

GENETIC ALGORITHM FOR SECTIONALIZER SWITCHES ALLOCATION IN DISTRIBUTION SYSTEM WITH DISTRIBUTED GENERATION

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ABSTRACT

This paper has the objective of investigating the Switch Allocation Problems (SAP), which encompass a series of decision-making faced by power distribution utilities with respect to the number, type and location of sectionalizing switches in a network in order to reduce operational costs while maintaining acceptable levels of reliability. This work addresses a SAP with distributed generation (DG) in the system. DG refers to having an electricity generator at or near the end-user, which can bring loss reduction in the electric network and also help to reduce the impact of system failure. The rationale is that DG may have a positive impact on reliability given its potential to provide alternative power supply paths after a contingency through islanding operation. This research proposes an optimization methodology based on genetic algorithms with a hierarchically structured population to solve the SAP with DG. Computational experiments are conducted to evaluate the methodology on real-life networks. The results show the effectiveness of the approach and the benefits in reliability that can be obtained from the use of DG.

KEYWORDS. Genetic Algorithm. Switch Allocation. Distribution Networks Reliability.

PO on Energy Area, Petroleum and Gas. Metaheuristic. Combinatorial optimization.

1. Introduction

There are 3 subsystems on the electric power system: generation, transmission and distribution systems, as depicted in Figure 1. The power distribution system is responsible for receiving the energy from the transmission system and deliver to the individual consumer. The goal is to deliver that energy with reliability, i.e with maximum quality and minimum outage possible, this is challenging work considering the scale of the distribution systems.

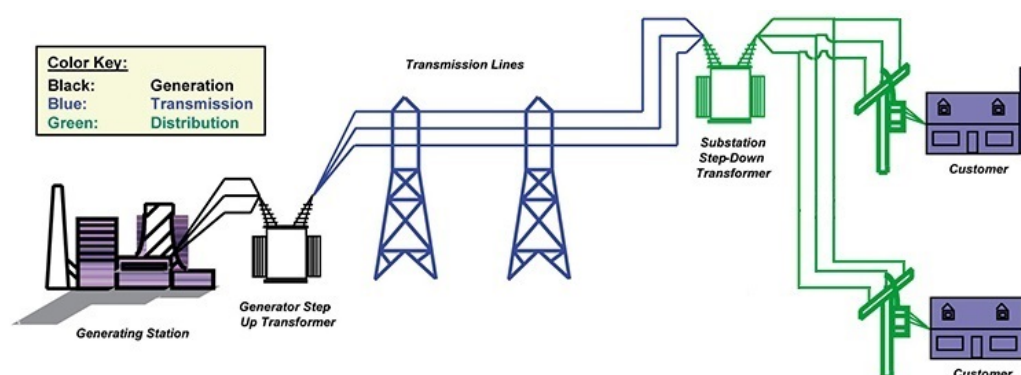


Figure 1: Example of a basic structure of Electric Power System [University of Idaho].

In the power distribution system when a contingency occurs, it propagates until it is located, isolated from the rest of the system, and then repaired. Sectionalizing switches help to mitigate the effects of a fault because it has the ability to reduce the overall interruption duration by isolating the clients upstream from the failure. When the system is operating in the normal state, these switches are normally closed, but in the occurrence of a contingency, this switch can be opened, isolating the upstream consumers reestablishing the power flow, minimizing the outage time of the consumers located above the failure.

If only the outage time was considered, the best solution would be to have sectionalizing switches on all possible places in the distribution system, but that would not be financially feasible to the distribution company. Therefore, the Switch Allocation Problem (SAP) seeks to maximize the system reliability and minimize the costs with the switches and Energy Not Supplied (ENS) choosing the best number of switches, location, and if is a manual switch or a remote controlled switch (RCS). The SAP for a radial distribution network is classified as a combinatorial optimization problem and it is NP-hard [Benavides et al., 2013], which makes difficult to use exact techniques to find the optimal solution in a reasonable time for large instances. However, near-optimal solutions can be obtained by heuristics approaches.

A differential search algorithm to solve the reliability optimization problem of radial distribution network is presented in [Ray et al., 2018]. [López et al., 2016] proposes a mixed-integer second-order conic programming (MISOCP) model to find the optimal solution for the reconfiguration problem of electrical distribution systems. A heuristic called discrete artificial bee colony was used in [Aman, 2016] to solve the optimum tie switches allocation and distributed generator placement based problem. [Alencar et al., 2018] proposes a technique based on genetic algorithm and uses a fuzzy expert system to initiate the population and make the individuals feasible, the results were positive reducing up to 9.39% in the system average interruption index (SAIDI).

We will base our study by the solution approach presented in [de Assis et al., 2012] and [de Assis et al., 2015] where the authors propose a metaheuristic based on genetic algorithm con-

cepts and pursue to optimize the multiobjective function for solving the Switch Allocation Problem (SAP), considering sectionalizing and tie switches in real networks. This paper proposes a procedure based on a genetic algorithm to solve the SAP in the radial distribution system considering distributed generation in the network in order to decrease system costs, by installing a minimum amount of sectionalizing switch at appropriate locations in the distribution network.

2. Distributed Generation

The use of distributed generation is already a reality in electric systems, but there are some topics still under study. There are studies exploring the SAP, but it is hard to find in the literature researches that are considering for this problem the DG.

Traditionally, we have a generation concentrated in large power plants, designed to supply energy to agglomerated consumers, the energy flows in only one direction in the distribution system, this is called Centralized Generation [Gonçalves, 2004]. Centralized generation makes reference to the large-scale electricity generation of centralized facilities. These facilities are usually located far away from end-users and connected to a network of high-voltage transmission lines. The distribution of a centralized generation occurs through the electric power grid to several end-users. Fossil-fuel-fired power plants, nuclear power plants, hydroelectric dams, wind farms, are examples of centralized generation facilities [EPA].

The environmental impacts of centralized generation can occur as (i) air pollutant emissions; (ii) water use and discharge; (iii) waste generation; (iv) land careless use. Besides that, there may be losses during generation and delivery of power to end-users. Opportunities exist to improve the energy efficiency of power plants, as well to locate electricity generation closer to end-users in order to reduce losses during electricity distribution [EPA].

The Distributed Generation (DG) model consider a smaller generation that can be placed in the primary or secondary power lines and can supply energy to one or more consumer. The DG brings new challenges to the system operation as bi-directional energy flow. Nonetheless when the power generated by DG is connected to the electric utility's lower voltage distribution lines, distributed generation can help provide clean and reliable power to additional customers and reduce electricity losses along transmission and distribution lines.

The island operation is when there is an independent source of energy feeding some customers isolated from the main power supply, whether this concept is applied with DG there can be a straightforward improvement on the distribution system reliability indices. The consumers indirectly impacted by a failure can have their energy restored without having to wait for the failure is repaired, so decreasing the restoration time for this costumers. The island operation is described in [S. Chowdhury e Crossley, 2009] as an active distribution network. The impacts of the island operation in the reliability indices are explored in [Rocha, 2014], in general, there was a positive impact on those indices.

One of the reasons the island operation is not widely spread yet is because of the synchronization problem underlying between the isolated and the main system. The synchronization is a problem that already attracts attention of the researchers of the area and is under study as seen in [Rocha et al., 2017], [Holsbach et al.] and [Rocha, 2014]. This paper focused on solving the SAP considering the existence of DG in the network and the proposed solution approach did not consider the dynamic operation in the distribution system.

A common characteristic of DG, like solar and wind-based energy, is the lack of predictability of the amount of energy that can be generated, these sources are weather dependent, so is not possible to know with precision the amount of energy generated in a near future. [Cavalheiro et al., 2018] attempts to model this behaviour by is considered 3 different values of generation, the

conclusion is that for a large scale network, such an approach it is not computationally feasible. In this paper we consider a constant amount of DG modeled by a negative load.

3. Reliability Indices

The Brazilian regulatory agency of energy companies (ANEEL) establishes quality standards to be followed in order to guarantee the network reliability, i.e., delivery of electric energy to consumers with the shortest possible service interruption time otherwise, the company is fined. There exists a variate of indices that have to be respected, like voltage and frequency variation limits, but for the SAP, the relevant ones are the continuity indicators, (i) the system average interruption index (SAIDI) and (ii) the energy not supplied (ENS), they are defined as [de Assis et al., 2015]:

$$SAIDI = \frac{\sum_{k \in S} U_k N_k}{\sum_{k \in S} N_k} \quad (1)$$

$$ENS = \sum_{k \in S} U_k L_k \quad (2)$$

Where N_k is the number of customers in sector k , sectors are defined as a group of nodes that cannot be electrically isolated by a protection device or a switch, S is the set of network sectors. L_k is the load of sector k , and U_k is the total duration of the interruption in sector k considering a fault in this same sector and interruption caused by failures in other sectors, defined by Equations (3) and (4):

$$U_k = \sum_{l \in S} \lambda_l t_{kl} \quad (3)$$

$$\lambda_l = \sum_{i \in V_l} \lambda_i \quad (4)$$

Where l is a sector that has a subset of nodes $V_l \in V$, λ_i is the average failure rate per year in node i , λ_l is the average failure rate per year in sector l . t_{kl} is the expected duration of an interruption in sector k caused by failures in sector l this value is a composition of 2 other times as seen in Equation (5).

$$t_{kl} = t_1 + t_2 \quad (5)$$

The search time t_1 is the average time spent to identify where the failure is located and open the upstream sectionalizing switch, isolating the impacted sectors. The average repair time t_2 is the time that takes to repair the system bringing it back to normal operation. The times t_1 and t_2 for the RCS are usually a fraction of the respective times for the manual switches. According to sector location and where the failure occurred, there are 3 cases possible to determine t_{kl} :

- **Case 1** - If sector k is upstream from sector l , and there is a protection device in between them, sector k is not affected, therefore $t_1 = t_2 = 0$.
- **Case 2** - Similar to Case 1, but instead of a protection device, there is a sectionalizing switch between them, so when a failure happens the sector k is impacted until the switch is opened in a $t_{kl} = t_1$ time, in this case $t_2 = 0$.

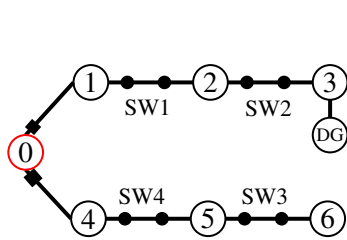


Figure 2: Distribution network example.

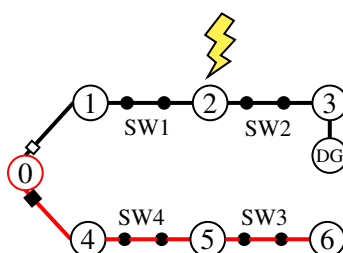


Figure 3: Network after the failure. Energy flow in red.

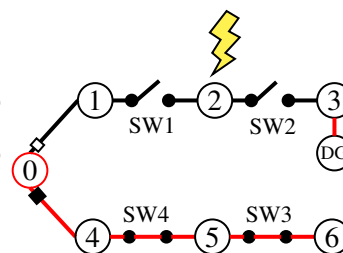


Figure 4: Network after switches operation. Energy flow in red.

- **Case 3** - If $k = l$ or the sector k is downstream from sector l , the time t_1 and t_2 are considered, unless in the case when there is a GD in sector k that can feed all the load of costumers in sector k , in this case $t_2 = 0$.

Figures 2, 3 e 4 exemplify a failure in the distribution network and the restoration time estimation. In these figures, the circles are sectors with a number of customers and power load associated. The sector 0 represents the main generation and in sector 3 there is a distributed generation. In this work it was assumed that the sector with DG can be electrically isolated from the system trough sectionalizing switches or protection devices, and the DG has the capacity to supply the load demand of its sector. $SW1$, $SW2$, $SW3$ and $SW4$ represent the sectionalizing switches in the distribution network.

Figure 2 shows an example of a distribution network with distributed generation and without any contingency. Figure 3 illustrates the system situation when a failure occurs in sector 2. The red line represents the remaining powered lines after the failure. The sectors 0, 4, 5 and 6 are not affected due to the protection devices present in substation (sector 0) that isolate them from the others sectors, the sectors 1, 2 and 3 are interrupted sectors, affected by failure. After waiting a time t_1 (failure location time) switches $SW1$ and $SW2$ can be opened isolating the failure, then sector 3 has energy restored due to the effect of the DG (Figure 4). Sectors 1 and 2 have to wait for time t_2 (repair time) for the failure to be repaired.

Table 1: Times considered due to failure in sector 2.

Sector	Interruption Time
0	0
1	$t_1 + t_2$
2	$t_1 + t_2$
3	t_1
4	0
5	0
6	0

4. Mathematical Model

The mathematical model proposed for SAP with DG is based on the one presented in [de Assis et al., 2015]. However in previous work, the authors did not consider distributed generation in the distribution system and in this paper, the authors contemplate the SAP only with section-

alizing switches, even though we consider the distribution system with DG, we did not perform the allocation of tie switches.

A radial distribution system can be modeled as a connected directed tree $T(V, A)$ rooted in substation, which can be considered the main power supply. Where a node $i \in V$ represents a load point with power demand or a connection point. The arcs $(i, j) \in A$ represents the network lines where the switches can be placed. The root node is the main power supply, an example can be seen in Figure 2. For more details see [de Assis et al., 2015]. The DG is added as a negative load, and is capable of feeding the consumers in it's own sector.

The mathematical model used is a simplified model of the one proposed in [de Assis et al., 2015] where we consider only the set of sectionalizing switches as decision variables defined as $x_{ij}^s \in X$, meaning if a sectionalizing switch of type s is allocated on arc (i, j) , then $x_{ij}^s = 1$.

$$\min \quad c_e ENS(X) + \sum_{(i,j) \in A} \sum_{s \in S} c_s(x_{ij}^s) \quad (6)$$

s.t.

$$SAIDI(X) \leq SAIDI_{lim} \quad (7)$$

$$f_{ij} x^s \leq F_s \quad \forall (i, j) \in A, \forall s \in S \quad (8)$$

$$x_{ij}^s \in \{0, 1\} \quad \forall (i, j) \in A, \forall s \in S \quad (9)$$

Where c_e and c_s are the energy not supplied and switches costs, respectively. S is the set of switch types. f_{ij} is the power flowing on arc $(i, j) \in A$. The objective function presented in Equation (6) aims to minimize the costs of ENS and the costs of switch (acquisition and maintenance). Equation (7) limited the SAID value. Constraints 8 represent the maximum power flow allowed at each edge according to the type of the switch. Constraints 9 define all variables as binaries.

5. Solution Approach

The solution method developed, to solve the Switch Allocation Problem (SAP) in a power distribution system is based on well-defined concepts of genetic algorithm. The proposed methodology is based on the approach established in [de Assis et al., 2012] with suitable adjustments to address the problem proposed in this paper.

- **Chromosome** - It is one dimension integer array, where each position represent an arc of the network that can receive a switch, and the value is one of the SW set or 0 if there is no switch in the position. Figure 5 exemplify the chromosome of Figure 2 where $SW1$, $SW3$ and $SW4$ are switches of type 1 and $SW2$ is a switches of type 5.

arcs	(0,1)	(1,2)	(2,3)	(0,4)	(4,5)	(5,6)
Chromosome	0	1	5	0	1	1

Figure 5: Chromosome representation of solution depicted in Figure 2.

- **Fitness Function** - It is a function that evaluates each individual's chromosome (integer array) to measure how good is the solution represented by this individual. For this work is determined the inverse of the objective function described in Equation (6).

- **Selection** - The population is hierarchically structured as a ternary tree, where all pair of leader and subordinate individuals perform the crossover. A leader individual has the highest fitness over its own subordinate (see Figure 6). If the offspring has higher fitness than the subordinate individual that generated it gets replaced by the offspring.
- **Crossover** - A one-point crossover is applied, in which a random position of the chromosome is selected, the first part of the leader is copied to the offspring, and the second part is copied from the subordinate.
- **Mutation** - this genetic operator is applied after the crossover. According to the mutation rate whether a certain position of the chromosome is selected for mutation the method considers three possibilities:
 - *if* there is no switch *then* with 10% chance allocate a manual one.
 - *if* there is a remote control switch (RCS) *then* replace it by a manual switch.
 - *if* there is a manual switch *then* remove it *or* replace it by a RCS, with the same probability.

The initial population is generated by a greedy randomized constructive heuristic, that generates each individual by randomly selecting the arcs that will receive a suitable switch from the set $S = \{1, \dots, |S|\}$. In this work the switch types available for use are shown in Table 3. Based on the future benefit of the allocated a switch in determined network position, the more beneficial is to have a switch in a certain place, the higher the probability of select this location to receive a switch. The population throughout the algorithm has exactly 13 individuals, they are arranged by their fitness as seen in Figure 6, each leader has a higher fitness than its subordinate. Using a structured population it's possible to achieve similar behavior than a more numerous unstructured population [Mendes et al., 2005].

The genetic algorithm runs for a number maximum of generations, but if the best individual does not change in a determined limit of generations a reset process is performed. In the reset process, the best individual is held, but all other individuals are discarded and a new set of individuals is generated by the constructive heuristic. The diagram illustrated in Figure 7 shows the complete process. The genetic algorithm implemented is described in Algorithm 1.

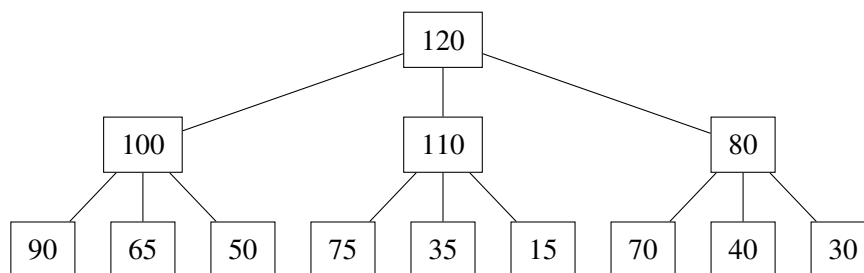


Figure 6: Structured population

6. Computational Experiments

The computational experiments were performed with the solution approach presented in Section 5 and instances that represent three different large real distribution networks the state of São Paulo, Brazil, provided by the distribution company responsible for them. Their characteristics are

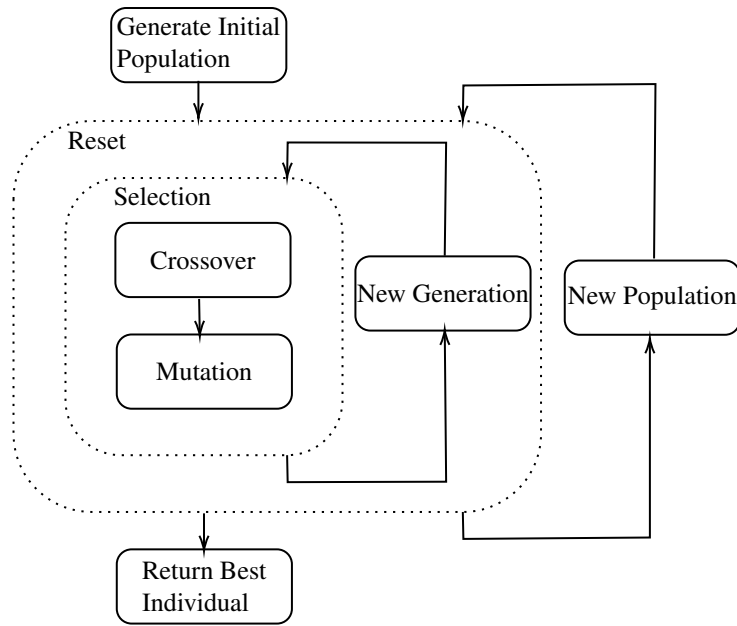


Figure 7: Genetic algorithm scheme

Algorithm 1 Genetic Algorithm

```

generation = 1
while generation ≤ maxGenerations do
    Population ← generateInicialPopulation()
    while not condition to stop do
        if bestSolution stopped improving or generation == maxGeneration then
            stop while
        end if
        Population ← SortPopulation()
        for each pair (leader, subordinate) ∈ Population do
            offspring ← crossover(leader, subordinate)
            r ← Random(0, 1)
            if r ≤ mutationRate then
                offspring ← Mutate(offspring)
            end if
            if Fitness(offspring) ≥ Fitness(subordinate) then
                subordinate ← offspring
            end if
        end for
        generation ++
    end while
end while

```

described in Table 2. The distributed generation (DG) were positioned to have around 5% of the total load. For the simulations it was used a personal laptop computer with 8GB of RAM, Ubuntu 18.04 and a Intel Core i7 7500U 2.70GHz, all the code was implemented in C++ language. The

switch types considered are presented in Table 3 and the values used in the parameters to solve the proposed problem is shown in Table 4. The times considered for an RCS are half of the manual switch times. The parameters used in the genetic algorithm for the experiments are described in Table 5.

Table 2: Networks

Network	Load(MW)	DG capacity (MW)	Length (m)	Nodes	Arcs
N1	3341	163 (4.88%)	8641	219	218
N2	3698	191 (5.16%)	55717	1088	1087
N3	3830	189 (4.93%)	272337	2431	2430

Three scenarios were performed for each network:

1. **Scenario 1 - Without DG** - The network has no installed switches and the switch allocation is performed according to the genetic algorithm implemented for SAP. In the first place, there is no DG in the networks, this is the baseline result. The values with a percentage symbol (%) in the tables represent the variation of the respective value when comparing to the reference.
2. **Scenario 2 - Evaluate with DG** - This scenario uses the results of switch allocation previously found for the networks (base scenario), but considering the existence of DG, it is just an evaluation (therefore the execution time is low) where the reliability indices are recalculated whereas DG in the networks, no optimization process is performed. This scenario is important because allows assessing the impact of DG in the reliability of distribution systems.
3. **Scenario 3 - Planned Network with DG** - The optimization process for the switch allocation is fulfilled with the DG already present in the network, is a similar case of the planning a new network forecasting the use of a DG.

Results for all distribution networks computed for each scenario are presented in Tables 6, 7 and 8. In these tables the line named *Nº Switches* presents the total amount of switches allocated in the solution, and the number in parenthesis, if presented, is the total amount of RCS.

An important constraint in the mathematical model is the target SAIDI, which the companies have to respect so the result can't be higher than this limit, on the other hand there is no constraint on the ENS index. This fact can be noticed on the results for the network 1 shown in Table 6, for the third scenario the ENS increases by 6.70% compared to scenario 1, but it uses only 2 manual switches instead of 5 used in the first test, which yields an overall cost reduction of 41.07% from the base scenario.

Table 3: Switch Types

Switch	Capacity (A)	Type	Cost (R\$)
C100	100	Manual	2817.00
C200	200	Manual	3817.00
C400	400	Manual	5017.00
C600	600	Manual	6185.00
A400	400	RCS	25000.00
A400	600	RCS	35000.00

Table 4: Model Parameters

Energy cost	R\$100.00
Load factor	0.6
Annual interest rate	10%
Amortization period	15 years
Location time (t_1)	0.91 hours
Repair time (t_2)	2.28 hours

Table 5: Genetic Parameters

Max Generations	50
Number of generations until reset	10
Mutation rate	30%

Table 6: Results for Network N1

Target SAIDI = 2.5	Scenario 1	Scenario 2	Scenario 3
ENS (MWh)	8.95	8.59 (-4.02%)	9.55 (6.70%)
SAIDI	2.49	2.15 (-13.65%)	2.23 (-10.44%)
Nº Switches	5	5	2
ENS Annual cost (R\$)	894.57	858.76 (-4.00%)	955.22 (6.78%)
Annually switches cost (R\$)	1983.28	1983.28 (0%)	740.72 (-62.65%)
Total Annual Cost (R\$)	2877.85	2842.04 (-1.24%)	1695.94 (-41.07%)
Execution time (s)	8.76	0.07	7.75

Table 7: Results for Network N2

Target SAIDI = 6.9	Scenario 1	Scenario 2	Scenario 3
ENS (MWh)	30.43	29.72 (-2.33%)	30.11 (-1.05%)
SAIDI	6.88	6.54 (-4.94%)	6.86 (-0.29%)
Nº Switches	15(1)	15(1)	10
ENS Annual cost (R\$)	3042.84	2972.13 (-2.32%)	3010.51 (-1.06%)
Annually switches cost (R\$)	8471.91	8471.91 (0%)	3835.09 (-54.73%)
Total Annual Cost (R\$)	11514.75	11444.04 (-0.61%)	6845.6 (-40.55%)
Execution time (s)	348.44	0.05	310.35

The results found for the second network are shown in Table 7 and it is possible to observe that there is a major reduction in the number of switches from 15 to 10, including the reduction in one RCS that is more expensive than a manual one, there was a cost decrease of 54.73% on the switches costs allocated when DG is considered. The experiments performed for the network 3, presented in Table 8 show that the ENS on the second scenario has decreased 6.77% only by adding DG to the network.

Table 8: Results for Network N3

Target SAIDI = 22.95	Scenario 1	Scenario 2	Scenario 3
ENS (MWh)	105.17	98.05 (-6.77%)	100.49 (-4.45%)
SAIDI	22.85	22.26 (-2.58%)	22.34 (-2.23%)
Nº Switches	7(1)	7(1)	4(1)
ENS Annual cost (R\$)	10517.14	9805.17 (-6.77%)	10049.01 (-4.45%)
Annually switches cost (R\$)	5798.26	5798.26 (0%)	4529.40 (-21.88%)
Total Annual Cost (R\$)	17115	16359 (-4.42%)	14183 (-17.13)
Execution time (s)	3720.42	0.06	3291.56

7. Final Remarks

The problem of allocating sectionalizing switches in a distribution system considering distributed generation (DG) has been examined, with the objective of reducing costs and outage impacts in networks with DG. In this paper we propose a solution methodology based on genetic algorithm with a constructive heuristic for the initial population. The use of a hierarchical structure brings computational efficiency by reducing the amount of individuals needed to achieve similar results than using a non structured population.

The proposed solution approach was evaluated with three large-scale networks. Three scenarios were set up to perform the computational experiments: (i) solve the optimization problem of sectionalizing switches allocation (SAP) without DG; (ii) Considering DG in the networks, evaluate the network reliability using the switches allocations obtained in the first scenario and (iii) solve the SAP including the presence of DG in the network.

The results show the metaheuristic ability in searching high quality solutions for the proposed problem, and it is still possible to observe the impact of DG in the reliability indices of the distribution network and the importance of developing research in this emerging area.

References

- Alencar, T., Rodrigues, A., e Silva, M. (2018). Alocação de chaves em redes de distribuição de energia elétrica via algoritmos genéticos baseados em sistemas especialistas fuzzy.
- Aman, M. M. (2016). *IET Generation, Transmission Distribution*, 10:2277–2284(7). ISSN 1751-8687. URL <https://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2015.0303>.
- Benavides, A. J., Ritt, M., Buriol, L. S., e França, P. M. (2013). An iterated sample construction with path relinking method: Application to switch allocation in electrical distribution networks. *Computers Operations Research*, 40(1):24 – 32. ISSN 0305-0548. URL <http://www.sciencedirect.com/science/article/pii/S0305054812001098>.
- Borges, C. L. e Falcão, D. M. (2006). Optimal distributed generation allocation for reliability, losses, and voltage improvement. *International Journal of Electrical Power Energy Systems*, 28 (6):413 – 420. ISSN 0142-0615. URL <http://www.sciencedirect.com/science/article/pii/S0142061506000482>.
- Cavalheiro, E. M., Vergílio, A. H., e Lyra, C. (2018). Optimal configuration of power distribution networks with variable renewable energy resources. *Computers & Operations Research*, 96:272 – 280. ISSN 0305-0548. URL <http://www.sciencedirect.com/science/article/pii/S0305054817302526>.
- de Assis, L. S., González, J. F. V., Usberti, F. L., Lyra, C., Cavellucci, C., e Zuben, F. J. V. (2015). Switch allocation problems in power distribution systems. *IEEE Transactions on Power Systems*, 30(1):246–253. ISSN 0885-8950.
- de Assis, L. S., González, J. F. V., Usberti, F. L., Lyra, C., e Von Zuben, F. (2012). Optimal allocation of remote controlled switches in radial distribution systems. In *2012 IEEE Power and Energy Society General Meeting*, p. 1–8.
- EPA, U. S. E. P. A. Centralized generation of electricity and its impacts on the environment. URL <https://www.epa.gov/energy/centralized-generation-electricity-and-its-impacts-environment>.

- Gonçalves, L. F. (2004). Contribuições para o estudo teórico e experimental de sistemas de geração distribuída. Master's thesis, Universidade Federal do Rio Grande do Sul - Programa de Pós-Graduação em Engenharia Elétrica.
- Holsbach, I., Ruaro, R., Lima, D., Cabral, N., Falleiros, J., Melo, M., Silva, M., Shinzato, P., Maurício, W., Oliveira, Y., et al. Impacto da geração distribuída no sistema elétrico de distribuição da rge.
- Jiang, F., Zhang, Z., Cao, T., Hu, B., e Piao, Z. (2013). Impact of distributed generation on voltage profile and losses of distribution systems. In *Proceedings of the 32nd Chinese Control Conference*, p. 8587–8591.
- Lopez, E., Opazo, H., Garcia, L., e Bastard, P. (2004). Online reconfiguration considering variability demand: applications to real networks. *IEEE Transactions on Power Systems*, 19(1):549–553. ISSN 0885-8950.
- López, J. C., Lavorato, M., e Rider, M. J. (2016). Optimal reconfiguration of electrical distribution systems considering reliability indices improvement. *International Journal of Electrical Power Energy Systems*, 78:837 – 845. ISSN 0142-0615. URL <http://www.sciencedirect.com/science/article/pii/S014206151500575X>.
- Mendes, A., Franca, P. M., Lyra, C., Pissarra, C., e Cavellucci, C. (2005). Capacitor placement in large-sized radial distribution networks. *IEE Proceedings - Generation, Transmission and Distribution*, 152(4):496–502. ISSN 1350-2360.
- Pombo, A. V., Murta-Pina, J., e Pires, V. F. (2017). Distributed energy resources network connection considering reliability optimization using a nsga-ii algorithm. In *2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, p. 28–33.
- Ray, S., Bhattacharjee, S., e Bhattacharya, A. (2018). Optimal allocation of remote control switches in radial distribution network for reliability improvement. *Ain Shams Engineering Journal*, 9 (3):403 – 414. ISSN 2090-4479. URL <http://www.sciencedirect.com/science/article/pii/S2090447916000046>.
- Rocha, L. F. (2014). *Avaliação Probabilística da Confiabilidade de Sistemas de Distribuição Incluindo Aspectos da Dinâmica do Ilhamento*. PhD thesis, Universidade Federal do Rio de Janeiro - COPPE.
- Rocha, L. F., Borges, C. L. T., e Taranto, G. N. (2017). Reliability evaluation of active distribution networks including islanding dynamics. *IEEE Transactions on Power Systems*, 32(2):1545–1552. ISSN 0885-8950.
- S. Chowdhury, S. P. C. e Crossley, P. (2009). *Microgrids and Active Distribution Networks*. The Institute of Engineering and Technology, London, United Kingdom.
- Tang, X. e Tang, G. (2010). Power flow for distribution network with distributed generation. In *2010 Asia-Pacific Power and Energy Engineering Conference*, p. 1–4.
- University of Idaho. Energy sustainability. URL <https://www.webpages.uidaho.edu/sustainability/chapters/ch06/ch06-p3a.asp>.