Multi-Objective Planning of Recloser-Based Protection Systems on DG Enhanced Feeders

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***Abstract*—Planning of protection systems has been a significant task in order to achieve an efficient behavior of distribution systems. Feeders that offer high robustness and reliability are essential to ensure continuous energy delivering to all customer loads. Since distributed generation (DG) has increased its penetration in distribution systems, it has become necessary to place protective devices (such as reclosers) in order to allow DG islanded operation, which decreases the energy not supplied. This paper addresses efficient placement of normally closed reclosers (NCRs). A multi-objective optimization is defined to reduce SAIDI, SAIFI, and system costs. This approach yields optimal planning of NCRs by applying the non-dominated sorting differential evolution algorithm (NSDE). The NSDE is implemented in Matlab, while the power system is modeled in DigSILENT in order to employ a co-simulation environment. Simulations are developed on a real test feeder for two cases: i) without DG; and ii) with 6 MW penetration of distributed sources.**

***Index Terms*—Co-simulation, distributed generation, evolutionary algorithm, optimum reclosers placement, protection system planning, Pareto optimization.**

I. Introduction

In the last years, distribution automation has gained significant relevance in planning and operation of distribution systems. The distribution system operator (DSO) looks for a suitable configuration of the feeder and the protection system, pursuing high reliability levels and full supply of energy. Towards a very reliable feeder, the system might require high investment in protection and operation devices such as reclosers, fuses, and sectionalizers. In this regard, two conflictive objectives arise for the DSO: reliability maximization and costs minimization. The number and location of protection devices in the system are critical variables to accomplish the aforementioned objectives. On this basis, this research focuses on recloser-based protection systems; specifically, the planning of normally closed reclosers (NCRs) is analyzed. These devices are located within the distribution system (DS), providing capability to isolate a fault section and restoring the grid service. In addition, these devices allow distributed generation (DG) to operate in isolated mode, which decreases the energy not supplied of the system. This is a key feature of the current smart grid concept, which encourages the usage of DG and the grid automation [1].

Since planning of protection systems aims to minimize costs while maximizing reliability, this decision-making may be modeled as a multi-objective optimization problem (MOOP). As reported by Deb in [2], the aggregating function approach and the ε-constraint method have been the most popular mechanisms to solve MOOPs by transforming the problem into a single-objective optimization problem (SOOP). Because this approach uses the traditional and widely studied methods to solve a SOOP, the problem management becomes simpler. On one hand, the aggregating function approach mixes all the objectives into one objective by using arithmetical operators such as addition, multiplication, among others [2]. The weighted sum of objectives is the most common alternative to deal with MOOPs, where a set of weights are determined in order to state the importance of every objective. Evidently, the output of such optimization strategy has a strong dependency on the decision-maker perspective, who chooses the weight for each objective. On the other hand, the ε-constraint method optimizes one objective while considers the rest as constraints by restraining each of them with predefined bounds. As in the aggregating function approach, the output of this optimization strategy depends on the decision-maker that defines the boundary limits of each objective.

In this way, several authors have developed the planning of protection systems by applying the aforementioned methods. Dehgani et al. [3] have proposed a compound index optimization in which SAIFI, SAIDI, and MAIFIe are minimized by using a genetic algorithm (GA). In the case of DG enhanced feeders, Wang et al. [4] have implemented the ant colony system (ACS) strategy to minimize an index composed by SAIFI and SAIDI. Pregelj et al. [5] have included MAIFIe in the composite index and used GA to solve the decision making problem. Furthermore, the optimal placement of reclosers

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and DG within the feeder is possible as it is proposed by Greatbanks et al. [6], [7]. In this way a GA is implemented to improve reliability indices.

However, MOOP transformation into SOOP may be considered as an incomplete solution to multi-objective decision problems since the outcome of such optimization is linked to the decision-maker point of view. In order to avoid potential biased solutions, the Pareto approach deals with a real MOOP, and provides an efficient set of solutions looking for trade-offs between considered objectives [2]. Nonetheless, there has been little research done on Pareto multi-objective planning of protection systems. For instance, a Pareto multi-objective optimization based on ACS is proposed by Tippachon et al. [8]. The authors address the placement of protection devices by aiming for cost minimization and reliability maximization, obtaining an efficient set of solutions. Nevertheless, this approach does not include DG penetration in the feeder and its possibility to operate in isolated mode. This feature may lead to a more reliable DS.

This paper provides an approach that considers a Pareto-based multi-objective optimization to enhance SAIFI and SAIDI, while investment costs are minimized on a DG enhanced feeder. In this regard, isolated operation of DG is enabled. The outcome of this optimization is a set of efficient solutions, which provides the amount and position of NCRs in the feeder. The optimal placement of NCRs is a decision-making problem described by nonlinear objective functions and combinatorial solutions. This kind of procedure usually has NP-Complete complexity level; hence, metaheuristic approaches are necessary to achieve efficient solutions. In a previous research on protection systems optimization, a performance comparison between genetic algorithm (GA) and differential evolution (DE) has been conducted [9]. Such comparison resulted in better behavior for DE. For this reason, this research uses the non-dominated sorting differential evolution (NSDE) [10] to attain the Pareto frontier of the optimization problem. The proposed approach is developed in a co-simulation environment by using Matlab and DigSILENT software, based on the data exchange principle used in [11].

The remainder of this paper is organized as follows. In Section II efficient planning of NCRs by applying a multi-objective optimization approach is described. Formulation of the optimization problem is presented in Section III, along with details of the objective functions. Section IV presents the heuristic algorithm to solve the multi-objective optimization problem, and the islanded operation approach. The test system and the simulation results are provided in Section V. Finally, in Section VI conclusions are drawn.

II. Multiobjective Optimization Approach

In most real world optimization problems, solutions should be obtained by considering multiple objectives instead of one. Since these objectives are often in conflict, a trade-off relation among them arises. That is, it is necessary to sacrifice the performance of one or more objectives to enhance another. Consider, in the context of this paper, the decision-making problem involved in the sizing of protection systems and placement of NCRs. The amount of protective devices in a DS can vary from any recloser to a few. There are two extreme hypothetical cases: i) no branch is capable of isolating a fault event; and ii) each branch is able to isolate a fault event by opening a switch. If reliability is the only objective of this decision-making problem, the ideal choice is the second case. Nevertheless, it is presumable that a full reliable DS is likely to be very expensive, involving high costs that the DSO is not willing to invest. Hence, the DSO decision-making process must be developed by taking into account several objectives such as high levels of reliability together with low costs.

Coello et al. [12] argue that the Pareto approach looks for compromises among objectives instead of finding a single solution. Therefore, the traditional optimality concept for a unique global optimal solution is not applicable. The optimality notion used in multi-objective optimization can be defined as: if there is no feasible solution rather than $\overrightarrow{x}^*$ which improves one objective function without affecting the rest, then $\overrightarrow{x}^*$ is Pareto optimal. The Pareto approach gives a set of efficient solutions that satisfy the preceding optimality condition. Since the Pareto optimal solutions are located in the bounds of the feasible outcome region, this set of results is called the Pareto frontier.

Finding a Pareto frontier is not simple. Indeed, determining an analytical expression of the bound containing these points is often impossible to attain [2]. Nevertheless, there are some methods that provide the Pareto frontier as a result of heuristic search. Pareto-based algorithms use the principle of dominance, which compares two feasible solutions on the basis of whether one dominates the other solution. Abraham et al. in [13], define the necessary conditions to have that x^1 dominates x^2:

1) The solution x^1 is no worse than x^2 in all objectives.
2) The solution x^1 is strictly better than x^2 in at least one objective.

Pareto-based algorithms look for non-dominated solutions, i.e., solutions that satisfy the aforementioned conditions. When a significant sample of these solutions is attained, it can be implied that a Pareto frontier is achieved.

III. Problem Formulation

As it was mentioned before, the addition of protective devices into a DS improves reliability indices. In this context, the optimization problem addressed here focuses on SAIFI and SAIDI reduction. Nevertheless, improving these indices requires investments in protection devices, so conflictive objectives arise. According to a standard MOOP formulation, the multi-objective optimization of a recloser-based protection system planning is characterized by the following decision-making problem:

$$\begin{aligned} \min \quad & \mathrm{SAIFI}\,(x)\,,\ \mathrm{SAIDI}\,(x)\,,\ \mathrm{Costs}\,(x) \\ \text{s.t.} \quad & x_i \in \{0,1\}\,, \\ & \Delta Ik_{v,w}{}'' \geq Ik_{min}^{''}, \quad \forall v,w \in X_R\ , \end{aligned} \tag{1}$$

where,

$$\text{SAIFI} = \frac{\sum_{j=1}^{m} A^F{}_j C_j}{\sum_{j=1}^{m} C_j} \quad (2)$$

$$\text{SAIDI} = \frac{\sum_{j=1}^{m} A^T{}_j C_j}{\sum_{j=1}^{m} C_j} \quad (3)$$

$$\text{Costs} = R_c \left[\frac{r(1+r)^t}{(1+r)^t - 1} \right] Q_r \ . \quad (4)$$

Here, A_j^F is the average customer interruption frequency of the load point *j*, A_j^T is the average customer interruption time of the load point *j*, C_j is the amount of customers in load point *j*, and m is the total number of load points in the feeder. On the other hand, considered costs of reclosers are normalized with an annualization factor and include investment as well as operational costs. In (4), r is the discount rate for the DSO, t is the lifetime of reclosers, Q_r the quantity of placed reclosers, and R_c the total costs of a single recloser (fixed costs plus variable costs). The planning problem formulated above has n branches susceptible of recloser installation. The decision variables $x = \{x_1 \ldots x_n\}$ belong to a binary domain that represents the existence of a recloser on the branch (each branch is connected to an upstream busbar and a downstream busbar D^b). The last constraint refers to the minimum initial symmetrical short circuit level (Ik''_{min}) between two busbars ($\Delta Ik_{v,w}''$) in the set X_R. The set X_R is composed by every busbar that has one branch with a recloser, i.e., $X_R = \{D_i^b : x_i = 1, i = 1, \ldots, n\}$. This constraint is necessary when placing NCRs because it guarantees appropriate conditions for coordinating the feeder protections.

IV. Heuristic Algorithm and Islanded Operation

A. Heuristic algorithms

Traditional analytical approaches, such as linear and non-linear programming, are unsuitable to solve the above detailed optimization problem. Another feasible alternative is to apply heuristic multi-objective algorithms. In general terms, these algorithms use evolutionary algorithms (EAs) along with the Pareto multi-objective approach, i.e., include selection, recombination, mutation, and the dominance conditions stated by Deb et al. [14]. Here, a generalized form of the chromosome that describes a solution to the problem is shown. Genes with a value of "1" indicate the existence of a recloser on the associated line-segments, while "0" indicates an unprotected branch. The length of the chromosome is equivalent to the total amount of branches susceptible of recloser installation, while the index points an explicit branch.

Since multi-objective evolutionary algorithms (MOEAs) are composed by EAs, it is presumable that the better the fitness, the greater the chances of an individual to inherit its genes to next generations, i.e., as the number of generations increases better solutions are achieved. In this way, calibration parameters such as the population size and the number of iterations become significant to achieve efficient solutions with a reasonable simulation time. A small population size may not provide an appropriate diversity of solutions, which may hinder or limit exploration over the search space, leading to suboptimal solutions. In the other extreme case, a large population size requires a large number of function evaluations. This feature may lead to demanding a prohibitive amount of computational or time resources. In terms of generations quantity, setting the amount of generations to a high value might cause the same effect on the algorithm as a large population size. In contrast, a small number of generations will not allow the society to evolve, feature that leads to suboptimal solutions. In this problem, the number of individuals and generations are set to 100. This configuration provides a suitable combination of speed and reliability.

Algorithm 1: NSDE Algorithm

```
Initialization of population: X_0 = {X_{1,0}, ..., X_{NP,0}}
Reliability assessment: fitness assignment for each solution.
for i = 1 to NP do
    f_1(X_{i,G}) = SAIFI(X_{i,G})
    f_2(X_{i,G}) = SAIDI(X_{i,G})
    f_3(X_{i,G}) = Costs(X_{i,G})
end
Fast non-dominated sort: Sorting of X_0 by taking into
account fitness of individuals and the dominance concept.
Selection: find the parents of offspring population Y_0.
Crossover: create the offspring population Y_0.
Mutation: make stochastic changes in Y_0.
for G = 1 to G_max do
    Combine populations: Z_G = X_{G-1} ∪ Y_{G-1}
    Reliability assessment: fitness assignment for each
    solution of Z_G.
    Fast non-dominated sort: Sorting of Z_G by taking into
    account fitness of individuals and the dominance concept..
    Creation of next population: X_{G+1}
    X_{G+1} = ∅, i = 1;
    while |X_{G+1}| + |F_i| ≤ N do
        Crowding distance assignment: Solutions
        arrangement in F_i according to their distance to other
        solutions in the front.
        X_{G+1} = X_{G+1} ∪ F_i;
        i = i + 1;
    end
    Descendant sorting of F_i according to crowding distance.
    X_{G+1} = X_{G+1} ∪ F_i[1 : (N − |X_{G+1}|)];
    Creation of next offspring population: Y_{G+1}
    Y_{G+1} = selection, crossover and mutation from X_{G+1}
end
```

B. Non-dominated Sorting Differential Evolution

NSDE (described in Algorithm 1) is a MOEA that was proposed by Iorio et al. [10]. This algorithm allows finding a diversified set of solutions converging near the true Pareto-optimal set. The core of this MOEA relies on the fast non-dominated sorting approach, which assigns all individuals to non-dominated fronts $\mathcal{F}$, and the crowding distance arrangement that preserves a diverse population.

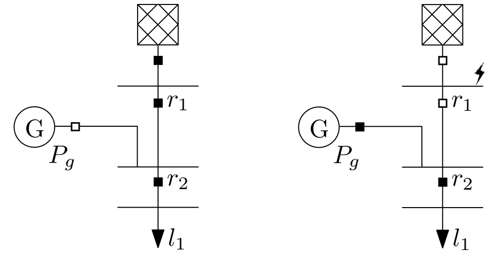
According to the Algorithm 1, the NSDE creates an initial population X_0 with NP individuals, which are sorted based on their non-domination level. In this way, each solution has a fitness equal to its non-domination rank (the lower, the better). Then, DE operators are used to produce an offspring population Y_0 with NP chromosomes. When the random population is successfully obtained, a combined population $Z_G = X_{G-1} \cup Y_{G-1}$ is created. This combined population is sorted according to the non-domination level of individuals in order to obtain the next generation components. The elements of lower non-dominated sets principally conform next generations. That is, solutions belonging to the non-dominated set $\mathcal{F}_1$ are prioritized above any other solution in the combined population. If the size of $\mathcal{F}_1$ is smaller than NP, all population members of $\mathcal{F}_1$ are chosen and the remaining members are selected from subsequent non-dominated fronts in the order of their ranking. This procedure continues until X_{G+1} is complete. Since it is necessary to obtain a diversified set of solutions, the last front individuals are chosen by using the crowding distance arrangement. Finally, selection, crossover, and mutation are applied to the population X_{G+1} in order to create a new offspring population Y_{G+1}.

C. Islanded Operation of DG

Even though unintentional islanded operation of distribution systems is not allowed globally, according to the smart grid concept one of the most important benefits of DG is its capability to operate in islanded mode when a fault event arises. This characteristic enhances reliability indices such as SAIDI and energy not supplied, and currently there is a growing interest for allowing intentional isolated operation by ensuring power balance and security constraints within the island [15]–[17].

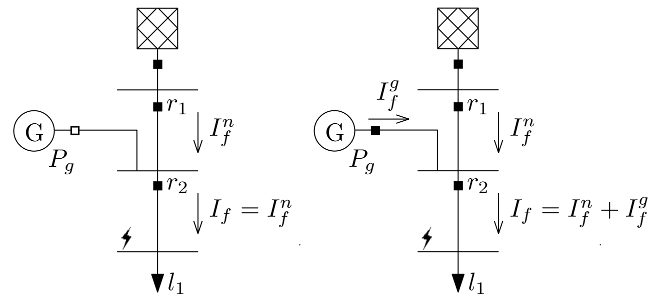
Since the main objective of this research is to assess the impacts of DG in the feeder reliability, some assumptions are necessary in the electrical system operation. It is widely known that DG increases the short circuit level in a feeder; besides, the normal operation of the system may experience some direction changes in its power flow. These features generate issues when coordinating protections, especially overcurrent and distance protections with direction relays [18]. Because of simplicity, in normal operation the distribution system functions as the system depicted in Fig. 1.a. This system does not consider power delivery from DGs when the main grid is available, but if a fault event arises in the feeder, DGs provide energy whenever feasible (Fig. 1.b). The previous operation assumption is related to avoid changing short circuit currents of the distribution feeder, for the protection system functions as in traditional feeders, i.e., the closest protection device to the fault operates (distance assumption).

To illustrate how short circuit currents change in DG-enhanced feeders, look at Fig. 2. On one hand, if a fault originates at the load busbar in a traditional feeder (Fig. 2.a), the total short circuit current I_f comes from the main grid I_f^n. This current is sensed by both r_1 and r_2, and considering the distance assumption r_2 should operate before r_1. On the other hand, if the same fault arises in a DG-enhanced feeder (Fig. 2.b), the total short circuit current I_f is no longer equal to the main grid current I_f^n because of the DG current contribution I_f^g. Here, r_1 senses I_f^n while r_2 detects the real short circuit current I_f. This behavior may lead to inaccurate coordination



(a) Normal (b) Fault

Fig. 1. Operation of a distribution system with DG. a) Distribution system when the main grid is available. b) Isolated operation when a fault event arises.



(a) Without DG (b) With DG

Fig. 2. Short circuit currents in a distribution system. a) Short circuit in a traditional system. b) Short circuit in a DG-enhanced feeder.

of the feeder protections; thus, distance assumption might not be longer valid. Another issue is the current direction, specifically when the fault arises upstream DG power plants. To avoid such problems, adaptive protections and bidirectional relays can be used. However, these solutions are out of the paper scope.

To show how this research deals with isolated operation under the previous assumptions, consider the system depicted in Fig. 3. This general feeder is composed by one DG power plant, two loads (l_1 and l_2), switches, and one connection to the main grid. Note that in addition to protection devices of DG and the main grid, there is one recloser (r_1) placed upstream busbar 2. Therefore, if a fault event arises upstream busbar 2, r_1 opens and isolates loads l_1 and l_2 from the main grid. This small area supplied by the DG power plant is known as an island, and has a total load $L_T = l_1 + l_2$. In this case, there are three feasible scenarios: i) P_g is lower than L_T, so load shedding is necessary for keeping the balance between demand and generation; ii) P_g equals L_T, in consequence no actions are required; and iii) P_g is greater than L_T, so generation must be reduced. In the first and third scenarios there is a loss of efficiency while the second scenario is the most appropriate. In i) load shedding becomes energy not supplied, and in iii) the

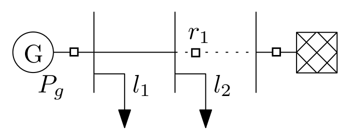


Fig. 3. Standard system with islanded operation and DG.

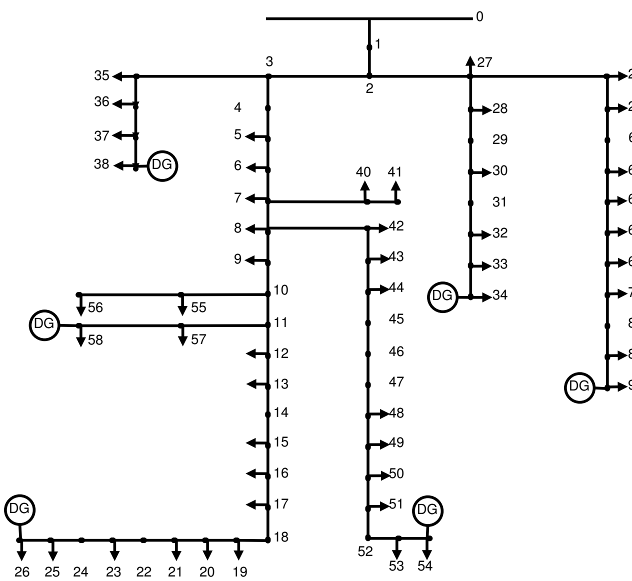


Fig. 4. 70-nodes test feeder with DG penetration, adapted from [19].

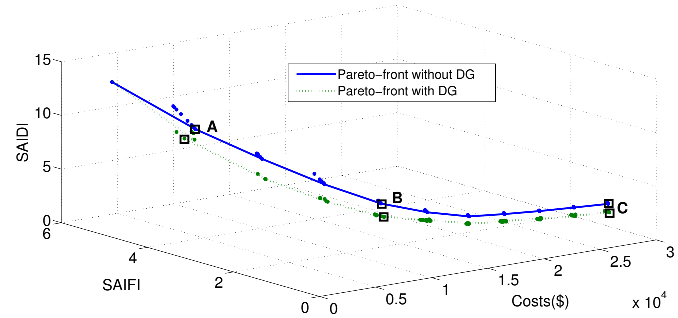


Fig. 5. NSDE non-dominated set of solutions.

lack of generation implies more loads and lines than necessary, which leads to a higher probability of failure within the island. In this context, placement of reclosers becomes significant to create efficient islands, such that produced energy of DG power plants is maximized.

V. Case Study and Results

A. Case Study

The proposed approach is tested on a 70-nodes and 8-laterals distribution feeder. This DS is derived from a real system that belongs to the North American utility PG&E (Fig. 4). Simulations are applied on the radial configuration of this distribution network considering two generation profiles: i) feeder without DG plants; and ii) penetration of six DG plants, each with 1 MW of installed capacity. Specific parameters of the system are detailed in [19].

To develop reliability assessments, a fault model must be defined for each element in the feeder. To simplify, solely line-segment faults are considered. This case study has a line-segment failure rate of 0.22 outages per year and per kilometer, and three hours for repairing a fault event. The annual equivalent cost of reclosers is set to 2900 USD for each installed device in the feeder. The switching time for these reclosers is equivalent to one minute, and it is assumed that the nearest device to the fault location actuates to isolate the flawed area. Finally, the minimum initial short circuit level is equal to 0.5kA.

B. Results

Based on the NSDE algorithm employed in Matlab and the power system modeled in DigSILENT, efficient values for SAIFI, SAIDI, and investment costs of reclosers are found from a Pareto perspective. Simulation results for the distribution feeder (Fig. 4), with both generation profiles, are presented in Fig. 5. Three representative solutions of the Pareto set are highlighted, and presented in detail in Table I; where alternative A corresponds to an extreme solution that completely encourages cost minimization, C is an extreme solution that outperforms reliability, and B is the most balanced solution within the optimal set. For instance, alternative A of the Pareto-front without DG in Fig. 5 shows high reliability indices (SAIDI $= 10,9$ and SAIFI $= 3,63$) but low costs ($2.900). In contrast, alternative C shows greater reliability (SAIDI $= 2,55$ and SAIFI $= 0,85$), but excessive costs ($29.000). Analyzing the shape of these Pareto curves, the steepest gradient takes place in the range of one to five reclosers. From this point, though adding a recloser heightens reliability, robustness of the feeder increases slightly. That is, reliability deviation of solution A in comparison with solution B is larger than the dissimilarity between alternatives B and C even though fewer reclosers are included. Moreover, when considering DG penetration and isolated operation, the system reliability is enhanced. The Pareto set experiences a displacement in direction of lesser SAIDI. This reduction reaches 20 percent on average when compared with the non-DG feeder. Although DG enhance SAIDI index, SAIFI does not experiment displacements because DG switches operate to protect the power plant. Therefore, customers inside a feasible island perceive the fault event.

The disposition of reclosers in the feeder is shown in Table I. As it can be seen in this table, several branches can be identified as decisive elements to improve system robustness. NCRs installation on 8-9, 27e-28e, and 27-28 upgrades system reliability to a high degree. Moreover, when a large number of devices are available, installation of reclosers encourages protection of large sections in the feeder. For instance, the section delimited by busbars 3 and 26 encompasses the majority of protective devices. Just after lateral sections are equipped with reclosers, the main trunk of the feeder is segmented; thus, zones with the capability of isolation when a fault event arises are created. As it can be seen in Table I, DG penetration is associated to reclosers placed near power plants for the sake of microgrids creation. To clarify, consider NSDE locations for ninth and tenth devices: i) when DG is included, the ninth recloser is displaced from branch 44-45 to branch 48-49, movement that reduces the size of the microgrid delimited by busbars 49 and 54. Besides, four branches that may augment fault probability inside the microgrid are discarded; and ii) when DG is considered, the tenth recloser is relocated from a

TABLE I
DETAILS OF HIGHLIGHTED NON-DOMINATED SOLUTIONS OF NSDE

Solution		SAIDI	SAIFI	Costs($)	Recloser positions
No DG	A	10,90	3,63	2900	6-7
	B	4,79	1,59	11600	10-11, 27-28, 27e-28e, 42-43
	C	2,55	0,85	29000	3-4, 10-11, 11-12, 21-22, 27-28, 27e-28e, 35-36, 42-43, 44-45, 10-55
With DG	A	9,90	3,66	2900	5-6
	B	3,63	1,52	11600	8-9, 27-28, 27e-28e, 43-44
	C	1,79	0,83	29000	3-4, 8-9, 11-12, 18-19, 27-28, 27e-28e, 3-35, 8-42, 44-45, 67-68

non-DG lateral to branch 67-68, allowing islanded operation of DG connected to node 90.

In summary, the NSDE algorithm appropriately provides the efficient placement of reclosers within a feeder, enhancing the system reliability by minimizing costs. In addition, considering DG in the feeder improves the SAIDI index since isolated operation is allowed. In this way, the algorithm encourages placement of reclosers near to the DG power plants.

VI. CONCLUDING REMARKS

A Pareto multi-objective optimization to optimize planning and operation of a DS is proposed. This methodology is used to determine the amount of reclosers in a feeder and their efficient location. The PG&E 70-nodes radial feeder is successfully tested with a co-simulation between Matlab and DigSILENT, achieving efficient solutions of sizing and placement of protective devices.

Optimal sizing and settlement of NCRs rely on a multi-objective optimization. This approach is proposed to find a Pareto optimal set of solutions toward SAIFI, SAIDI, and cost minimization. NSDE algorithm is effectively implemented to attain an efficient set of alternatives.

Simulation results show the importance of both protective devices and DG to enhance reliability in radial distribution feeders. Reclosers are located near DG power plants to allow islanded operation, thus increasing operating time and energy delivery. Additionally, when several reclosers are available, the larger sections of the feeder are segmented into small areas increasing self-healing freedom degrees.

The data exchange principle between Matlab and DigSILENT provides a co-simulation environment that seems efficient for solving complex optimization and control problems, especially new trends in smart grids.

As a further research, the authors suggest to work on the bidirectional power flow issues of distributed generation and its possibilities to effectively operate in isolated mode, as it is expected in the smart grid scheme. Furthermore, the co-simulation between Matlab and DigSILENT can be very useful to address complex problems in smart grids.

REFERENCES

[1] H. Farhangi, "The path of the smart grid," *IEEE Power and Energy Magazine*, vol. 8, no. 1, pp. 18–28, January 2010.

[2] K. Deb and D. Kalyanmoy, *Multi-Objective Optimization Using Evolutionary Algorithms*. New York, NY, USA: John Wiley & Sons, Inc., 2001.

[3] N. Dehghani and R. Dashti, "Optimization of recloser placement to improve reliability by genetic algorithm," *Energy and Power Engineering*, vol. 3, no. 4, pp. 508–512, 2011.

[4] L. Wang and C. Singh, "Reliability-constrained optimum placement of reclosers and distributed generators in distribution networks using an ant colony system algorithm," *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 38, no. 6, pp. 757–764, 2008.

[5] A. Pregelj, M. Begovic, and A. Rohatgi, "Recloser allocation for improved reliability of dg-enhanced distribution networks," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1442–1449, 2006.

[6] J. Greatbanks, D. Popovic, M. Begovic, A. Pregelj, and T. Green, "On optimization for security and reliability of power systems with distributed generation," in *Power Tech Conference Proceedings, 2003 IEEE Bologna*, IEEE, 2003.

[7] D. Popović, J. Greatbanks, M. Begović, and A. Pregelj, "Placement of distributed generators and reclosers for distribution network security and reliability," *International Journal of Electrical Power & Energy Systems*, vol. 27, no. 5, pp. 398–408, 2005.

[8] W. Tippachon and D. Rerkpreedapong, "Multiobjective optimal placement of switches and protective devices in electric power distribution systems using ant colony optimization," *Electric Power Systems Research*, vol. 79, no. 7, pp. 1171 – 1178, 2009.

[9] M. Velasquez, A. Cadena, and C. Tautiva, "Optimal planning of recloser-based protection systems applying the economic theory of the firm and evolutionary algorithms," in *Proceedings of the 2013 4th IEEE/PES Innovative Smart Grid Technologies Europe*, Oct 2013.

[10] A. W. Iorio and X. Li, "Solving rotated multi-objective optimization problems using differential evolution," in *AI 2004: Advances in Artificial Intelligence*. Springer, 2005, pp. 861–872.

[11] A. Stativa, M. Gavrilas, and V. Stahie, "Optimal tuning and placement of power system stabilizer using particle swarm optimization algorithm," in *2012 International Conference and Exposition on Electrical and Power Engineering (EPE)*, Oct 2012, pp. 242–247.

[12] C. Coello, G. Lamont, and D. Van Veldhuisen, *Evolutionary Algorithms for Solving Multi-Objective Problems*, 1st ed. KAP, ch. 1, pp. 11–97.

[13] A. Abraham and L. Jain, *Evolutionary multiobjective optimization*. Springer, 2005.

[14] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: Nsga-ii," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.

[15] Econnect Ltd and Distributed Generation Programme, "Islanded operation of distribution networks," Department of Trade and Industry of the United Kingdom, Tech. Rep., 2005.

[16] C. Gracen, R. Engel, and T. Quetchenbach, "A guidebook on grid interconnection and islanded operation of mini-grid power systems up to 200 kw," Lawrence Berkeley National Laboratory and Schatz Energy Research Center, Tech. Rep., 2013.

[17] "IEEE guide for design, operation, and integration of distributed resource island systems with electric power systems," *IEEE Std 1547.4-2011*, pp. 1–54, July 2011.

[18] M. Geidl, *Protection of power systems with distributed generation: state of the art*. ETH, Eidgenössische Technische Hochschule Zürich, EEH Power Systems Laboratory, 2005.

[19] M. Baran and F. Wu, "Optimal capacitor placement on radial distribution systems," *IEEE Transactions on Power Delivery*, vol. 4, no. 1, pp. 725–734, 1989.