International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 13, Number 12 (2020), pp. 4206-4210
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Optimal Protection Coordination in Microgrids using a Hierarchical Clustering Algorithm

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Abstract

This paper presents a hierarchical clustering algorithm approach to the optimal coordination of directional overcurrent relays (OCRs) in microgrids. The proposed approach takes advantage of the fact that modern OCRs are able to consider multiple setting groups; therefore a clustering analysis of the microgrid is performed to take into account multiple operational modes. Since the number of available setting groups is lower than the number of possible operational modes of the microgrid, the unsupervised learning technique known as hierarchical clustering algorithm was implemented to determine a number of clusters equal to the number of setting groups. Once the clustering is performed, the optimal settings of the OCRs are obtained by means of a genetic algorithm (GA). Several tests are performed on a benchmark IEC microgrid evidencing the robustness and applicability of the proposed approach.

Keywords – Hierarchical clustering, protection coordination, microgrids, operative scenarios, unsupervised learning techniques.

I. INTRODUCTION

Protection against failures is of paramount importance in the planning and operation of distribution systems. A proper protection coordination scheme must be able to isolate a portion of the system when a fault takes place and avoid unnecessary disconnection in areas that are not affected by the fault [1]. In this sense, a protection scheme must guarantee the fast tripping of the main relay, and in the event that it fails, it must be backed up by another protective device. The radial topology of traditional distribution systems facilitates their protection coordination since power flows are unidirectional. Nonetheless, the increasing participation of distributed generation (DG) in modern distribution networks (DNs) has brought along new challenges in the protection coordination problem. DG can be defined as small-scale generation allocated in the distribution system or near the end user, and is mainly based on renewable resources [2], [3]. The introduction of this type of generation changes the topology of the network as well as the magnitude and direction of short-circuits, making the protection coordination a challenging task.

The advent and increasing popularity of microgrids that are used to integrate DG as well as other distributed energy resources (DERs) in distribution networks has also brought a change in paradigm in the protection coordination problem [4]. One of the most distinctive features of a microgrid is the fact that it can operate in grid-connected or islanded mode. In the former operation mode the microgrid exchanges power with the main grid; while in the later one, the demand is supplied by the DG units located within the microgrid. This last feature increases the security of the network, since if any disturbance occurs in the main grid the microgrid is able to change the operation into insolated mode providing uninterrupted power to at least some of the main loads.

The implementation of microgrids brings along important protection challenges related to bidirectional power flows due to the presence of DERs, and the dynamic operational modes of the microgrid. Several studies have been conducted regarding the protection coordination of microgrids. In [5], a particle swarm optimization (PSO) algorithm is implemented to ensure the proper coordination of microgrids. PSO is an optimization procedure based on the behavior of fish schools and bird flocks. This methodology was also implemented in [6] considering a multi-objective approach. In [7], single contingencies are included in the protection coordination scheme. The authors in [8] proposed a novel metaheuristic approach known as IWO (Invasive Weed Optimization) to solve the coordination problem in microgrids with participation of DG. In [9], the authors proposed a TLBO (Teaching Learning-Based Optimization) approach for coordination of overcurrent relays with the aim of reducing the incidence of nuisance tripping in network topology changes.

In [10], the authors proposed a setting group-based adaptive protection approach to consider multiple operative scenarios that result from connecting and disconnecting DG of a microgrid. The setting groups are limited according to the capabilities of commercial relays. In [11], the authors take advantage of the feature that allows saving multiple setting groups within digital OCRs to adapt such settings to the current topology of the network; based on this research, the authors in [12] developed a technique for OCRs coordination using a Self-Organizing Map clustering algorithm.

In this paper, we propose a novel protection coordination of OCRs in microgrids based on the works presented in [10], [11] and [12]. In this case, the number of setting groups is limited to the capabilities of commercial relays. Therefore, the proposed approach adopts a machine learning technique to intelligently group operational modes according to the groups available in commercial relays. Several tests are performed on an IEC microgrid that features 16 operational modes on which 4 setting groups are considered.

The rest of the document is structured as follows: Section II presents the mathematical formulation of the coordination problem. Section III describes the proposed methodology. Section IV presents the tests and results; finally conclusions are presented in Section V.

II. MATHEMATICAL FORMULATION

The objective function of the optimal coordination problem consists on minimizing the operation time of the OCRs as indicated in equation (1). In this case, t_{if} is the operation time of relay *i* when fault *f* takes place, while *m* and n are the number of relays and faults, respectively.

$$min\sum_{i=1}^{m}\sum_{f=1}^{n}t_{if} \tag{1}$$

The objective function given by (1) is subject to a set of constraints as described by equations (2) - (8). Equation (2) corresponds to the coordination criterion. This indicates that the back up relay must actuate after the main relay with a margin of time known as CTI (coordination time interval). In this case, t_{if} and t_{jf} are the operation time of main and back relays, respectively.

$$t_{if} - t_{ij} \geq CTI \tag{2}$$

Equation (3) describes the relay characteristic. In this case, A and B are constant parameters of the relay curve, TMS_i is the time multiplying setting of relay *i*, I_{fi} is the fault current and $ipickup_i$ is the pickup current.

$$t_{if} = \frac{A.TMS_i}{(\frac{I_{fi}}{ipickup_i})^B - 1} \tag{3}$$

Equations (4)-(7) indicate the lower and upper limits of the operation time, time setting multiplying, pickup current and number of setting groups (SG_i), respectively.

$$t_{imin} \leq t_{if} \leq t_{imax} \tag{4}$$

$$TMS_{imin} \leq TMS_i \leq TMS_{imax} \tag{5}$$

$$ipickup_{imin} \leq ipickup_i \leq ipickup_{imax} \tag{6}$$

$$SG_{imin} \leq SG_i \leq SG_{imax} \tag{7}$$

III. METHODOLOGY

3.1 Hierarchical clustering

Hierarchical clustering is an unsupervised learning technique that groups similar objects into clusters. Hierarchical clustering algorithms permit to identify homogeneous groups of data location from a similarity matrix. Finding the hierarchical structure involves calculating the distance between each pair of points and then use these distances to join pairs of points [13]. These algorithms perform the clustering in a bottom-up fashion. Each sample starts with its own group, and then the two more similar groups are combined into a new larger group until all samples are joined together.

Figure 1 illustrates an example of hierarchical clustering. In this case, six elements are allocated in a square. The first two elements that are combined to form a cluster are 5 and 6. This is done by computing the distance based on the length of a straight line drawn from one element to another, which is commonly referred as the Euclidean distance (however other distance metrics can be used). The closest element to the new set formed by 5 and 6 is 4; then elements 4, 5 and 6 form a new cluster. The process continues until all elements are grouped together as indicated in the dendogram.

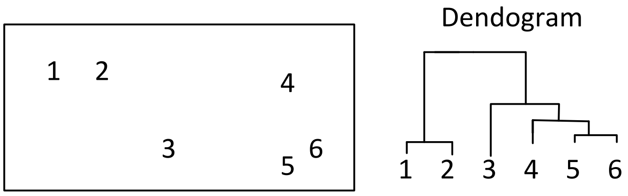

Figure 1. Illustration of hierarchical clustering

In this research, we used the Single, Complete and Ward methods to compute the distances as indicated by Equations (8) to (10), respectively. In the single method, the distance d_{ij} between groups g_i and g_j corresponds to the minimum distance between two points x and y belonging to groups g_i and g_j, respectively. The same is applicable for the Complete method but considering the maximum distance. In the Ward method the total variance between the group is minimized. At each step groups g_i and g_j with a minimum distance d_{ij} merge, A pair of groups is found that yields a minimal increasing of the total variance within the group after fusion.

$$d_{ij} = min_{x\in g_i, y\in g_j} d(x,y) \tag{8}$$

$$d_{ij} = max_{x\in g_i, y\in g_j} d(x,y) \tag{9}$$

$$d_{ij} = \left\|x_i - y_j\right\|^2 \tag{10}$$

3.2 Proposed approach

This section describes the proposed approach for the optimal coordination problem. Initially, the microgrid under study is modeled in DigSilent Power Factory and several simulations are performed to characterize its behavior. This step is performed to obtain information regarding the short-circuit currents seen by the relays for a set of operational modes and faults. A cluster analysis is then performed with this information. Then, the optimal coordination of OCRs is carried out for each of the clusters obtained. A conventional GA is used in this step. Figure 2 depicts the flowchart of the proposed methodology.

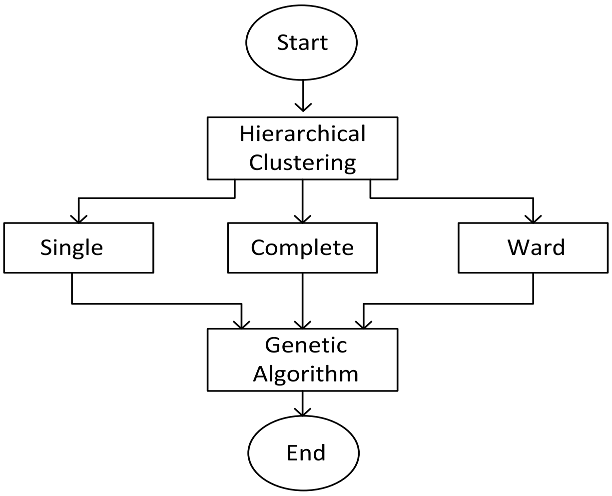

Figure 2. Clustering and OCR coordination

V. TESTS AND RESULTS

To show the applicability of the proposed approach several tests are carried out on the IEC microgrid depicted in Figure 3.

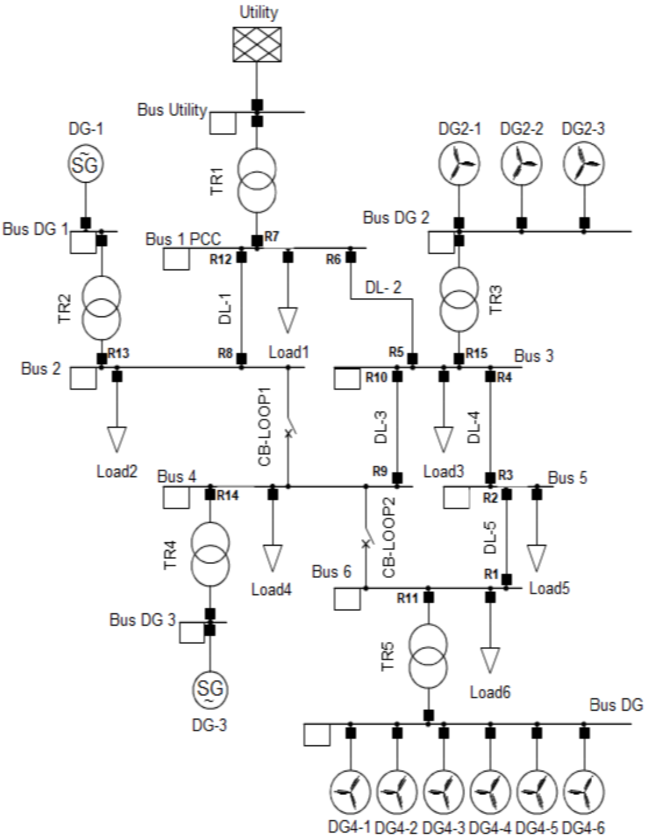

Figure 3. Benchmark IEC microgrid

The parameters of this system can be consulted in [14] while the characteristics of the protection scheme can be found in [15]. In this case, 16 operational modes (OMs) are considered. Such OMs are obtained by different generation and topological conditions that arise by modifying the states of switches CB-1 and CB-2, as well as the fact that the microgrid may operate in grid-connected and islanded modes.

All relays are labeled with number preceded by the letter R, as indicated in Figure 3. A coordination time interval (CTI) of 0.3 seconds is considered to guarantee the enforcement of the constraint given by Equation (2). Also, normally inverse IEC characteristic curves are used for all OCRs. Also a maximum of 4 setting groups is considered for all relays and the failures were considered in the lines of the microgrid.

Table 1. Description of operational modes

Operative Mode	DG1-DG2	DG3-DG4	Grid	CB1	CB2
OM1	OFF	OFF	ON	OPEN	OPEN
OM2	ON	ON	ON	OPEN	OPEN
OM3	ON	OFF	ON	OPEN	OPEN
OM4	ON	ON	OFF	OPEN	OPEN
OM5	OFF	OFF	ON	CLOSE	CLOSE
OM6	ON	ON	ON	CLOSE	CLOSE
OM7	ON	OFF	ON	CLOSE	CLOSE
OM8	ON	ON	OFF	CLOSE	CLOSE
OM9	OFF	OFF	ON	CLOSE	OPEN
OM10	ON	ON	ON	CLOSE	OPEN
OM11	ON	OFF	ON	CLOSE	OPEN
OM12	ON	ON	OFF	CLOSE	OPEN
OM13	OFF	OFF	ON	OPEN	CLOSE
OM14	ON	ON	ON	OPEN	CLOSE
OM15	ON	OFF	ON	OPEN	CLOSE
OM16	ON	ON	OFF	OPEN	CLOSE

For comparative purposes, the coordination problem was initially solved without clustering. In this case, the operation time was 724.8052 seconds with violation of 13 constraints regarding the CTI, which is not admissible. Then, a Hierarchical clustering was performed considering the Single, Complete and Ward Methods. The results are presented in Tables 2 and 3. Note that the Single and Complete methods achieved the same results presented in Table 2. In this case, there are still two violations of the CTI and a total operation time of 469.3726, which corresponds an improvement when compared with the test without clustering. When the Ward method is applied, a new clustering is reached. In this case, only one violation of the CTI is obtained and the total operation time is 474.2702. Despite of the fact of having one violation of the CTI, these results are promising, since a fine tuning may be applied latter to eliminate such violation. This would not be possible in the case without clustering that features 13 violations and a considerably higher operational time.

Table 2. Results using the Single and Complete methods

Cluster	Operational Modes	Operation Time	CTI violations
1	OM4 – OM8 – OM12 – OM16	109.1561	0
2	OM1 – OM2 - OM3 –OM13 – OM14 - OM15	127.4997	1
3	OM5 – OM7 - OM9 – OM10 - OM11	202.0690	1
4	OM6	30.6478	0
Total Time		469.3726	2

Table 3. Results using the Ward method

Cluster	Operational Modes	Operation Time	CTI violations
1	OM4 – OM8 – OM12 – OM16	109.1561	0
2	OM1 – OM3 –OM13 – OM15	58.0175	0
3	OM5 – OM7 - OM9 –OM11	145.1465	1
4	OM2 – OM6 - OM10 OM14	161.9506	0
Total Time		474.2702	1

IV. CONCLUSIONS

Protection coordination of modern distribution networks has become increasingly complex due to the presence of DG and microgrids. Since microgrids are able to operate in grid-connected and islanded modes, and may have different operational topologies, traditional approaches for OCRs coordination are rendered inefficient. This paper proposes a novel approach that takes advantage of digital OCRs that feature several setting groups. The main contribution consist on applying clustering analysis to the different operational modes of a microgrid to then classify a number of clusters equal to the number of setting groups of OCRs. Then a GA is used to perform the protection coordination of each group. Promising results are found after several tests performed on a benchmark IEC microgrid evidencing the applicability of the proposed approach.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Colombia Scientific Program within the framework of the call *Ecosistema Científico* (Contract No. FP44842- 218-2018). The authors also want to acknowledge Universidad de Antioquia for its support through the project *Estrategia de Sostenibilidad.*

REFERENCES

[1] M. N. Alam, “Adaptive Protection Coordination Scheme Using Numerical Directional Overcurrent Relays,” *IEEE Trans. Ind. Inform.*, vol. 15, no. 1, pp. 64–73, Jan. 2019, doi: 10.1109/TII.2018.2834474.

[2] M. Bazrafshan, L. Yalamanchili, N. Gatsis, and J. Gomez, “Stochastic Planning of Distributed PV Generation,” *Energies*, vol. 12, no. 3, p. 459, Jan. 2019, doi: 10.3390/en12030459.

[3] F. S. Abu-Mouti and M. E. El-Hawary, “Optimal Distributed Generation Allocation and Sizing in Distribution Systems via Artificial Bee Colony Algorithm,” *IEEE Trans. Power Deliv.*, vol. 26, no. 4, pp. 2090–2101, Oct. 2011, doi: 10.1109/TPWRD.2011.2158246.

[4] Z. Chen, Q. Liu, X. Xiao, N. Liu, and X. Yan, “Integrated mode and key issues of renewable energy sources and electric vehicles’ charging and discharging facilities in microgrid,” in *2nd IET Renewable Power Generation Conference (RPG 2013)*, Sep. 2013, pp. 1–4, doi: 10.1049/cp.2013.1759.

[5] Y. Damchi, H. R. Mashhadi, J. Sadeh, and M. Bashir, “Optimal coordination of directional overcurrent relays in a microgrid system using a hybrid particle swarm optimization,” in *2011 International Conference on Advanced Power System Automation and Protection*, Oct. 2011, vol. 2, pp. 1135–1138, doi: 10.1109/APAP.2011.6180976.

[6] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, “MOPSO/FDMT-based Pareto-optimal solution for coordination of overcurrent relays in interconnected networks and multi-DER microgrids,” *Transm. Distrib. IET Gener.*, vol. 12, no. 12, pp. 2871–2886, 2018, doi: 10.1049/iet-gtd.2018.0079.

[7] K. A. Saleh, H. H. Zeineldin, and E. F. El-Saadany, “Optimal Protection Coordination for Microgrids Considering N $-$1 Contingency,” *IEEE Trans. Ind. Inform.*, vol. 13, no. 5, pp. 2270–2278, Oct. 2017, doi: 10.1109/TII.2017.2682101.

[8] S. T. P. Srinivas and K. S. Swarup, “Optimal Protection Coordination for Microgrid Considering DG and Line Outages Using IWO-ILP Technique,” in *2018 20th National Power Systems Conference (NPSC)*, Dec. 2018, pp. 1–6, doi: 10.1109/NPSC.2018.8771734.

[9] P. Ray, D. P. Mishra, and S. R. Arya, “An Intelligent Approach for Protection Coordination of Overcurrent Relay in Smartgrid,” in *2019 IEEE 1st International Conference on Energy, Systems and Information Processing (ICESIP)*, Jul. 2019, pp. 1–6, doi: 10.1109/ICESIP46348.2019.8938354.

[10] A. Samadi and R. Mohammadi Chabanloo, “Adaptive coordination of overcurrent relays in active distribution networks based on independent change of relays’ setting groups,” *Int. J. Electr. Power Energy Syst.*, vol. 120, p. 106026, Sep. 2020, doi: 10.1016/j.ijepes.2020.106026.

[11] M. Ojaghi and V. Mohammadi, “Use of Clustering to Reduce the Number of Different Setting Groups for Adaptive Coordination of Overcurrent Relays,” *IEEE Trans. Power Deliv.*, vol. 33, no. 3, pp. 1204–1212, Jun. 2018, doi: 10.1109/TPWRD.2017.2749321.

[12] S. M. E. Ghadiri and K. Mazlumi, “Adaptive protection scheme for microgrids based on SOM clustering technique,” *Appl. Soft Comput.*, vol. 88, p. 106062, Mar. 2020, doi: 10.1016/j.asoc.2020.106062.

[13] Z. Nazari, D. Kang, M. R. Asharif, Y. Sung, and S. Ogawa, “A new hierarchical clustering algorithm,” in *2015 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)*, Nov. 2015, pp. 148–152, doi: 10.1109/ICIIBMS.2015.7439517.

[14] S. Kar, S. R. Samantaray, and M. D. Zadeh, “Data-Mining Model Based Intelligent Differential Microgrid Protection Scheme,” *IEEE Syst. J.*, vol. 11, no. 2, pp. 1161–1169, Jun. 2017, doi: 10.1109/JSYST.2014.2380432.

[15] S. M. Saad, N. El-Naily, and F. A. Mohamed, “A new constraint considering maximum PSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes,” *Sustain. Cities Soc.*, vol. 44, pp. 445–457, Jan. 2019, doi: 10.1016/j.scs.2018.09.030.