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Multi-Objective Optimization of Electrical Distribution Network Operation Considering Reconfiguration and Soft Open Points

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Abstract

High penetration levels of Distributed Generations (DG) significantly affect the operations of electrical distribution networks. In this paper, Distribution Network Reconfiguration (DNR), and the implementation of Soft Open Point (SOP) – a distribution-level power electronic device are investigated as effective solutions to facilitate large DG penetrations while meeting network operational constraints. DNR is developed based on the ant colony optimization, and the optimal SOP outputs are determined using the Taxi-cab algorithm after determining the network configuration. Both optimization problems are formulated within a multi-objective framework using the Pareto optimality. The performances of DNR and SOP to improve network operations are demonstrated on a modified 33-bus distribution system with various DG penetrations.

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Keywords: Distribution Network Reconfiguration (DNR); Soft Open Points (SOP); Distributed Generation (DG); Pareto optimality

1. Introduction

Distribution Network Reconfiguration (DNR) is the process of altering the topology of an electrical distribution network by changing switch status (open/close), thus redirects power flows within the network, in order to achieve certain objectives while satisfying network operational constraints.

DNR is a mixed-integer, non-linear optimization problem [1]. Although in theory a global optimal configuration can be obtained by enumerating all feasible solutions and choosing the one which meets the objective best, simple exhaustive searches are rarely sufficient for the complicated real DNR applications.

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There are solutions using heuristic algorithms to eliminate choices that are unlikely to lead to good configurations. In [2], a branch and bound type heuristic method is presented. Although this method is rapid in determining a configuration which reduces the power losses, it considers only one pair of switching operations at a time. The result highly depends on initial switch states. A power flow method-based heuristic algorithm is proposed in [3]. However, this method is only suitable for small systems and becomes prohibitive when handling large distribution networks.

There are also DNR approaches based on artificial intelligence, which often incorporates with metaheuristics. In [4], a particle swarm optimization method is proposed to maximize the power system reliability while minimizing the power losses. A harmony search algorithm for DNR problems with the objectives of improving voltage profiles and minimizing real power losses is proposed in [5]. Compared to heuristic algorithms, metaheuristics are able to handle large-system and multi-objective optimization problems. Furthermore, they are problem-independent so that can be applied to different networks.

A number of literatures formulate the reconfiguration problem as multi-objective. In [6], a simultaneous reconfiguration optimization method is proposed by aggregating all the objectives into one and considering different weighting factors. In [7], a fuzzy satisfaction method is used. It considers the desired objective value as a priori, which is hardly feasible in practice. In this paper, the Pareto optimality, which provides a set of diverse solutions representing trade-offs between different objectives is used. The objectives focused on are power loss reduction, load balance and DG penetration level increase.

An alternative solution to redirect power flows without changing the network topology is the implementation of Soft Open Point (SOP). It is a power electronic device installed in place of a Normally Open Points (NOP) between adjacent feeders of radial distribution networks, having the capability to transfer real power and control reactive power between its connecting points [8]. In this paper, the optimal SOP outputs are determined based on the result of DNR to provide further improvements along each of the aforementioned objectives.

2. Problem formulation

2.1. Multi-objective functions

The multi-objectives of both DNR and SOP output optimizations were similar including minimizing the power loss, the load balancing and maximizing the DG penetration level. The objectives are presented as P_{loss}, *LBI* and *DGPL* as shown below:

A. Minimizing the power loss (P_{loss})

$$obj_1 = minP_{loss} = \sum_{i=1}^{n_{branch}} I_i^2 \times r_i \tag{1}$$

I_i is the current passing through branch i and r_i is the resistance of the branch. n_{branch} is the total number of branches in a distribution network.

B. Load balancing

Load balancing is achieved by minimizing the load balance index (*LBI*), which is defined as:

$$obj_2 = minLBI = \sum_{i=1}^{n_{branch}} \left(\frac{I_{i-actual}}{I_{i-rated}}\right)^2 \tag{2}$$

where $I_{i-actual}$ and $I_{i-rated}$ are the real and rated current of branch i.

C. Maximizing the DG penetration level (DGPL)

$$obj_3 = maxDGPL = \frac{\sum P_{DG}}{\sum P_{load}} \times 100\% \quad (3)$$

$\sum P_{DG}$ is the sum of active power injections from all connected DGs, and $\sum P_{load}$ is the total active power demand of the system. In this study, the upper boundary of *DGPL* was set to be 200%.

2.2. Constraints

The backward-forward sweep method was adopted to evaluate the network performances among the candidate solutions. The following network constraints were considered including power flow conservations; thermal limits of transformers and lines; voltage limits; radial configurations and serving all loads.

3. Solution methodology

3.1. DNR optimization using the Ant colony optimization (ACO) method

When solving the multi-objective DNR optimization problem, the search space of different network configurations is explored by means of ACO, which is derived from the inspiration of foraging behavior of natural ant colonies [9, 10]. It is a metaheuristic solution based on the mutual interactions among artificial agents named as ants. The discrete optimization problem is formulated as a graph, and each ant generates a solution by leaving a pheromone trail on the path from nest to food. The pheromone evaporates with time, and will be reconstructed more rapidly on a shorter path. The amount of pheromone deposited on each path is directly proportional to the quality of the solution. The transition of ants between nodes is determined by a probabilistic selection rule based on the value of pheromone deposition which will cause more ants to choose the shorter path. Over a period of time, the path corresponding to the optimal solution is the one that presents the highest pheromone deposition.

3.2. SOP output optimization using the Taxi-Cab method

An SOP can be implemented with Back-to-Back Voltage Source Converters (B2B VSC) connecting two adjacent feeders of the network as shown in Fig.1. The operational constraints of an SOP are:

$$P_{C1} + P_{C2} = 0 \quad (4)$$

$$\sqrt{P_{C1}^2 + Q_{C1}^2} \leq S_{C1} \quad (5)$$

$$\sqrt{P_{C2}^2 + Q_{C2}^2} \leq S_{C2} \quad (6)$$

where P_{C1} and Q_{C1}, P_{C2} and Q_{C2} are real and reactive power injections/absorptions of each VSC to/from the connecting point. S_{C1} and S_{C2} are the rated capacity of each VSC. These device operational boundaries are further considered in addition to the constraints illustrated in Section 2.2.

When optimizing the SOP output, a general optimization method named as Taxi-cab [11] is used. The outputs of an SOP: $[P_{C1}, Q_{C1}, Q_{C2}]$ (P_{C2} is not included as it equals to P_{C1}) are specified as the decision variables. Objectives P_{loss} and LBI ($obj_{n\,(n=1,2)}$ in Section 2.1) are to be minimized, while *DGPL* is incorporated with input variables and is considered as negative loads. In the optimization procedure, decision variables $[P_{C1}, Q_{C1}, Q_{C2}]$ are presented as unit vectors in the searching space. Along each unit vector, $obj_{n\,(n=1,2)}$ is a function of one decision variable. The minimization of obj_n along each vector is accomplished by applying the golden ratio search algorithm. The procedure is repeated along each vector consecutively to generate a sequence of minimal values of obj_n until no further decrease can be achieved. This method is simple in implementation and does not require calculating the derivatives of the objective functions.

3.2. Visualization of multi-objective optimization solutions using the Pareto optimality

In multi-objective optimization problems, since there rarely exists a single solution that can simultaneously optimize all objectives, the Pareto optimality is used. It compares candidate solutions which satisfy the imposed constraints in the concept of dominance, and provides a set of trade-off solutions amongst different objectives. 'A' is said to be dominated over 'B', if and only if Eq.7 and Eq.8 are satisfied concurrently.

$$\forall i \in [1, 2, \dots, n_{obj}]: f_i(A) \le f_i(B) \tag{7}$$

$$\exists i \in [1,2, \dots, n_{obj}]: f_i(A) < f_i(B) \tag{8}$$

The set of obtained non-dominated solutions is referred to as the Pareto set, and the image of the Pareto set presented in the solution space is referred to as the Pareto frontier.

4. Test system and results

4.1. Test system

A program has been written in MATLAB software based on the proposed methodologies. The widely used 33-bus distribution system [12] was adopted as the test system. It is rated at 12.66 kV with a total demand of 3.7 MW and 2.3 MVar. The initial open switches are s33-s34-s35-s36-s37. To analyze the impact of various DG penetration levels, the system was modified to consider four sites for DG as shown in Fig.2. Power injections from DGs were calculated according to Eq.3, and all DGs were modeled as negative PQ loads with a power factor equal to one.

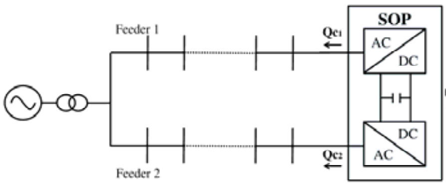

Fig. 1. A distribution network with an SOP connected

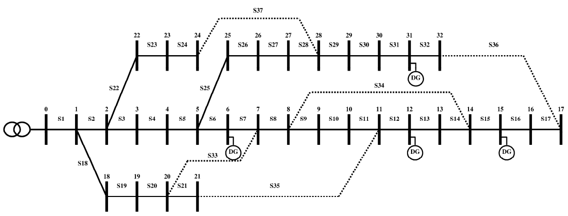

Fig. 2. The modified 33-bus distribution system

4.2. Multi-objective DNR results

Fig. 3 presents the obtained Pareto frontier in three dimensions. Table 1 presents the solutions with optimal values along each objective and the sets of open switches in those solutions. Results show that the three objectives cannot be optimized simultaneously. Each of them is obtained with different network configurations and certain DG penetration levels, which verifies the significance of using the Pareto optimality in solving multi-objective problems. Results also show that DNR is able to improve *DGPL* without violating any network operational constraints. It can be illustrated from the results that, with the increasing *DGPL*, P_{loss} and *LBI* will decrease first. However, when *DGPL* increases to a high value, P_{loss} and *LBI* will start to increase. It reveals the fact that DG has the capability to reduce power losses and balance the load within a certain penetration level. However, large DG penetrations will change the direction of power flow and increase the burden of power transfer of the network.

Among solutions in the Pareto set, the network configuration with s7-s9-s14-s28-s32 open is selected as an optimal solution. This is because the topology is taken by the majority of solutions in the Pareto set. The minimum P_{loss} and the *LBI* obtained by this topology are 65.228 kW and 0.03743 which are close to the optimal values in Table 1, namely 64.676 kW and 0.0286. In addition, the optimal value along *obj3*, i.e. *DGPL* equals to 200%, can be obtained. If DNOs are interested in optimizing one of the three objectives, this topology can be changed to the preferred one through simple switch operations. For instance, by closing s28 and open s37, a network with minimum P_{loss} is obtained. Consequently, this topology is adopted for SOP output optimization in the next section.

4.3. Multi-objective SOP output optimization results

After obtaining the optimal network configuration in Section 4.2, SOP is installed into the network replacing each of the open switches (s7-s9-s14-s28-s32) at a time. The optimal outputs of SOP are calculated using the method in Section 3.2. Fig. 4 presents the Pareto frontier of SOP output optimization. The optimal solutions along each objective are presented in Table 2, with the corresponding SOP locations and outputs. Results show that SOP is able to reduce P_{loss} and *LBI* by further 58.21% and 52.45%. When the DG penetration is low, SOP transfers real power to support the feeder with large power demand and injects reactive power to the network as compensators. When the DG penetration is high, SOP transfers real power from the feeder with large DG injections to the feeder with large power demand, and absorbs reactive power from the network to mitigate the voltage rise issue.

Branch28 is the optimal site for SOP installation. As shown in Table 2, the optimal solutions along each objective can be obtained with SOP installed in Branch28. The solutions obtained when SOP operates in Branch28 take the majority in the Pareto set.

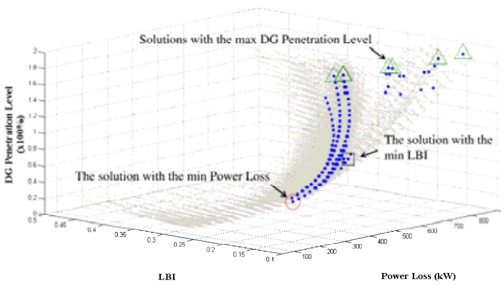

Fig. 3. Pareto frontier of DNR optimization

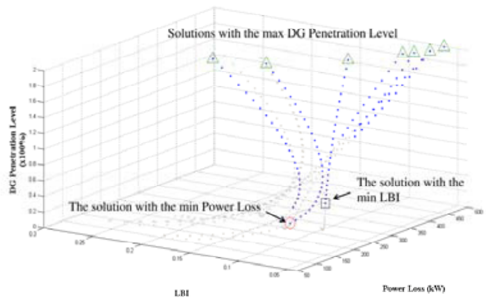

Fig. 4. Pareto frontier of SOP optimization

Table 1. Optimal solutions along each objective with the DNR optimization

	Power Loss (kW)	LBI	DG Penetration (%)	Open Switches
min Ploss	**64.676**	0.0892	65	s7-s9-s14-s32-s37
min LBI	141.164	**0.0286**	120	s7-s9-s14-s24-s33
max DGPL	333.682	0.1185	**200**	s7-s9-s14-s23-s32
	495.418	0.1046	**200**	s7-s9-s14-s24-s37
	304.838	0.1221	**200**	s7-s9-s14-s28-s32
	333.894	0.1183	**200**	s7-s10-s14-s23-s32
	305.051	0.1218	**200**	s7-s10-s14-s28-s32
	493.344	0.11	**200**	s7-s11-s14-s24-s26

Table 2. Optimal solutions along each objective with the SOP optimization

	Power Loss (kW)	LBI	DG Penetration (%)	SOP Location	SOP Outputs [Pc1, Qc1, Qc2] (kW; kVar)		
min Ploss	**27.03**	0.0379	65	Branch28	-308.603	197.396	1191.75
min LBI	58.117	**0.0136**	90	Branch28	-587.925	1110.235	1081.322
max DGPL	496.916	0.0627	**200**	Branch7	-475.528	-708.846	-1719.97
	444.898	0.0731	**200**	Branch9	-48.156	-1113.17	-636.081
	465.475	0.065	**200**	Branch14	382.373	-1022.72	-683.459
	268.98	0.1568	**200**	Branch28	-76.886	219.527	1251.913
	353.482	0.1054	**200**	Branch28	-389.383	-536.697	-414.218
	247.798	0.2035	**200**	Branch32	513.97	1014.928	327.435
	430.969	0.0796	**200**	Branch32	325.693	-848.004	-712.556

5. Conclusion

In this paper, the reconfiguration problem and the optimal SOP operation problem are formulated within a multi-objective framework using the Pareto optimality. The obtained results show the effectiveness of using DNR and SOP to improve the distribution network operation, focusing on power loss reduction, load balance and DG penetration level increase. The obtained Pareto frontiers present great diversity, high quality and proper distribution of the non-dominated solutions among all feasible solutions, which allow the Distribution Network Operators to choose from based on their priorities and necessities.

References

[1] D. Shirmohammadi and H. Hong, "RECONFIGURATION OF ELECTRIC DISTRIBUTION NETWORKS FOR RESISTIVE LINE LOSSES REDUCTION," *IEEE Trans. Power Deliv.,* vol. 4, pp. 1492-1498, 1989.

[2] S. Civanlar, J. J. Grainger, H. Yin, and S. S. H. Lee, "Distribution feeder reconfiguration for loss reduction," *Power Delivery, IEEE Transactions on,* vol. 3, pp. 1217-1223, 1988.

[3] S. K. Goswami and S. K. Basu, "A new algorithm for the reconfiguration of distribution feeders for loss minimization," *Power Delivery, IEEE Transactions on,* vol. 7, pp. 1484-1491, 1992.

[4] B. Amanulla, S. Chakrabarti, and S. Singh, "Reconfiguration of Power Distribution Systems Considering Reliability and Power Loss," *IEEE Trans. Power Deliv.,* vol. 27, pp. 918-926, 2012.

[5] R. Rao, S. Narasimham, M. Raju, and A. Rao, "Optimal Network Reconfiguration of Large-Scale Distribution System Using Harmony Search Algorithm," *IEEE Trans. Power Syst.,* vol. 26, pp. 1080-1088, 2011.

[6] I. Roytelman, V. Melnik, S. S. H. Lee, and R. L. Lugtu, "Multi-objective feeder reconfiguration by distribution management system," *IEEE Transactions on Power Systems,* vol. 11, pp. 661-667, 1996.

[7] Y. T. Hsiao and C. Y. Chien, "Multiobjective optimal feeder reconfiguration," *IEE Proceedings - Generation, Transmission and Distribution,* vol. 148, pp. 333-336, 2001.

[8] J. M. Bloemink and T. C. Green, "Increasing distributed generation penetration using soft normally-open points," ed, 2010, pp. 1-8.

[9] M. Dorigo, V. Maniezzo, and A. Colorni, "Ant system: optimization by a colony of cooperating agents," *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on,* vol. 26, pp. 29-41, 1996.

[10] M. D. a. L. M. Gambardella, "Ant colonies for the traveling salesman problem," *BioSystems,* vol. 43, pp. 73-81, 1997.

[11] J. H. M. a. K. Fink. (2004). *Module for the Powell Search Method for a Minimum*. Available: http://mathfaculty.fullerton.edu/mathews/n2003/PowellMethodMod.html

[12] M. E. Baran and F. Wu, "NETWORK RECONFIGURATION IN DISTRIBUTION-SYSTEMS FOR LOSS REDUCTION AND LOAD BALANCING," *IEEE Trans. Power Deliv.,* vol. 4, pp. 1401-1407, 1989.