SERVICE RESTORATION IN DISTRIBUTION SYSTEMS WITH DISTRIBUTED GENERATORS USING TABU SEARCH

Benvindo Rodrigues Pereira Junior
Escola de Engenharia de São Carlos – EESC - USP
Departamento de Engenharia Elétrica e de Computação
Av. Trabalhador São Carlense, 400, 13566-590, São Carlos, SP.
brpjunior@gmail.com

Geraldo Roberto Martins da Costa
Escola de Engenharia de São Carlos – EESC - USP
Departamento de Engenharia Elétrica e de Computação
Av. Trabalhador São Carlense, 400, 13566-590, São Carlos, SP.
Geraldo@sc.usp.br

Javier Contreras
Universidad de Castilla La-Mancha – UCLM
Departamento de Ingeniería Eléctrica
Av. Camilo José Cela, Campus Universitario, 13071, Ciudad Real, Espanha.
Javier.Contreras.@uclm.es

José Roberto Sanches Mantovani
Faculdade de Engenharia de Ilha Solteira – FEIS - UNESP
Departamento de Engenharia Elétrica
Av. Professor José Carlos Rossi, 1370 - Ilha Solteira-SP CEP 15385-000
mant@dee.feis.unesp.br

RESUMO

Neste artigo propõe-se um modelo e uma técnica de otimização para a restauração do serviço em sistemas de distribuição de energia elétrica. A função objetivo visa minimizar a quantidade de seções desligadas devido uma determinada falta no sistema. A geração distribuída é considerada no problema de restauração e os despachos de potência ativa e reativa são encontrados através um fluxo de potência ótimo. O problema de restauração é formulado como um problema de programação não linear inteira mista e um algoritmo busca tabu é utilizado para resolver o modelo apresentado. Para avaliar este método, são apresentados resultados para um sistema de 24 barras.

PALAVARAS CHAVE. Otimização combinatorial, Metaheurísticas, Confiabilidade.

ABSTRACT

This paper proposes a model and an optimization technique for service restoration in distribution systems. The objective function seeks to minimize the amount of sections turned off due to outages in the system. Distributed generation is considered in the restoration problem and the dispatches of active and reactive power are found solving an optimal power flow. The restoration problem is formulated as a nonlinear mixed-integer programming problem and a tabu search algorithm is used to solve the resulting model. To evaluate this method, results for a 24-bus system are presented.

KEYWORDS. Combinatorial optimization, Metaheuristics, Reliability.

1. Nomenclature

Sets and Indexes

nb	Set of system buses;
nDG	Set of distributed generators installed in the system;
$nFEj$	Set of feeders of substation *j*;
nl	Set of system lines;
$nsec$	Set of sections affected by the outage;
$Secrej$	Set of sections restored through substation *j*;
nSS	Set system substations;

Functions

$G(V,\theta)$	Equations of power flow;
$f(x_i)$	Switching function.

Costs

C_{swi}	Switching operation costs;

Binary variables

x_i	Decision to restore (0) or not (1) section *i*;

Continuous variables and their limits

V_k	Voltage at bus *k*;
V_{max}	Minimum voltage level of the feeder;
V_{min}	Maximum voltage level of the feeder;
I_j	Current through line *j*;
I_{cable}^{j}	Maximum current allowed through line *j;*
$losses_j$	Losses of lines connected by substation *j*;
$P_{SS_j}^{i}$	Active power at the beginning of feeder *i* of substation *j*;
$Q_{SS_j}^{i}$	Reactive power at the beginning of feeder *i* of substation *j*;
P_{DG}^{g}	Active power injected by DG unit installed at bus *g* in MW;
$P_{DG\,min}^{g}$	Minimum active power limit of a DG unit installed at bus *g* in MW;
$P_{DG\,max}^{g}$	Maximum active power limit of a DG unit installed at bus *g* in MW;
Q_{DG}^{g}	Reactive power injected by DG unit installed at bus *g* in MVAr;
$Q_{DG\,min}^{g}$	Minimum reactive power limit of a DG unit installed at bus *g* in MVAr;
$Q_{DG\,max}^{g}$	Maximum reactive power limit of a DG unit installed at bus *g* in MVAr;
S_{sec}^{i}	Load of section *i* in MVA;
S_{fe}^{ij}	Load of feeder *i* of substation *j* in MVA;
S_{SS}^{j}	Capacity of substation *j* in MVA.

2. Introduction

Distribution systems are very susceptible to contingences, which often cause interruptions of power supply due to the action of protection devices. Given these interruptions, regulatory agencies impose on the distribution companies (DISCOs) goals with the objective of maintaining the quality of power supply services. These goals are quantified through quality indices (system average interruption duration index (SAIDI), average system availability index (ASAI), customer interruption duration (CID) at each load node, and the non-supplied energy(NSE) [1-3]) [4].Not complying with these goals may result in fines and financial losses by the DISCOs, which justifies their research investment in techniques and models for the development of efficient tools that are able to improve quality and reliability indices.

A procedure widely adopted by the DISCOs to improve such indices and maintain the limits required by regulatory agencies is System Restoration, which allows that part of the system affected by outages (turned off) due to a contingency or preventive maintenance of network equipment can be partially or even totally restored, changing the system topology [4].

The system restoration involves the formulation and solution of a nonlinear and complex combinatorial optimization model subject to several technical and operational constraints. In addition to sectionalizing devices and tie lines used to control power supply interruptions, distributed generators (DGs), equipment that has been a great area of study in the past few years, can contribute to restore loads, provided that they are placed in strategic places. Nonetheless, their use in distribution systems increases the complexity of the system restoration problem.

Over the years, many papers have presented models and proposed solution techniques to solve such a problem [4-10]. In this paper the focus is the distribution networks restoration with distributed generators (DGs). The insertion of microgenerators contributes to increase the reliability, but at the same time also increases the complexity of the operation and planning of distribution systems. The main points are still uncertain related to the overcurrent protection devices and the operation of automatic action, such as reclosers and sectionalizers. The possibility operating of the distribution system through one or more dispersed generators (intentional islanding mode) emerges as an interesting alternative to ensure the electricity provision to the portion of the system that was de-energized indirectly by the fault. In this way the restoration problem is formulated as in [4], but this formulation offers significant contribution, since it considers DG presence. The resulting model was solved using the same solution technique shown in [4], which was adapted to consider the DG. The active-reactive power constrains of DGs are included in the set of constraints of the model, once the power output of a DG can vary with the new system topology. Results for a 24-bus system are presented.

3. Mathematical Model

Distribution system restoration problem is formulated as a Mixed-Integer Nonlinear Programming Problem (MINPP) in which the main goal is to restore the largest number of customers with few switches operations in the shortest possible time. Some considerations are taken into account in the model development:

- DGs are dispatchable;

- Only off sections due to faults may be relocated;

- Sections under influence of a DG are turned off when such a DG is affected by an outage;

- DGs can operate in an islanded area (microgrids).

So the restoration problem is formulated as follows:

$$OF = Min\left(\sum_{i\in nsec} S_{sec}^{i}.x_i + \sum_{i\in nsec} C_{swi}.f(x_i)\right) \quad (1)$$

subject to:

$$G(V,\theta,x_i) = 0 \quad (2)$$

$$\sum_{i\in nFEj} S_{fe}^{ij} + \sum_{i\in Secrej} S_{sec}^{i} + losses_j \leq S_{SS}^{j} \qquad \forall j \in nSS \quad (3)$$

$$I_j \leq I_{cable}^{j} \qquad \forall j \in nl \quad (4)$$

$$V_{min} \leq V_k \leq V_{max} \qquad \forall k \in nb \quad (5)$$

$$x_i = \{0,1\} \qquad \forall i \in nsec \quad (6)$$

$$P_{SS_j}^{i} \ , Q_{SS_j}^{i} \ \geq 0 \qquad \forall i \in nFEj \quad (7)$$

$$P_{DG\,min}^{g} \leq P_{DG}^{g} \leq P_{DG\,max}^{g} \qquad \forall g \in nDG \quad (8)$$

$$Q_{DG\,min}^{g} \leq Q_{DG}^{g} \leq Q_{DG\,max}^{g} \qquad \forall g \in nDG \quad (9)$$

The objective function (1) is to minimize the amount of turned off sections with the least possible changes in the network, since the restorative state is temporary. Function $f(x_i)$ is defined as the number of changes in the switches necessary to set up a specific topology. This function is multiplied by C_{swi} to avoid unnecessary switching.

The minimization of the objective function is subject to a set of constraints: (2) represents the set of nonlinear equations (Kirchhoff's Laws) that ensures the active and reactive power balance at all the buses of the restored system; (3) ensures that the power capacity available in a substation should be sufficient to supply the loads connected to its feeders, the loads of restored sections through their feeders and losses during the restorative state; (4) ensures that current limits of cables are not exceeded; (5) refers to the quality of power supply, ensuring that the voltage at buses in the restorative state are within preset limits by regulatory agencies; (6) represents the decision variable state of a specific section; (7) prevents reverse flow through the substation due the power output of DGs; (8) and (9) ensure the power production of DGs within its technical limits.

In the presented model the violated constraints are considered in the objective function through penalty techniques. Thus, the violation of these constraints implies an increase in the value of the objective function according to (10) [4].

$$OF = Min\left(\sum_{i\in nsec} S_{sec}^{i}.x_i + \sum_{i\in nsec} C_{swi}.f(x_i) + \sum_{i\in M} \mu_i\,|b_i|\right) \quad (10)$$

where μ_i is a penalty factor applied to the i-th violated constraint and b_i specifies how much this constraint is violated.

4. Solution technique

The problem of service restoration (1) - (9) is solved by a tabu search algorithm. Tabu search is a powerful metaheuristic technique [11] that has been widely used to solve large and complex optimization problems. The algorithm used to solve the proposed model was adapted from [4], to taking into account specific characteristics of the problem, obtain reliable results and have low computational cost. The tabu search algorithm is described below.

A. Codification

First, the concept of section should be clarified. In this work, section is defined as a group of branches and load points among adjacent sectionalizing devices (Figure 1).

The coding for the restoration problem uses a decimal base, and it is formed by two vectors (*P*1 and *P*2). The first one represents the source sections, i.e., the section whereby a specific turned off section is restored. The other one represents the turned off section due an outage.

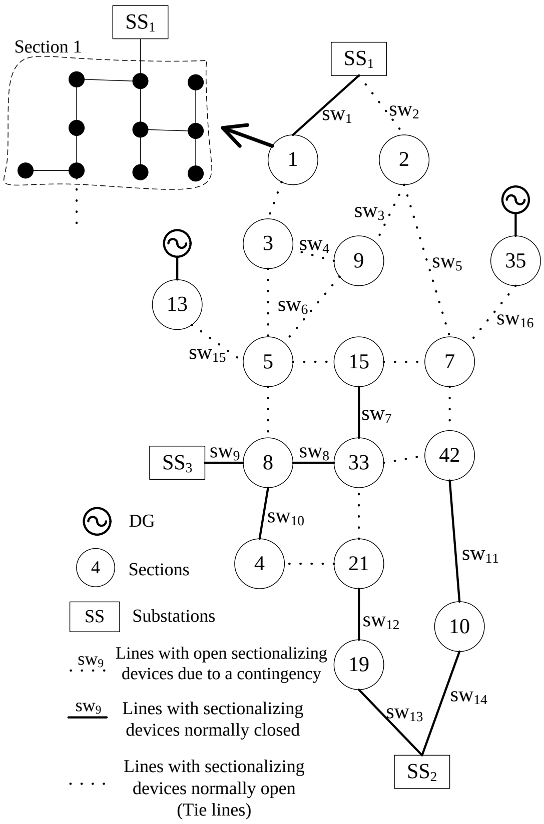

Figure 1 - Distribution system representation (Adapted from [4]).

Consider that, in Figure 1, sections 3, 5, 7, 9, 13 and 35 were disconnected due to a contingency in Section 2. The codification for this scenario is represented in Figure 2.

P1	0	0	0	0	0	0	← Source sections
P2	13	3	5	9	7	35	← Turned off sections

Figure 2 - Solution codification for an outage in section 2 (Adapted from [4]).

To make up *P*1, in addition to the possibilities presented in [4] (substations, sections that remained on; and sections that was restored) DGs are also used to restore out sections. For example, sections 13 and 35 may be restored using a DG present in the section and sections 5 and 7 restored by sections 8 and 42, respectively. Once section 5 was restored through section 8, for example, this can restore sections 3 and 9. Thus, Figure 3 shows an example of the complete solution.

P1	DG	5	8	5	15	7	← Source sections
P2	13	3	5	9	7	35	← Turned off sections

Figure 3 - Complete codification (Adapted from [4]).

B. *Neighborhood structure*

Neighborhood is one of the most important concepts of tabu search and the algorithm efficiency is directly influenced by it. The codification used in this work for the service restoration problem allows in an easy and practical way generates an efficient neighborhood. The neighborhood structure consists in amending the source sections of the specific turned off section. In this case, a neighbor differs from the current solution in only one source section. Thus, the number of neighbors generated at each iteration is equal to the number of sections to be restored. Sections sources can only be replaced by energized sections, substations, DGs or zero, representing that this section is disconnected from the system. Using the proposed solution encoding in Figure 3, might be possible the following neighbors: change DG of section 13 by 5; change 3 of section 5 by 1; change 5 of section 9 by 0, and other ones. These neighbors are illustrated in Figure 4.

N1	5	5	8	5	15	7	← Source sections
N2	DG	1	8	5	15	7	← Source sections
N3	DG	5	8	0	15	7	← Source sections
P2	13	3	5	9	7	35	← Turned off sections

Figure 4 - Possible neighbors to proposed solution of Figure 3 (Adapted from [4]).

One of the most differences compared to [4] along with constraints (7), (8), and (9) is the OPF (optimal power flow) solution, due to DGs presence that makes the traditional distribution systems in active networks. For each neighbor, an OPF is solved to find the DG's dispatches and evaluate the objective function. The OPF is solved by a genetic algorithm (GA) based on the Chu-Beasley algorithm [12-16] that uses a power flow sweep (backward/forward sweep) algorithm [14-16] designed for weakly meshed networks and with a bus model with voltage control (PV-bus) [14-16].

C. *Tabu List and convergence criteria*

The tabu list (TL) stores the attributes during *k* iterations, avoiding the return of the process to previously visited solutions. The attribute stored in the TL is the exchange in the source sections made to generate a new solution. To provide greater process flexibility, an aspiration criterion is used to allow that good quality solutions that share prohibited attributes may be visited. The aspiration criterion adopted is the improvement of the objective function.

The convergence criteria adopted are: the maximum number of iterations carried out by the algorithm, or, if the incumbent solution remains unchanged for a predetermined number of iterations, the process is considered converged.

5. Results

The developed algorithm to solve the proposed model for system restoration was tested in a 24-bus system (20.0 kV) adapted from [17] and illustrated in Figure 5. System data are presented in Appendix I.

To carry out these tests, it was considered that all lines of the system have some kind of sectionalizing device. The dotted lines are tie lines that may be used to restore the system. The daily load curve used during the restoration process has three load levels: 0.65, 0.8 and 1.0. Voltage limits are 0.95 and 1.05 pu. DGs characteristics are described in Table 1, whereas Table 2 presents results of outages in every section of the system and in the DGs. The results were found using an *n*-1 criterion, but others like *n*-2, *n*-3 can be used due the easy and practical codification structure.

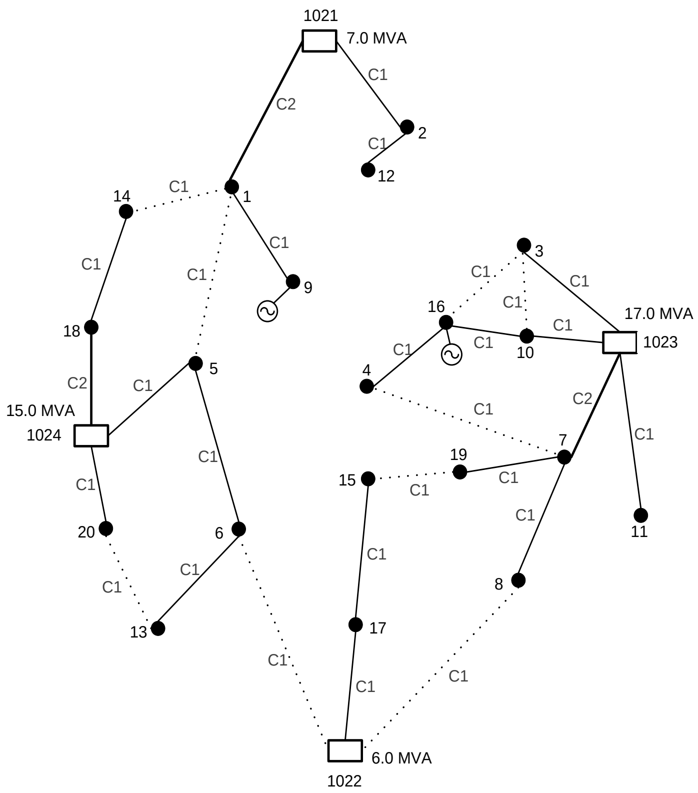

Figure 5 - System test.

Table 1 – DG Data

Power	Min	Max
P_{DG}^{g} (MW)	0	3.0
Q_{DG}^{g} (MVAr)	PF* = 0.95 capacitive	PF* = 0.85 inductive

* PF – Power factor

Some cases will be detailed below in order to verify the influence of DGs in the restoration problem of distribution systems. The first one takes place when a contingency occurs in section 1. The DG present at bus 9 makes the restoration of this section possible through an islanded operation. However, the same DG turned off sections 1 and 9 when there is a contingency due the high load connected at bus 1 and the low capacity of substation 1021. The same occurs with the DG installed at bus 16. It provides the restoration of buses 4 and 16 when section 10 is out, but turned off sections 10 and 16 when it is out, making it possible to restore only section 4. In Figure 6 the characteristics of the restoration state to a contingency in section 10 are presented. For this topology, the active and reactive power outputs of the DG installed at bus 16 for the load level of 1.0 (worst case) are 2575.76 MW and 523.03 MVAr, respectively, and the demand of power through substation at node 1023 is 15.26 MVA.

To run all of the cases presented in Table 2 the CPU time was 0.97 s using a notebook Intel® Core™ i7, 2.0 GHz and 8.0 Gb of RAM memory. The algorithm was implemented in FORTRAN.

Table 2 – Restoration results

Contingency Sections	Affected	Turned off	Restored
#1	9	-	9
#2	12	12	-
#3	-	-	-
#4	-	-	-
#5	6,13	6	13
#6	13	-	13
#7	8,19	8	19
#8	-	-	-
#9	1	1	-
#10	4,16	-	4,16
#11	-	-	-
#12	-	-	-
#13	-	-	-
#14	-	-	-
#15	-	-	-
#16	4,10	10	4
#17	15	15	-
#18	14	-	-
#19	-	-	-
#20	-	-	-
#DG 9	1,9	1,9	-
#DG 16	4,10,16	10,16	4

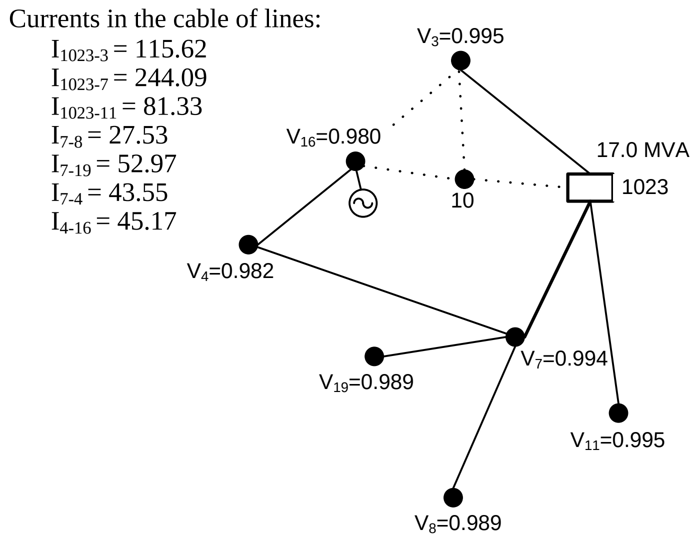

Figure 6 - Characteristics of the part of system with new topology. (Currents in A and voltage in p.u.).

6. Conclusions

Distributed system restoration is a difficult task for DISCOs, since it is a combinatorial optimization problem. In this work this problem is modeled as a non-linear mixed-integer problem and solved by a tabu search algorithm. The results prove the speed and efficiency of the proposed algorithm to find the restorative state due outages in the system, which can be readily applied in the analysis of large systems. The results were found using an *n*-1 security criterion.

As observed in the results, DGs can aid in the restoration process, making it possible for some sections to operate in an islanded mode during the repair time of the contingency. Nonetheless, sometimes DGs also can turn off sections influenced by it if some contingency affected the section where it is allocated or even the DG itself. In this way, this tool may be used to contribute to find the best place for DGs, the capacity of a substation and lines, and to improve the reliability of the system.

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Apendix I

Table 3 - System bus data

Bus	Power		Bus	Power	
	kW	kVAr		kW	kVAr
1021	0.00	0.00	**9**	1504.50	932.40
1022	0.00	0.00	**10**	2040.00	1264.28
1023	0.00	0.00	**11**	2380.00	1474.98
1024	0.00	0.00	**12**	1096.50	679.55
1	4607.00	2855.17	**13**	1647.50	877.82
2	1028.50	637.40	**14**	2686.00	1664.63
3	3383.00	2096.60	**15**	1377.00	853.38
4	2083.17	1258.12	**16**	1037.00	642.67
5	399.50	247.58	**17**	2040.00	1264.28
6	1557.33	925.23	**18**	1785.00	1106.25
7	3706.00	2296.77	**19**	1538.50	953.48
8	799.00	495.18	**20**	3221.50	1996.50

Table 4 - system line data

Noi	Nof	Cable	D(m)	Noi	Nof	Cable	D(m)
1021	**1**	C2	2200	**1024**	**18**	C1	1500
1021	**2**	C1	1700	**1024**	**20**	C1	900
1	**14**	C1	1200	**5**	**6**	C1	2400
1	**5**	C1	2220	**6**	**13**	C1	1200
1	**9**	C1	1200	**13**	**20**	C1	2200
2	**12**	C1	1100	**1022**	**6**	C1	2700
1023	**3**	C1	1200	**1022**	**17**	C1	1500
1023	**10**	C1	1300	**1022**	**8**	C1	1900
1023	**11**	C2	1600	**7**	**8**	C1	2000
1023	**7**	C1	900	**7**	**19**	C1	1200
3	**10**	C1	1100	**10**	**16**	C1	800
3	**16**	C1	1200	**14**	**18**	C1	1000
4	**7**	C1	2600	**15**	**17**	C1	1200
4	**16**	C1	1300	**15**	**19**	C1	1600
1024	**5**	C1	700				

Table 4 - Cable data

Type	R(Ω/km)	X(Ω/km)	I_{max}(A)
C1	0.614	0.399	197
C2	0.407	0.380	314