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Optimal Coordination Of Multiple Setting Group Type Overcurrent Relays

ABSTRACT

Relay coordination optimization issues are multi-objective, multi-constrained problems that aim to reduce each relay's operation time while satisfying all relevant constraints. Fulfillment of the coordination time interval (CTI) and time limitations for relay operations are the coordination constraints. To solve coordination optimization issues, decision-making variables are defined such that the objective function is minimized with due satisfaction of necessary constraints. The majority of the most recent research that is currently available defines relay coordination for fixed network topologies, but in practice, it varies for a variety of reasons, including maintenance and element failures. Over current relays now have the capability of storing multiple relay settings but the number of relay settings that can be stored in relays is far less than the possible number of network configurations, which is why a suitable clustering technique such as K-Means can be used to cluster out various network topologies using a proper clustering index. Because both the objective function and the constraints are time dependent, time dependent attributes such as average relay operating time are used as the clustering index instead of the conventional index fault current deviation.

Keywords: CTI, K-Means, DG, DOCR, GA, DIgSILENT

1. INTRODUCTION

With the introduction of Distribution Generation (DG), the distribution network has been transformed out of a passive to an active one. The emergence of DG into the distribution network provides numerous benefits whilst also posing several challenges. One of the major challenges is difficult relaying due to bidirectional current flow and changing fault current magnitude. Over current relays are commonly used to protect distribution systems. In order to ensure the reliability of the protection system, backup relays that are coordinated with the respective primary relays are deployed in addition to the primary relays. Relay coordination problems are addressed by defining two main decision variables: Time Multiplier Setting (TMS) and Plug Setting (PS). Shortcomings of time graded and current graded backed up protection systems are addressed by the introduction of the inverse time current characteristic. Both the operating time of the relay and the pickup current can be adjusted with the correct selection of decision variables. Relay coordination problems are addressed using either a linear programming method in which optimized values of TMS' are determined for fixed values of IPs or a nonlinear programming method in which both decision variables are kept free to take any value. For enhanced flexibility here nonlinear programming method is adopted to address relay coordination problem. Here, it is also assumed that each of the over current relays can store four different relay settings. The purpose of this research is to obtain optimized relay settings for various network topologies; however, activating the proper relay settings for a given network configuration is not within the scope of this work. The distribution portion of the IEEE 14 bus system is used as the test system for this work. 14 distinct topologies are defined using N-1 contingencies. Various network topologies are grouped into four clusters based on average relay operating time using the K-Means clustering algorithm. For all four clusters, one dedicated optimised relay setting is obtained, and CTI satisfaction is verified for all topologies within the same cluster. PowerFactory DIgSILENT software is used to simulate the test system, while MATLAB is used for clustering and optimization.

In [1], using the K-mean algorithm, various topologies formed with N-1 contingencies are clustered based on the magnitude of fault currents. The coordination problem is formulated using non-linear programming method. Hybrid water cycle-moth flame algorithm is used to optimize relay settings. The authors demonstrated the superiority of the proposed approach by comparing the results to those obtained by other optimization algorithms. In [2], authors clustered 14 topologies, but with different clustering indices. The clustering indices used in this study were time-dependent attributes. Another major difference was the method of problem formulation used. A different clustering algorithm K-medoids is used for clustering different network topologies in [3]. Pick up current has been used as the clustering index in the literature. Several limitations have been identified, including its suitability for smaller datasets and the requirement of using K-means to determine initial medoids. The work was focused on cluster formation rather than optimization. In [4], the performance of three different clustering methods, including K-Means, Self-organized mapping, and Hierarchical clustering, has been used. For appropriate clustering method selection, a separate heuristic adjustment is proposed. Authors compared results when all topologies are divided in two, three and four clusters. The research is further extended in [5], where Principle Component Analysis (PCA) is introduced to improve the performance of K-means algorithm. In [6], without any communication facility, the problem of restraining another backup protection on the operation of one backup protection is addressed. The authors proposed a Time Current Voltage (TCV) characteristic for conventional directional over current relay (DOCR), which was expanded for Dual setting DOCR that is having two separate relay settings for forward and reverse flow of fault current in [7]. In [8], authors proposed a voltage-current based time inverse relay model. The authors have taken into account the fact that the fault current magnitude alters the relay operating time and clustering is performed on the basis of DG penetration. Coordination problems discussed so far was addressed for DOCRs following

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standard relay characteristics. In [9], authors have obtained optimal relay coordination for standard relay characteristics and marked that the flexibility can be enhanced by making relay operating time constant as additional decision variables instead of considering them constant. Similar approach is imolemented in [10] to coordinate overcurrent relays with user defimed relay characterisitcs. [11] Also achieves relay coordination for user-defined relay characteristics, but the characteristics are modified by keeping the upper limit of the pickup current variable rather than fixed. In [12], the performance of problem formulation using linear programming and nonlinear programming methods is compared. Authors also compared performance of various optimization techniques and marked GA as better performing tool as compared to others. In [13], [14] authors presented a review on the evolution took place in the protection of the microgrid. Authors compared various adaptive protectiction system alogwith their benefits and shortcommings. In [15] authors addressed problem in relay coordination due to change of network configuration and variations in renewable generations. Authors implemented hybrid PSO-ILP algorithm and achieved relay coordination for multiple setting group type overcurrent relay. Number of coordination constraints increase drastically when multiple network topologies are considered for coordination. In [16], Authors proposed hybrid GA to optimize the objective function alongwith large number of coordination constraints. In [17], authors critically examined the upper bound of relay operating time and presented a review on various constraints for OCR coordination and their objective functions. Clustering of various network configurations are done using SOM technic in [18] and its performace is compared with k-means algorithm. Authors in [19] attained relay coordination for dual setting overcurrent relays with considering N-1 contingencies and for fundamental configuration. The problem of coordination is considered as MNLP problem in the literature. Similar work is presented in [20] for conventional overcurrent relays. In [21], authors obtained relay coordination using improved firefly algorithm. Self adaptive weight is proposed in order to obtain the best solution and reject the worst solution in the literature. In [22], authors defined relay coordination for a system containing dual setting Time Current Voltage overcurrent relays and Time Current Voltage overcurrent relays. It is shown in the literature that with the approach almost similar total relay operating time is resulted but with less overall coat of relaying. In [23], authors attained relay coordination considering uncertainities like simultaneous and single contingencies, islanded or grid connected operation of the network. Coodination defined using the approach showed in the literature is having less influence of operation of DOCRs. Three domains DG allocation, DG planning and protection are simultaneously combined in [24]. Authors defined DG citing and sizing such that it has lowest adverse impact on the protection system.

The vast majority of recent literature defines optimal relay coordination for fixed network topologies which change frequently for a variety of reasons, including maintenance. The literature that takes into account multiple network configurations groups various configurations based on the amount that the fault current deviates from the average value. With the incorporation of the nonlinear programming method of problem formulation, other time-dependent attributes like average relay operating time or CTI may be considered as more sensible clustering indices. To the best of the author's knowledge, there is no literature available that performs clustering based on time-dependent attributes and formulates problems using nonlinear programming.

2. RESEARCH METHOD

The distribution portion of IEEE 14 bus system is simulated in PowerFactory DIgSILENT software. Detailed parameters are available in [25]. The original test system consists of a synchronous based 10 MW generation at bus 06. To increase DG penetration, two synchronous-based 10MW generations are assumed to be connected at bus 13 and bus 09. Detailed generator parameters are described in [1]. Fig. 1 presents the test system, while Fig. 2 demonstrates the simulated test system. Considering N-1 contingencies, total 14 distinct network topologies are defined. Description of all defined topologies is mentioned in Table 1.

After simulating the test system, fault currents are estimated by simulating the fault at near ends. All near end faults are assumed to be three phase bolted faults occurring at 4%-line length from the relay. Near end fault currents are calculated for all fourteen defined topologies.

Table 1. Network Topologies

Topology	Element Taken Out	Topology	Element Taken Out
T-1	Line 6-12	T-8	Line 6-11
T-2	Line 12-13	T-9	None
T-3	Line 13-6	T-10	Generator at bus 13
T-4	Line 13-14	T-11	Generator at bus 9
T-5	Line 14-9	T-12	Generator at bus 6
T-6	Line 9-10	T-13	Utility
T-7	Line 10-11	T-14	All Generators

Considering the fact that there will be many more possible network topologies while using multiple setting group type overcurrent relays than the relay settings that can be stored in the relays, similar groups of topologies are to be clustered together, and one dedicated optimized relay settings should be defined for each cluster. Similar network topologies are clustered using the K-means algorithm, which is a very effective tool for gathering groups of data that are similar to same cluster’s data but distinct from data from other clusters. The K-means algorithm organizes data into clusters based on their

Euclidian distance from the cluster's centroid. The algorithm can discretize N-dimensional data into K clusters. Here 14 single-dimensional topologies are clustered in four clusters considering average relay operating time as the clustering index. Relay operating times are calculated by taking into account near end fault currents and assuming unity TMS. Values of pickup current are taken as per [2]. K-means algorithm execution results in the formation of four distinct clusters, as shown in Table 2. Clusters 1 and 2 can accommodate seven and five topologies, respectively, whereas clusters 3 and 4 can only accommodate one topology in each. The average relay operating time of all fourteen topologies ranges between 1.8518s and 2.2305s. In ascending order, the centroids of all four clusters are1.8508s, 1.9195s, 2.028s and 2.2305s.

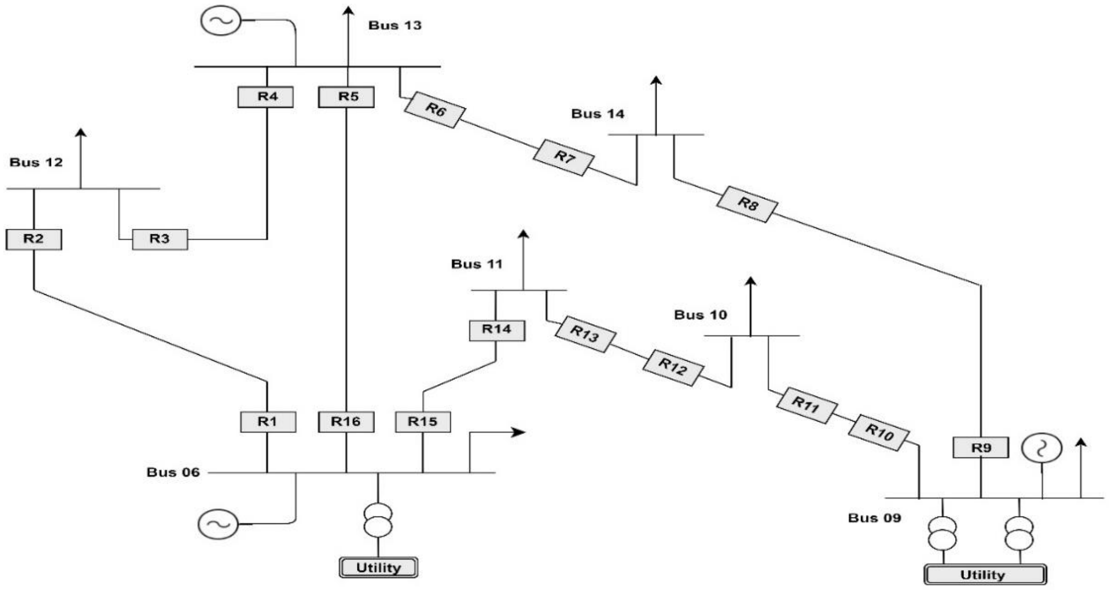

Figure 1. TEST SYSTEM

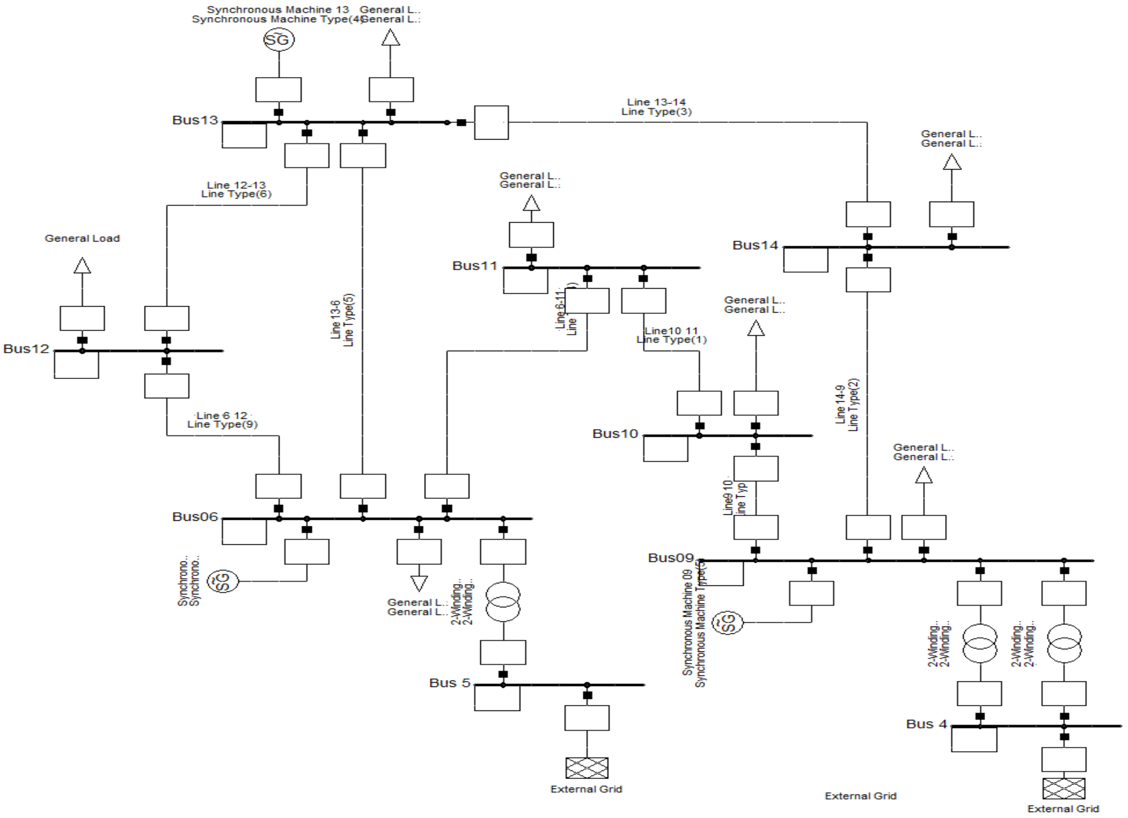

Figure 2. SIMULATED TEST SYSTEM

Table 2 CLUSTER FORMATIONS

Cluster-1	Cluster-2	Cluster-3	Cluster-4
T-1, T-2, T-4, T-5, T-7, T-8, T-9	T-3, T-6, T-11, T-12, T-13	T-10	T-14

Like all optimization problems, relay coordination optimization problems also require defining an objective function, determining bounds, and defining constraints. The MATLAB optimization toolbox's genetic algorithm (GA) is used to perform the optimization. The optimization problem is split in three subsections including Constructing Objective Function, Defining Bounds and Determining Constraints which are described below in detail. All the DOCRs used here assumed to be Standard Inverse DOCRs.

The objective function of the problem is formed by summing up all primary relay operating times which is to be minimized and shown by (1). The operating time of the overcurrent relay may be given by (2).

$$\text{O.F.} = \Sigma t_p;\ p=1,2,3,\ldots,16 \tag{1}$$

$$t_p = \text{TMS} * \frac{A}{(\frac{I_f}{I_p})^{B} - 1} \tag{2}$$

t_p represents operating time of p^{th} primary relay, whereas TMS, I_f and I_P represents Time Multiplier Setting, Fault Current and Pickup current of the relay, values of relay characteristic constants and their values according to IEC-60255 STD are shown in table 3.

Table 3 Values of Relay Characteristic Constants According to IEC-60255 STD

Relay Characteristic Curve	A	B
Standard Inverse (SI)	0.14	0.02
Very Inverse (VI)	13.5	1
Extremely Inverse (EI)	80	2

For this test system, 32 variables must be defined from the bounds-defined range as the minimization problem is solved using the nonlinear programming method. Sixteen variables are assumed for the TMS' of all sixteen relays and their bounds are specified by the manufacturers. Here, it is assumed that the relays will accept any TMS value between 0.05 and 1.1. Another sixteen variables are assumed for the pickup currents of all sixteen relays. Unlike TMS bounds, pickup current bounds of each relay must be calculated separately. The lower bound of pickup current is determined by rated current, while the upper bound is determined by short circuit current. Lower bounds are set at 1.5 times the rated current, and upper bounds are set at 66% of the minimum short circuit current. The lower and upper bounds are mathematically expressed in (4) and (5), respectively. Pickup Currents for all sixteen relays must be chosen from the range described in (6).

$$0.05 <= \text{TMS}_p <= 1.1;\ p = 1,2,3,\ldots,16 \tag{3}$$

$$I_{Pminp} = 1.5\ I_{Lp};\ p = 1,2,3,\ldots,16 \tag{4}$$

$$I_{Pmaxp} = 2/3\ I_{SCp};\ p = 1,2,3,\ldots,16 \tag{5}$$

$$I_{Pminp} < = I_{Pp} < = I_{Pmaxp};\ p = 1,2,3,\ldots,16 \tag{6}$$

I_{Lp} and I_{SCp} represents rated current and short circuit current passing through p^{th} relay, while, I_{Pminp} and I_{Pmaxp} represents lower and upper pickup current limits of p^{th} relay.

Coordination Time Interval (CTI) and relay operating time boundaries are two constraints that must be considered while optimizing relay coordination. In the event of a fault, the primary relay must detect the fault and should initiate a trip signal to the associated circuit breaker. If the primary relay fails to operate in an unusual circumstance, the backup relay should come into play after a certain amount of time known as CTI. Each primary-backup relay pair must comply to the CTI, which varies from 0.2 to 0.5s. Here, it is assumed that each primary-secondary relay pair will maintain a CTI of 0.2 seconds. Satisfaction of CTI is to be checked for 22 identified primary-backup relay pairs as shown mathematically in (7). Maintaining each relay's operating time within the predetermined limits is another constraint that needs to be addressed. It is assumed that all primary relays operate within the range of 0.05 to 1s and it is shown mathematically in (8).

$$t_{bi} - t_{pi} >= 0.2;\ i = 1,2,3,\ldots,22 \tag{7}$$

$$0.05 < = t_p < = 1;\ p= 1,2,3,...,16 \tag{8}$$

t_{bi} and t_{pi} represents operating times of backup and primary relays of i^{th} pair. Here it is ranging from 1 to 22 identified relay pairs.

Once optimized relay settings are obtained, satisfaction of all required constraints for each primary-backup relay pair must be verified. In some clusters, optimized relay settings are defined for more than one topology, and in those cases, optimally defined relay settings must satisfy CTI constraints for all topologies in the same cluster. Clusters 1 and 2 accommodate seven and five topologies, respectively, and CTI satisfaction is verified for those clusters. Table 4 shows the verification of CTI satisfaction for topology T-10. Table 4 shows that no CTI violation occurs and that the relay operation time remains within the defined limits. For topologyT-10, the objective function value comes out to be 4.4809s.

3. RESULTS AND DISCUSSION

The described approach yields optimized relay settings for all fourteen network topologies, which are divided into four clusters. The relay settings defined for clusters 1 and 2 are validated for each topology of the same cluster, and the CTI constraint is validated. Table 4 shows that the lowest CTI observed is 0.2010s, which is the CTI between R6 and R16 and is greater than 0.2s. The highest observed CTI value is 0.3229s between R4 and R7. The minimum and maximum primary relay operating time noticed is for R5 and R10 respectively and found within its limits. The objective function for all four clusters is described in table 5. Cluster 1 has the lowest objective function value of 3.6500s, while Cluster 4 has the highest objective function value of 5.0820s. The sum of the objective functions of all four clusters is 18.2867s.

4. CONCLUSION

The test system under consideration is protected by multiple setting group type DOCRs. The method allows for network topology changes and defines optimal relay settings for a wide range of possible configurations. Taking into account N-1 contingencies, 14 network topologies are defined and grouped into four clusters using the K-means algorithm. Because the clustering index is a time-dependent attribute, the clustering of various topologies is done more effectively. For each of the four clusters, optimized relay settings are defined. When defined relay settings are applied to the relays, the fulfilment of necessary constraints, such as CTI and relay operating time limits, are verified. The elimination of online relay setting calculations is the primary benefit of the proposed approach, which eliminates the risk of applying incorrect relay settings. Another advantage of the proposed approach is that it reduces data traffic on communication lines by transmitting only the serial number of previously saved settings over communication lines. Local substations can recognize the network topology and corresponding relay settings can be activated without involving the control center.

Table 4 Constraint Validation For Cluster 3 Topology T-10

Cluster 3												
Primary Relay						**Backup Relay**						**CTI**
Relay	**CTR**	**F.Current**	**TMS**	**IP**	**Op Time**	**Relay**	**CTR**	**F.Current**	**TMS**	**IP**	**Op Time**	
1	300	17241	0.1416	648.2	0.2923	5	320	982	0.1020	291	0.5797	0.2874
1	300	17241	0.1416	648.2	0.2923	14	160	2371	0.0500	1180.3	0.4983	0.2059
2	100	4149	0.2112	16.5	0.2529	4	300	4149	0.0738	1347.7	0.4540	0.2011
3	100	4321	0.1835	82.303	0.3117	1	300	4321	0.1416	648.2	0.5127	0.2010
4	300	15403	0.0738	1347.7	0.2068	16	400	4884	0.1204	802.08	0.4582	0.2513
4	300	15403	0.0738	1347.7	0.2068	7	120	1810	0.0501	938.02	0.5297	0.3229
5	320	12304	0.1020	291	0.1836	3	100	1185	0.1835	82.303	0.4690	0.2854
5	320	12304	0.1020	291	0.1836	7	120	2062	0.0501	938.02	0.4414	0.2579
6	250	14403	0.1126	768.48	0.2610	16	400	4812	0.1204	802.08	0.4620	0.2010
6	250	14403	0.1126	768.48	0.2610	3	100	1232	0.1835	82.303	0.4620	0.2010
7	120	4447	0.0501	938.02	0.2217	9	300	4447	0.0889	1042.1	0.4229	0.2012
8	150	3628	0.0500	1139.7	0.2988	6	250	3628	0.1126	768.48	0.4998	0.2010
9	300	15228	0.0889	1042.1	0.2260	11	200	2424	0.0900	566.95	0.4272	0.2012
10	400	15692	0.1630	960.01	0.3972	8	150	2039	0.0500	1139.7	0.5982	0.2010
11	200	3332	0.0900	566.95	0.3493	13	200	3332	0.0825	1179.2	0.5503	0.2010
12	300	8840	0.0885	1181.3	0.3016	10	400	8840	0.1630	960.01	0.5027	0.2012
13	200	5573	0.0825	1179.2	0.3662	15	400	5573	0.0885	1892.5	0.5673	0.2012
14	160	4436	0.0500	1180.3	0.2609	12	300	4436	0.0885	1181.3	0.4619	0.2010
15	400	15898	0.0885	1892.5	0.2849	5	320	1236	0.1020	291	0.4864	0.2015
15	400	15898	0.0885	1892.5	0.2849	2	100	316	0.2112	16.5	0.4860	0.2012
16	400	17293	0.1204	802.08	0.2661	14	160	2483	0.0500	1180.3	0.4671	0.2010
16	400	17293	0.1204	802.08	0.2661	2	100	203	0.2112	16.5	0.5743	0.3082
Total Primary Relay Operating Time:					**4.4808914**							

Table 5 Objective Function For All Clusters

Cluster	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Total**
Objective Function	3.6500	5.0738	4.48089	5.0820	18.2867

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