Methodology for distribution network reconfiguration in smart grid system regarding power loss, grid reliability and the utilization factor of substations, considering a new reality of energy supply and consumption

Daniel Szente Fonseca[1], Gustavo de Góis Himeno[1], Marcelo Aparecido Pelegrini[1], Tadeu Ferreira dos Santos[2].

[1]Sinapsis – Inovação em Energia, São Paulo, Brazil
[2]CEB – Companhia Energética de Brasília – Distribuição S/A, Distrito Federal, Brazil

Abstract— This paper proposes a new methodology for distribution network reconfiguration (DNR), in a Smart Grid (SG) scenario, regarding power losses, grid reliability and the utilization factor of substations; as well as an approach to model the effects of electric vehicle charging stations, distributed energy generators and energy storage systems in the electric grid. The proposed methodology first deals with the problem setting, that is, it determines the state of the grid (in terms of electrical parameters and variables, power loss, reliability indicators and utilization factor for each substation) and its topology. Then, it's defined the universe of possible solutions, to which is applied a simple formulation of Genetic Algorithm (GA) that solves the optimization problem. To demonstrate the applicability of this methodology in a real network, the methodology was implemented in the specialized commercial power system simulator SINAP Grid and applied in a case study. Its results showed that it is possible to accommodate so many objectives in one solution, however, the state of the grid and its initial topology influence greatly in the outcome of the solution.

Keywords—Distributed generation, Grid reconfiguration, Grid reliability, Power losses, Smart Grid.

I. INTRODUCTION

The new reality of energy supply and consumption (such as electric vehicle charging stations, distributed energy generators and energy storage systems) in distribution networks resulted in a new challenge for its planners: how to guarantee that the grid will be able to support this new reality while also trying to improve its reliability, operation cost and asset management[1].

One way to adapt the grid in order to manage this new reality is to formulate network reconfiguration methods[2] able to consider many objectives that result in a grid topology that best fits the planner's goal.

In the past, the alteration of the topology of the distribution network was made only a few times a year -if made at all- given that most of the switchgear was not capable to be remotely controlled, which meant that the process of reconfiguration would have had to be done manually, that is, the process used to happen in a slower pace and be more expensive.

However, with the advent of Smart Grids, these predicaments could be resolved provided that remotely controlled switches -such as automatic circuit recloses-could be distributed along the network.

Given that, this paper's main objective is to formulate a methodology that will provide an optimized topology that will best fit the planner's demands.

The solutions provided must consider the new reality of energy supply and consumption. The section II of this paper will discuss the impact of the elements of this new reality in the electric grid, as well as how they will be modelled for the simulation. The section III will briefly explain the handling of the GA. Then, the section IV will explain how the methodology will evaluate reliability, operation cost and asset management of the network. The section V will discuss the methodology to define the universe of possible solutions and, following that, the section VI will present the network selected to be a case study, and the results of the application of the

methodology. Finally, section VII will bring the conclusion of the study.

II. MODELING THE NEW REALITY OF ENERGY SUPPLY AND CONSUMPTION

In the past, in a distribution network, there used to be a unique point of the circuit that would supply energy throughout the rest of it, accordingly to the other points of the circuit that would demand electrical power. The growing of this demand, classically, was easy to predict, in such manner that was not uncommon for planners to classify consumers in residential, commercial, industrial, etc., and get reliable results in their predictions. This scenario has, however, changed.

Firstly, now,it's easier to add distributed generation along the network, which would mean new points of energy supply, and certainly change the power flow.

Secondly, as consumption increases, the motivation for a redistribution of consumption along the hours of a day -the load profile- emerges; This process can be done with energy storage systems, which have become more accessible -financially and commercially- in recent years. To the planner's perspective this means that some points of the circuit would be able to produce and consume electrical energy, creating a new paradigm.

Thirdly, as energy storage systems, such as electric batteries,became more reliable, so did the production of electric vehicles and consequently their diffusion to the general public, which means the construction of charging stationsbecame necessary. This indicates a problem for the planners because high levels of energy and power are needed to recharge an electric vehicle whereas it's harder to predict its consumption and consequently its impact in the network.

However, from a mathematical point of view, these new elements in the circuit can be modelled as simply as new points of production or consumption of energy, with some specific details for each new element. For this paper, in order to evaluate their impact in a future scenario, in many nodes of the network chosen for the case study, distributed energy generators, electric batteries and electric vehicle charging stations were inserted.

The distributed energy generators were treated as points of supply, that provide energy based on a typical load curve for each type of generator (solar powered, wind powered, etc.).

The electric batteries were modeled as consumers for the off-peak hours and producers of energy for the on-peak hours, in way that, from the perspective of the substation, less power would be demanded on-peak

hours.However, ignoring the losses in energy storage, there would not be a reduction in the energy demand, because the energy not-demanded in the on-peak hours was demanded in the off-peak hour. This process is usually known as "peak-shaving".

The electric vehicle charging stations were handled as points of high consumption, allocated in the residences of house-holds elected to have electric vehicles. It was considered that vehicles would be charged at night, as it more likely to happen.

III. GENETIC ALGORITHM

The Genetic Algorithm (GA) is a metaheuristic very popular in many applications of engineering, biology and computer science, mainly because of the simplicity of its implementation, and the reliability of its results. implementation is simple, and its results are very reliable, even when the problem in question becomes very complex due to, for example, non-linearities, multiple maxima and minima of the function and discontinuities[4].

One great advantage of this algorithm is that its formulation depends on a very simple mathematical expression that describes the aim of the results, in such a way that it is not needed to indicate explicitly the steps to the result, which will be specific to each problem. Moreover, the GA works with a population of alternatives for the solution, and not only with one solution, which grants it a great robustness; also, the GA works directly with objective function and not with its derivatives; finally, the GA uses some stochastic elements, which help to capture more realistic solutions.

In the GA, each candidate solution is codified in a *string* of *bits*, which, in this context, will each represent a different grid topology; and each *string* will be rated accordingly to its fitness to the conditions of the problem. The implementation and the codification of each candidate solutions were made following the methodology described in [3].

IV. EVALUATING GRID RELIABILITY, OPERATION COST AND ASSET MANAGEMENT

This section will explain how the GA will evaluate the candidate solutions (the candidates were generated in the Initialization Phase [3]) regarding the grid reliability, its operation cost and its asset management.

1. Global rate

The rate for the context of the static topology is calculated as shown in (1):

$$Rate = (\beta) \cdot [\mu_{transgression}] + (1 - \beta) \cdot [(\alpha_{loss}) \cdot (\mu_{loss}) + (\alpha_{continuity}) \cdot (\mu_{continuity}) + (\alpha_{SUF}) \cdot (\mu_{SUF})] \quad (1)$$

Whereβ is the level of grid restrictions, which can be interpreted as the tolerated voltage level and load transgression.

$\alpha_{loss}, \alpha_{continuity} and \alpha_{SUF}$ are, respectively, the ponderation regarding the loss rate, the continuity rate and the substation's utilization factor rate. They are set in such manner that (2) is satisfied:

$$\alpha_{loss} + \alpha_{continuity} + \alpha_{SUF} = 1 \quad (2)$$

$\mu_{transgression}, \mu_{loss}, \mu_{continuity} and \mu_{SUF}$are, respectively, the grades regarding the grid's equipment voltage and load transgression, the loss rate, the continuity rate and the substation's utilization factor rate.

2. Transgression rate

The transgression rate ($\mu_{transgression}$) is defined as the lowest value between the rate given to the transgression of voltage in the load buses and to the transgression of load on transformers and generators. This analysis is made for all hours of the day, as shown in (3):

$$\mu_{transgression} = \min(\mu_{bus}, \mu_{transformer}, \mu_{generator}) \quad (3)$$

Each rate in (3) can be calculated by (4):

$$\mu = \frac{N_{total} - N_{precarious}}{(N_{total}) \cdot (1 - tol)} \quad (4)$$

In whichμ is the rate for the transgression of voltage in the load buses, transformers and generators. N_{total} is the total number of equipment in analysis. $N_{precarious}$ is the number of equipment that were diagnosed as precarious according to the transgression of voltage or load.tol is the percentage of equipment transgression tolerated (its default value is set to 20%).

3. Loss rate

The loss rate (μ_{loss})is calculated by (5):

$$\mu_{loss} = \frac{Loss_{ref} - Loss}{Loss_{ref} \cdot factor_{loss}} \quad (5)$$

Where$Loss$is the integrated technical losses in 24 hours calculated for the topology of the alternative in analysis.$Loss_{ref}$ is the integrated losses in 24 hours calculated for the original topology of the network in analysis.$factor_{loss}$ is a factor that indicates a possible goal in the reduction of technical losses (its default value is 0,3).

If μ_{loss} is less than zero or if $Loss$ is greater than 5% of the injected energy, the loss rate value becomes equal to zero.

4. Continuity rate

The continuity rate ($\mu_{continuity}$) is calculated by (6):

$$\mu_{continuity} = \alpha_{SAIDI} \cdot \mu_{SAIDI} + \alpha_{SAIFI} \cdot \mu_{SAIFI} + \alpha_{ENS} \cdot \mu_{ENS} \quad (6)$$

In whichα_{SAIDI}, α_{SAIFI} and α_{ENS} are, respectively, the ponderation regarding the network'sSAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index) and ENS (Energy Not Supplied). They are set in such manner that (7) is satisfied:

$$\alpha_{SAIDI} + \alpha_{SAIFI} + \alpha_{ENS} = 1 \quad (7)$$

Each Continuity Index is calculated by (8):

$$\mu_{ContinuityIndex} = \frac{Index_{ref} - Index}{Index_{ref} \cdot factor_{continuity}} \quad (8)$$

In which$Index$and$Index_{ref}$are the index being evaluated for the topology in analysis and for the original topology.$factor_{continuity}$is a factor that indicates a possible goal in the reduction of the index.The default value for $factor_{SAIDI}$ is 0,3, for $factor_{SAIFI}$ is 0,2 and for $factor_{ENS}$ is 0,3.

5. Substation's Utilization Factor Rate

The continuity rate (μ_{SUF}) is calculated by (9):

$$\mu_{SUF} = \sum_{j=1}^{N} \alpha_{SE_j} \cdot \mu_{SE_j} \quad (9)$$

In whichN is the total number of substations in analysis and$\alpha_{SE_j}$is theponderation regarding the substation j, they are set in such manner that (10) is satisfied:

$$\sum_{j=1}^{N} \alpha_{SE_j} = 1 \quad (10)$$

And μ_{SE_j} is the rate regarding the utilization factor for the substation j, and is calculated by (11):

$$\mu_{SE_j} = \frac{SUF_j - SUF_{ref_j}}{SUF_{ref_j} \cdot factor_{SUF}} \quad (11)$$

In which SUF is the substation's utilization factor for the substation j, which is defined by (12):

$$SUF_j = \frac{Peak_{Load_j}}{Rated_{capacity_j}} \quad (12)$$

In which $Peak_{Load_j}$ is the peak load of the energy demanded to the substation$j$ in 24 hours, and $Rated_{capacity_j}$ is the sum of the capacities of the transformers in the substation$j$.

Regarding (11), SUF_{ref_j} is the substation's utilization factor for the substation j, in the original topology of the network in analysis. And $factor_{SUF}$ is a factor that indicates a possible goal in the increase of the substation's utilization factor, its default value is 0,5.

V. DEFINING THE UNIVERSE OF POSSIBLE SOLUTIONS

This section will discuss the methodology applied to define the universe of possible solutions. This methodology was applied to the switchgear able to maneuver. For each able switchgear, two solutions are added to the universe of possible solution, for this switchgear may be closed or opened.

This means that the number of possible solutions grows exponentially with the number of switchgears added to the problem. Additionally, not all possible solutions will be valid solutions, for instance, the solution where all switchgear are opened will not be valid.

Thus, to define to universe of possible solutions, where the GA will be applied, solutions that the maneuvers result in disconnection of customers will not me considered possible.

Also, the radiality of the network will be kept.In such manner that solutions that result in mesh networks will not be considered possible.

VI. CASE STUDY

In order to apply the methodology developed, it was implementedin the specialized commercial power system simulator SINAPGrid, and a case study was elaborated using the electric network of Ceilândia Norte (CN) e Ceilândia Sul (CS), two substations in Brasília, the Federal District of Brazil. These two substations belong to the electric utility CEB (CompanhiaElétrica de Brasília – Distribuição S/A).

These electric networks, as they are today, do not have the elements (such asdistributed energy generators, electric vehicle charging stations, and energy storage systems) of the new reality of energy consumption and production considered in this project. So, in order to adapt the grids, the new elements were inserted in the circuits.

For the distributed generators, 15 solar generators, of $2,5 \ MW_P$, were allocated along the 15 feeders with the higher load. For the electric vehicle charging stations, assuming a penetration of 80% in houses with a propension of having electric vehicles, 53 charging stations were allocated. Finally, 34energy storage systems were allocated in the same buses of the solar generators and in the buses that had consumers charged by the power they consume and not only the energy; for these consumers, the use of an energy storage system capable of redistribute the consumption along the hours of a day would be advantageous because it would reduce the global cost of electrical power.

Each substation has 16 feeders with 130 normally open switchgear between them, some between two different feeders, and some between buses of the same feeder. The consumption profile of the feeders is very similar, amounting each substation a consumption of 30 GWh/month.

Knowing these characteristics of the network, the methodology was applied with the parameters shown in Table 1:

Table 1 - Parameters for the optimization

Parameter	Value	Parameter	Value
β	0,3	α_{SAIFI}	0,3
α_{loss}	0,5	α_{ENS}	0,3
$\alpha_{continuity}$	0,3	$factor_{ENS}$	0,3
α_{SUF}	0,2	$\alpha_{SE_{CN}}$	0,5
$factor_{loss}$	0,3	$\alpha_{SE_{CS}}$	0,5
α_{SAIDI}	0,3	$factor_{SUF}$	0,5

The result of the optimization is a network that managed to reduce the technical losses and increase the SUF of the CS substation. However,the results show an increase in the reliability indices and a reduction in the SUF of the CN, both of these resultare not desirable but theyexpected in this type of optimization. The Table 2 show these results.

Table 2 - Results of the optimization

	Default Value	Result Value	Difference (%)
Losses (MWh)	105,458	85,288	19,13%
SAIDI (hours/year)	2,611	2,679	-2,60%
SAIFI (interruptions/year)	1,116	1,159	-3,85%
ENS (MWh/year)	190,833	196,407	-2,92%
SUF CN	0,277	0,259	-6,50%
SUF CS	0,258	0,275	6,59%

VII. CONCLUSION

In conclusion, the developed methodology can be applied to real electrical networks and suggests a new configuration that will optimize it, regarding the parameters set for the calculations and the new reality of energy supply and consumption.

It's important to point out that the optimization process has multiple objectives, so the suggested topology will not necessarily be able to improve all the indicator individually, as the case study has shown. In addition, the original state of the grid is also a significant factor, as the rates utilized in the optimization depend on the differences between the suggested topology and the original.

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