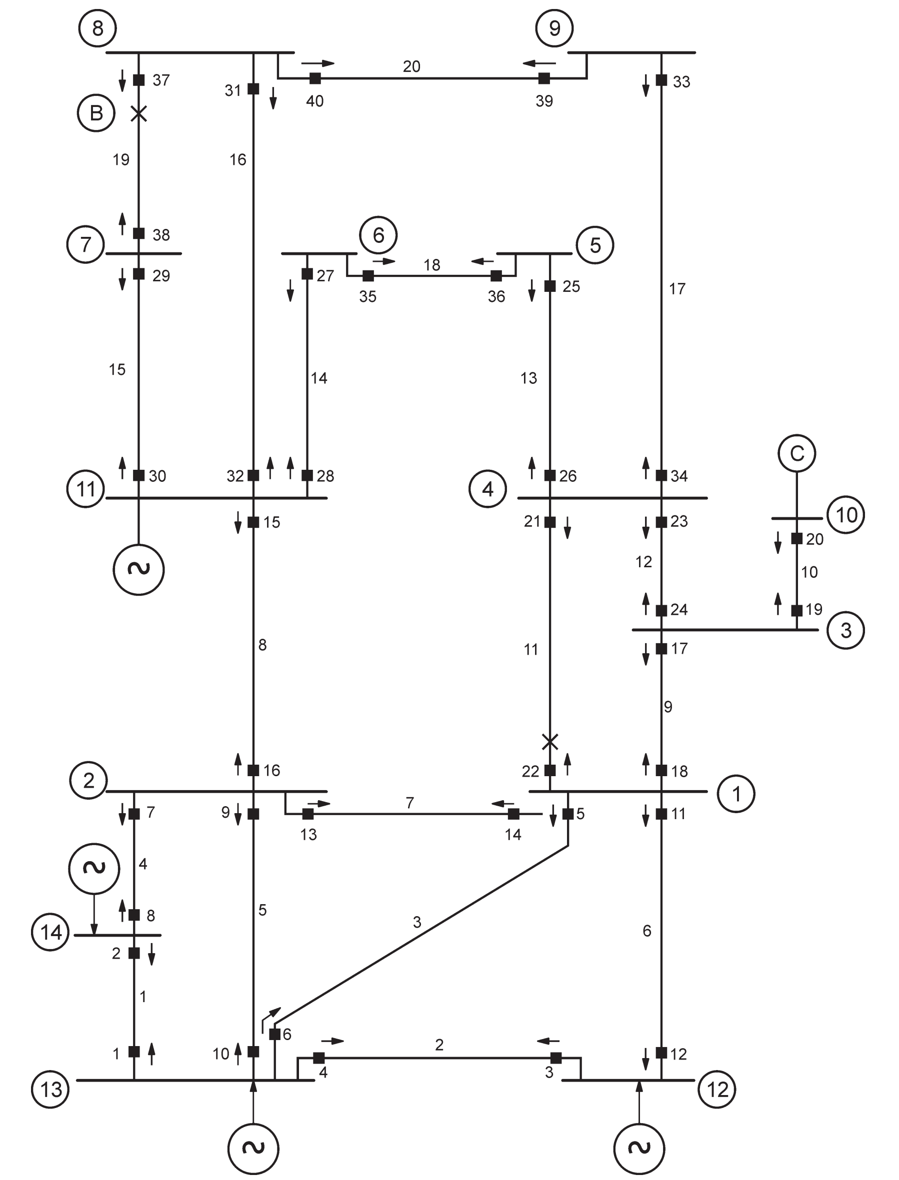

FIG. 2 IEEE 14-BUS POWER SYSTEM

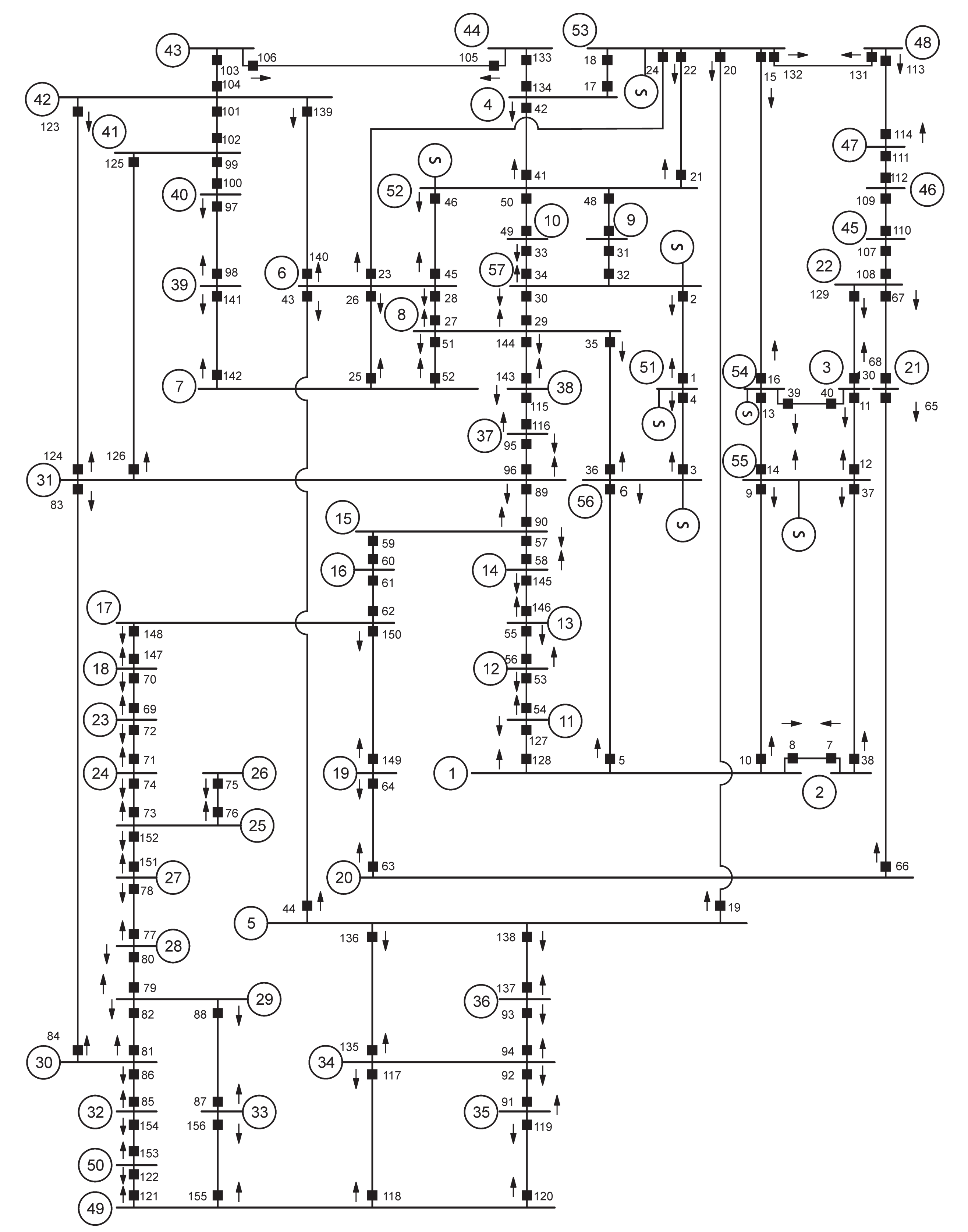

FIG. 3 IEEE 57-BUS POWER SYSTEM

The optimal TMS of the relays of the studied systems were determined by the Simplex Method as well as the Charalambous Algorithm. It was observed that there was a saving of 68.15% in the execution time in case of IEEE 14-bus power system and 76.76% in case of IEEE 57-bus power system, when Charalambous Algorithm was applied.

Table 2 gives the complete coordinated Time Multiplier Settings of the relays for IEEE 14-bus power system.

TABLE 2

COORDINATED TMS OF THE RELAYS OF IEEE 14-BUS SYSTEM

Relay	TMS(0.05 - 1.10)	Relay	TMS(0.05 - 1.10)
1	1.0	21	0.514
2	0.5	22	0.541
3	0.889	23	0.870
4	0.318	24	0.523
5	0.753	25	0.876
6	0.351	26	1.019
7	0.765	27	0.636
8	0.176	28	0.968
9	0.778	29	0.050
10	0.470	30	0.820
11	0.486	31	0.387
12	1.10	32	0.765
13	0.464	33	0.836
14	0.935	34	0.752
15	1.094	35	0.881
16	0.392	36	0.824
17	0.669	37	0.249
18	0.668	38	0.758
19	0.05	39	0.724
20	0.379	40	0.845

Table 3 gives the TMS values of some of the relays of the IEEE 57-bus power system obtained by using Simplex method and the Charalambous Least *p*th Algorithm. The comparison clearly shows the results are very close to each other. This method is superior as far as the execution time needed to calculate the time multiplier settings of relays is concerned. The computational effort needed is also less.

TABLE 3

COMPARISON OF THE METHODS

Relay	Simplex Method (TMS) (0.05 – 1.10)	Charalambous Algorithm (TMS) (0.05 – 1.10)
1	0.724	0.737
2	0.188	0.190
3	0.733	0.749
4	0.242	0.244
5	0.785	0.790
6	0.406	0.411
7	0.741	0.745
8	0.529	0.538
9	0.810	0.819
10	0.480	0.486
11	0.485	0.488
12	0.910	0.922
13	0.329	0.334
14	0.639	0.649
15	0.827	0.843
16	0.220	0.222
17	0.611	0.619
18	0.523	0.529
19	0.664	0.670
20	0.704	0.709
21	0.609	0.617
22	0.495	0.500
23	0.664	0.673
24	1.016	1.022
25	0.351	0.357
26	1.040	1.044
27	0.349	0.357
28	0.685	0.697
29	0.608	0.618
30	0.151	0.154
31	0.504	0.512
32	0.208	0.211
33	0.496	0.504
34	0.202	0.206
35	0.733	0.743
36	0.523	0.526
37	0.883	0.889

6.0 CONCLUSIONS

In this paper Charalambous Least *p*th Algorithm has been presented for optimal coordination of directional overcurrent relays. Comparison between the Simplex Method and the Charalambous Algorithm is made. It has been reported that the application of Charalambous Algorithm saves considerable computational effort and time.

7.0 REFERENCES

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