Load Shedding Through Optimal Power Flow to Support Self-Healing Actions in Distribution Feeders

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Abstract— **One of the main characteristics of the smart grid is the implementation and development of tools that allow the minimization of system vulnerability as well as an increase in security, reliability and power quality in distribution systems. This paper presents the development of a methodology to support self-healing through demand-side management (load shedding). This methodology allows the self-healing system to restore more loads when compared to traditional methods, through the indication of loads to shed in each bus of the distribution system, taken into account power quality constraints. The methodology was implemented using a Binary Particle Swarm Optimization (BPSO) to self-healing switching determination and Optimal Power Flow (OPF) for the load shedding scheme. The methodology proved to be able to restore more load in an optimal way, minimizing losses and assuring power quality.**

Keywords—self-healing; load shedding, optimal power flow, binary particle swarm optimization; smart grid.

I. INTRODUCTION

According to [1] the smart grid, when fully developed, will allow the involvement of clients as well as improvements in the generation, transmission and distribution, using tools that allow minimizing the vulnerability of the system as well as an increase in security, reliability and power quality. Some concepts that are either encouraged or enabled through the smart grid are:

- Self-Healing: the grid's ability to self-heal, i.e. perform continuous self-assessments to detect, analyze, respond to, and as needed, restore grid components or network sections in order to maintain grid reliability, security, affordability, power quality and efficiency [2];
- Demand-Side Management (DSM): the planning and implementation of activities to influence consumer use of electricity in ways that will produce desired changes in the load curve of an electric system [3].

The grid of the future will be distributed, interactive and will have a large scale communication backbone. This will enable better coordination and interaction between the various actors in the energy market [4].

The smart grid will also allow the integration of several of its functionalities in a complex and efficient decision making system, e.g. the integration of self-healing and DSM. This integration could be done in a way that more loads could be restored, when a fault occurs, and a bigger social and economic benefit would also be achieved.

DSM is usually treated as a function of load curve modulation: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape. To support self-healing actions usually is used peak clipping, through the direct control of devices to decrease the overall demand of a group of customers, or load shedding of selected customer or group of customers. To implement this appropriate contracts as well communication and control infrastructure should be available.

Some works have previously considered the use of load shedding in self-healing schemes. In [5] a self-healing approach using islanding and rate of frequency decline-based load shedding is presented. In this approach when a fault occurs first islands are formed searching for the optimum cut sets considering the least generation-load imbalance. Afterwards a two-phase load shedding scheme is proposed for both small and large disturbances. It was found that the load shedding scheme raises the stability performance of the system by shedding less load compared to the conventional load shedding scheme.

In [6] a scheme for load shedding that asses voltage stability based on a dynamic voltage stability criterion is presented, formulated using a voltage stability risk index. The system uses real-time measurements available through a synchrophasor based wide area monitoring and control system.

In Brazil, due to economic constraints, many distribution grids do not operate with as many equipment such as reclosers as it would optimally be needed, therefore it's usually considered the two and a half switches configuration, which allows the establishment of three load blocks in each feeder. Due to this restrictions (the small amount of reclosers/switches installed), when a self-healing action is proposed some load blocks may not be fully supplied by other feeder, therefore a group of costumers that actually could have their power restored stayed disconnected because

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it is not possible to restore the whole block. This characteristic motivated the development of the methodology that will be presented in this paper.

The organization of the rest of the paper is as follows. The methodology for self-healing and load shedding is present in II, case study is present in III, the results of the simulations in IV and, finally, conclusions are given in section V.

II. METHODOLOGY

This section discusses the methodology developed to self-healing optimization enhanced by bus-based load shedding. The algorithm can be seen in Fig. 1 and it is divided in two phases, the first determines the switching configuration for self-healing and the second the bus-based load shedding, if necessary.

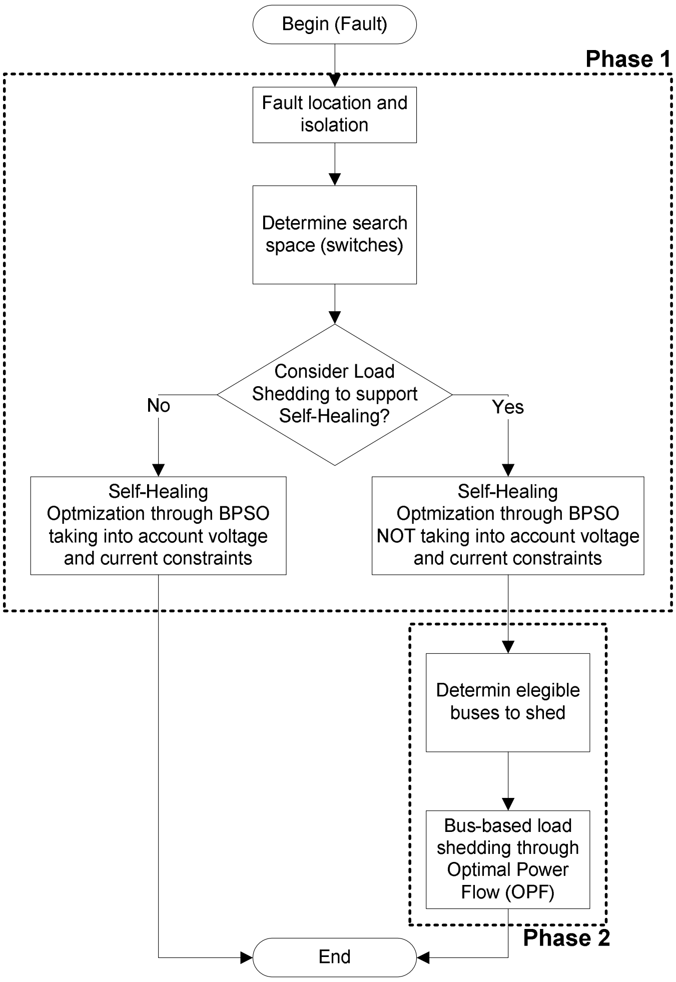

Fig. 1. Methodology algorithm for self-healing with load shedding.

This methodology is a continuous work. Previous studies were presented in [7] and [8]. [7] discusses deterministic and probabilistic approaches to the self-healing problem. [8] presents a methodology to self-healing with multiple feeders and multiple faults with optimization through genetic algorithms.

A. Self-Healing (Phase 1)

The algorithm presented in [8] was improved in terms of computational performance on this paper through the utilization of Binary Particle Swarm Optimization (BPSO) instead of genetic algorithms. PSO has several advantages compared to the genetic algorithm: lower number of parameters to adjust, less probabilistic transitions and ease to implement. In general it can be stated that the advantages of PSO include not having its base in differential equations, lower sensitivity to the nature of Objective Function (OF) and does not require a good initial solution [9].

The BPSO algorithm proposed in [10] was used, with the parameters showed in TABLE I. .

TABLE I. BPSO PARAMETERS.

Parameters	**Value**
Transfer Function	V4 as in [10]
Iteration	200
Population	50
Maximum inertia weight	0.9
Minimum inertia weight	0.4
c1 (cognitive parameter)	2
c2 (social parameter)	2
Maximum particle's velocity	6

This phase of the algorithm first determines the search space based on the fault(s) isolation. Afterwards the optimization through Binary Particle Swarm Optimization (BPSO) is performed to determine a switching to restore load

This optimization may be performed without considering the voltage and current constraints, if the bus-based load shedding will be later performed, or considering the voltage and current constraint, if the bus-based load shedding will not be performed.

The self-healing was modelled as multi-objective function, showed in (1). It is composed by three objective function (OF), the first OF is the maximization of load supply, the second OF is the minimization of the switching (commutations) needed to the self-healing action proposed and the third is the minimization of system technical losses after the reconfiguration. The problem is subject to voltage limits according to the Brazilian standards [11], as presented in (2), and maximum current ($Imax$) in the first branch connected in the substation, as presented in (3).

$$OF_{SH} = w1 \cdot \left(\frac{S_{tot}}{S+1}\right) + w2 \cdot \left(\frac{sw}{sw_{tot}}\right) + w3 \cdot \left(\frac{ls}{ls_{tot}}\right) \tag{1}$$

Constraints:

$$1.05 \geq V \geq 0.93\, p.u. \tag{2}$$

$$I_1 \leq Imax \tag{3}$$

where w1, w2 and w3 are weights to the OFs, S_{tot} the maximum load supplied, S the load supplied after self-healing, sw the amount of commutation of the switches, sw_{tot} the total number of switches (defined in the search space), ls represent the system technical losses after self-healing, ls_{tot} the sum of system losses of all feeders studied and I_1 the current in the first branch connected to the substation. In the first objective the denominator S was added in "1" so that the fraction will be mathematically feasible even when the optimization would not be able to restore any loads.

Beyond these constraints, the feeders may not operate in parallel, i.e. each feeder should contain only one main power source (substation). Furthermore the system must retain its radial configuration, not presenting any closed loop after the self-healing switching. These constraints are analyzed each iteration of the BPSO.

B. Load Shedding (Phase 2)

The second phase of the methodology only occurs if the load shedding is to be performed. On this phase first the eligible buses to be shed are determined, so that only buses from the blocks that are currently not energized will be shed. The determination of the amount and which buses are to be shed are determined through OPF, which determines an optimal set minimizing technical losses and attending voltage and current constraints.

The formulation of the OPF is presented in [12], where balance equations of active and reactive power are modeled using the rectangular representation of the voltage phasors. The OF to minimize load shedding was considered as following:

$$OF_{LS} = \alpha^t \cdot \Delta Pd \tag{4}$$

where α^t is a vector of size nc (amount of eligible buses to shed) containing the cost of reduction per bar and ΔPd is a vector of dimension nc with the amount of load to be shed in each bus.

The problem is subject to power balance equations, generation limits and voltage magnitude limits. The complete formulation is presented in [12]. Nevertheless changes were proposed through an additional restriction to the problem, as presented in (5) (magnitude current limit ($Imax$) in the feeder first branch connected to the substation).

$$\left[real\left(\frac{V_i - V_j}{Z_{ij}}\right)\right]^2 + \left[imag\left(\frac{V_i - V_j}{Z_{ij}}\right)\right]^2 \leq Imax_{ij}{}^2 \tag{5}$$

where V is the voltage, i and j are the nodes and Z is the branch impedance.

III. CASE STUDY

This section presents the case studies that will be analyzed. The methodology was tested on a set of five real urban medium voltage feeders (13kV), where feeder one (FD1) has a total load of 2.89MVA – 57 buses; feeder two (FD2) 6.30MVA – 118 buses; feeder three (FD3) 5.40MVA – 108 buses; feeder four (FD4) 5.59MVA – 113 buses; feeder five (FD5) 6.39MVA – 158 buses. All the feeders were previously presented in [7].

The topology is showed in Fig. 2, where the gray squares represent the normally closed (Sij) switches and the smaller gray square the circuit breaker (CBij). Each feeder is divided in three load blocks (BLij), where "i" shows the feeder code and "j" the block code. Furthermore the white squares represent the tie switches (TSij), normally opens switches that connect a feeder to another ("i" and "j", in this case, are the feeders' code).

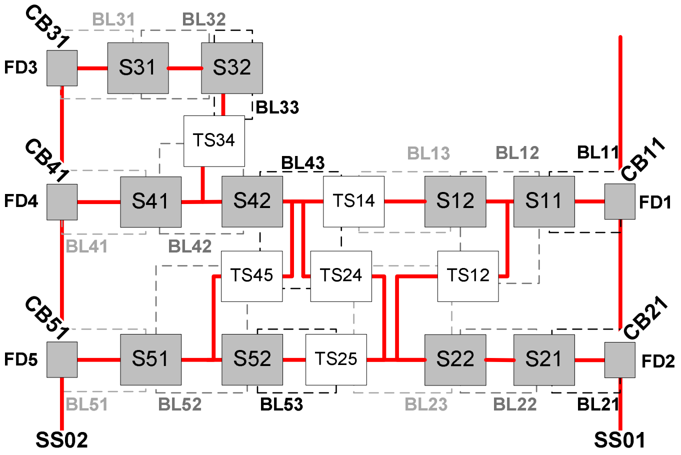

Fig. 2. Nominal system configuration.

To compare the influence of the load shedding in self-healing problems a case study that considers an extreme situation, the fault on substation 2 (SS02). This fault causes the opening of CB31, CB41 and CB51, causing the loss of energy supply to consumers in three feeders: FD3, FD4 and FD5.

The maximum current value for each feeder is 404.14A, so that the maximum power flow on the substation won't exceed 9.1MVA. The weights values of the objective function presented in (1), w1, w2 and w3, are respectively 10, 1 and 1. Therefore a greater importance is given to restore loads and a smaller importance to the minimization of switching and losses.

Only the buses of the feeder relocated can be shed, being the buses from the base feeder not eligible. All eligible buses have the same priority to shed.

IV. RESULTS

For the evaluation of the multi-objective function presented in (1), a load flow analysis is necessary. It was performed with the backward/forward sweep method through OpenDSS [12]. The main script was developed in Matlab (MATrix LABoratory).

To assess the impact of load shedding in self-healing two analysis were performed: i) Self-healing without bus-bases load shedding; ii) Self-healing with bus-based load shedding, as presented in the flowchart from Fig. 1.

The first analysis refers to the situation when the BPSO constraints penalize the multi-objective function, i.e. both restrictions (2) and (3) are active and influence on the switching of the self-healing method. The self-healing action under the described condition is showed in Fig. 3, where FD1 can only restore power to the blocks of FD4, without violating current and voltage limits. The FD2 can't restore power to any blocks of the system, because if it restores power to only BL53 that has 3.93MVA, for example, it already violates the current limit. The same would happen if it restores power to BL43.

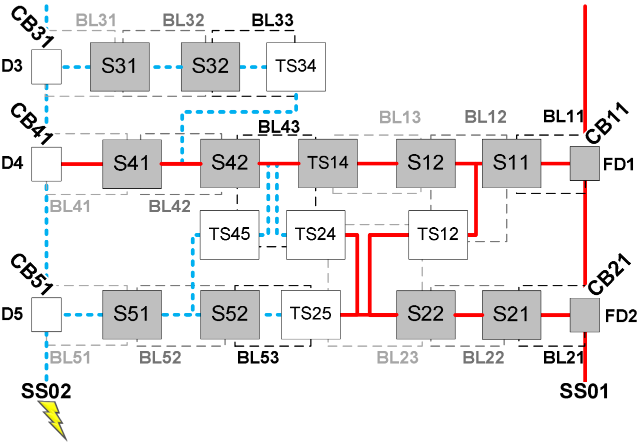

Fig. 3. Reconfiguration after the self-healing without bus-based load shedding.

The second analysis considers the bus-based load shedding after the self-healing. As voltage and current limits are not taken into account in this analysis, FD1 can restore power to all blocks of FD3 and FD4, as shown in Fig. 4. FD2 can restore power to all blocks of FD5. However, after the self-healing switching, the current limit was extrapolated in both feeder and the voltage limit slightly violated in FD1, as shown in Fig. 5. It is then necessary to perform the OPF analysis to determine which buses must be shed as well as the amount of load to be shed, for the system to operate within normative conditions.

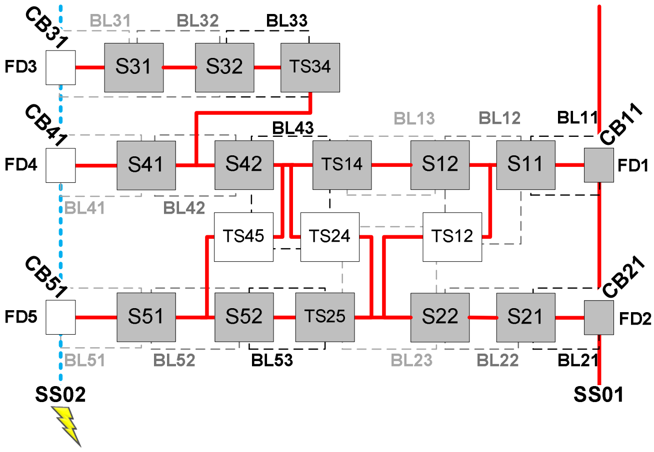

Fig. 4. Reconfiguration after the self-healing with bus-based load shedding.

Load shedding was applied in FD1 and FD2 (considering its new configuration). TABLE II shows FD1 and FD2 results of supplied load. The current values violated the established limits.

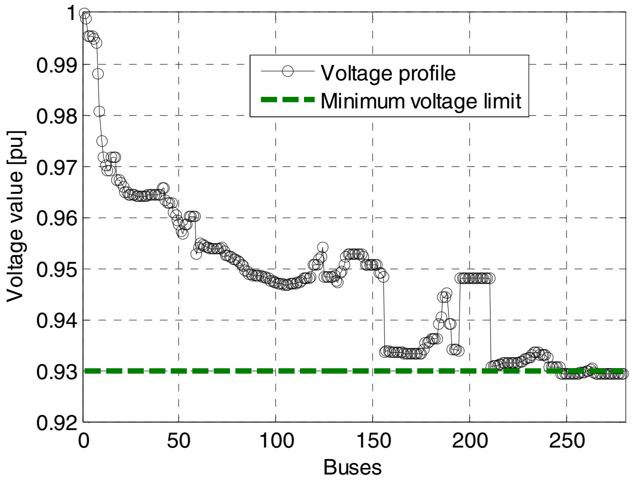

Fig. 5. Voltage profile in Feeder 1 (FD1) after self-healing.

TABLE II. RESULTS AFTER THE SELF-HEALING.

Feeder	Supplied load [MVA]	Power Flow [MVA]	Current in the first branch [A]
Feeder 1 (FD1)	13.9	14.45	641.89
Feeder 2 (FD2)	12.6	13.13	583.34

Fig. 6 and Fig. 7 present the cumulative sum of apparent power in each bus. In Fig. 6 it can be visualized that the first 57 buses remained with the same power before and after load shedding, because those were the feeder base buses, and therefore not eligible for load shedding. 36.26% of the load in FD1 was shed, resulting in a supply of 8.86MVA.

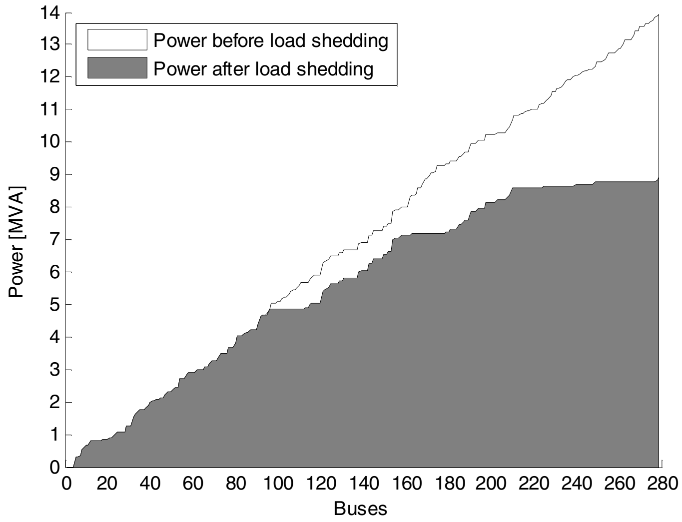

Fig. 6. Camparation before and after did the load shedding for feeder 1 (FD1).

As in FD1, the first 118 buses of FD2 weren't shed. 103 buses were shed resulting in 28.89% of shed, or 8.93MVA supplied load.

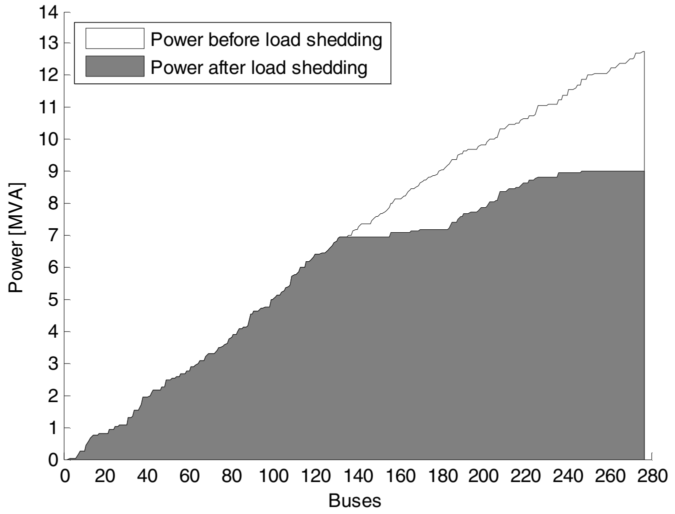

Fig. 7. Camparation before and after did the load shedding for feeder 2 (FD2).

Fig. 8 shows that the method with bus-based load shedding could supply more loads then the method without bus-based load shedding in both cases. As the FD1 has 31.98% (supplied load + losses) of its capacity, it can supply, in the considered load conditions, more 6.19MVA. Therefore FD1 can restore FD4 entirely or blocks of feeders 3 or 5 without the load shedding method. But, if load shedding would be considered, it can restore even more power and, as the OPF objective function is minimize the losses, the OPF will shed the buses more distant from substation. For example it can shed some buses farther from substation in FD4 to restore buses (with more loads) near the substation in FD3.

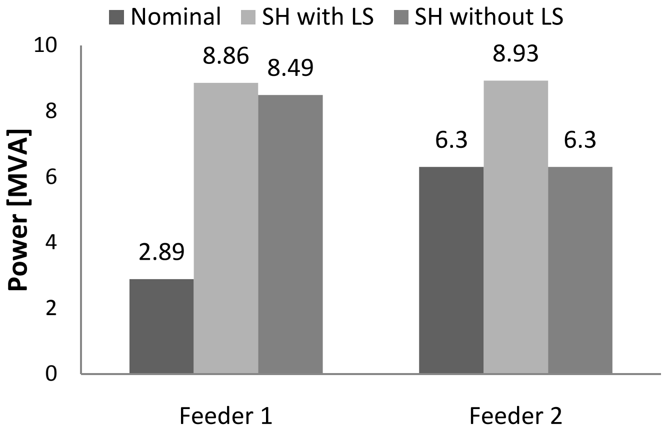

Fig. 8. .Comparisson between self-healing with and without bus-based load shedding

In FD2 there was a more noticeable difference between the methods, because it can just restore 2.6MVA. The next blocks BL43 and BL53 have more than 3MVA, therefore the supply of these blocks without the bus-based load shedding scheme would violate the power flow limit, for this reason the method with load shedding is more efficient.

V. CONCLUSION

The methodology developed of self-healing with bus-based load shedding demonstrates to be efficient and to be able to restore more power than the methods of self-healing that don't have the load shedding, minimizing losses at the same time.

It should be noted that using this method, in both cases there is an increase of restored load rather than a without the load shedding. The method represented a greater increase (41.7%) in the Feeder 2 without extrapolate constrains that was applied in the OPF, as the current and voltage limits, whereas the OPF find the optimal configuration of which bars is needed to make the shed.

But in order to use this method is necessary the increase participation of the customer on the operation of the power grid through demand-side management and the decrease of the building costs of smart meter, one may expect an increasing number of these devices in the distribution systems. The smart meters could then be used to support self-healing actions, through the connection/disconnection from selected customers in distribution feeders. This could help to implement bus-based load shedding in distribution feeders.

For future researches the implementation of the load shedding for the consumers level will be studies, where the shed could be done though the selection of smart meters, considering a priority list of loads as an input to the OPF.

REFERENCES

[1] J. Momoh, ‘Smart Grid: Fundamentals of Design and Analysis,” Wiley, 2012.

[2] National Energy Technology Laboratory (NETL), “A Systems View of the Modern Grid,” 2007.

[3] C.W. Gellings, “The Conecpt of Demand-Side Management for Electric Utilities,” Proceeding of the IEEE, Vol. 73, No. 10, p. 1468-1470, 1985.

[4] IEA (International Energy Agency), “Technology Roadmap – Smart Grids,” 2011.

[5] H. You, V. Vittal and Z. Yang, “Self-Healing in Power Systems: An Approach Using Islanding and Rate of Frequency Decline-Based Load Shedding,” IEEE Transactions on Power Systems, Vol. 18, No. 1, 2003.

[6] K. Seethalekshmi, S.N. Singh, S.C. Srivastava, “A Synchrophasor Assisted Frequency and Voltage Stability Based Load Shedding Scheme for Self-Healing of Power System,” IEEE Transactions on Smart Grid, Vol. 2, No. 2, 2011.

[7] L. Siebert, A.R. Aoki, A.R.R. Souza, L.R. Ferreira, A.F. Bonelli, F.O. Toledo, (2013), “Deterministic Versus Probabilistic Approaches to Self-Healing in Smart Grid,” 22nd Internation- al Conference on Electricity Distribution (CIRED), 10-13 Jun., 2013.

[8] L.R. Ferreira, L.C. Siebert, H. Ayala, A.R. Aoki, and L.C. M. Direito, “Solução do problema de self-healing para redes de distribuição radiais através de otimização via algoritmo genético,” Simpósio Bras. Automação Intel., 2013.

[9] M. R. Alrashidi and M. E. El-Hawary, “A survey of particle swarm optimization applications in electric power systems,” *Evolutionary Computation, IEEE Transactions on*, Vol. 13, n. 4, p. 913–918, 2009.

[10] S. Mirjalili and A. Lewis, “S-shaped versus V-shaped transfer functions for binary Particle Swarm Optimization,” *Swarm Evol. Comput.*, Vol. 9, p. 1–14, Apr. 2013.

[11] ANEEL(Agência Nacional de Energia Elétrica), (2012), “Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional – PRODIST Módulo 8 – Qualidade da Energia Elétrica”.

[12] T.S. Fernandes, J. Lenzi, M.A. Mikilita, “Load shedding strategies using optimal load flow with relaxation of restrictions,” IEEE Transactions on, IEEE, v. 23, n. 2, p. 712–718, 2008.

[13] R.F. Arrit, R. Dugan, R. Henry, T. McDermott. (2008, August 30). OpenDSS, [Online], Available: http://sourceforge.net/projects/electricdss