Optimal Location of Normally Open Switches in Order to Minimize Power Losses in Distribution Networks

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***Abstract*— This paper presents a deterministic optimization technique for the optimal location of normally open switch on a real distribution network, located in north of Portugal. The goal is to find the optimal radial topology that minimizes the power losses. The method is developed in TOMLAB software, and is formulated as a mixed integer quadratic programming problem. Given the current characteristics of the network, the method is based on optimal power flow through DC model. The power losses are given by the Joule effect, calculated according to each distribution line. In order to prove the viability of the obtained results, the proposed methodology is compared with a software used by Portuguese operator for distribution networks planning.**

***Index Terms*— Distribution network reconfiguration, Normally open switch, Optimal power flow, Power losses.**

NOMENCLATURE

R_{ij}	Resistance between bus *i* and bus *j*
S_{ij}	Apparent power between bus *i* and bus *j*
NL	Total number of lines
$Sgen_i$	Apparent power produced in bus *i*
L_i	Load in bus *i*
NB	Total number of buses
$Sgen_i^{\min}$	Minimum apparent power produced in bus *i*
$Sgen_i^{\max}$	Maximum apparent power produced in bus *i*
y_{ij}	Binary decision variable associated with the distribution line *ij*
y_{ij}^j	Binary decision variable to connect distribution line *ij* to bus *j*
L_R	Active power losses reference
ΔZ	Margin for which the incentive is zero
$CO_{\max}$	Maximum compensation
$PE_{\max}$	Maximum penalty
W_{Losses}	Energy losses
β	Losses factor
T	Number of hours in a year
$P_{PeakLosses}$	Active power peak losses

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I. INTRODUCTION

Usually, distribution networks are meshed in design, but are operated in a radial way. It is possible to set an optimal radial topology by an appropriate maneuver of existent switches. By searching for the most suitable objective function, it is possible to optimize the location of switches, and thus maximize the distribution network benefit. In distribution networks two types of switches can be found, the normally open (NO) and normally closed (NC). It is the switching of these devices that allows the radial operation of the distribution networks.

In 1975 Merlin and Back [1], presented the first technical reconfiguration of distribution networks to minimize the power losses. Since then, many other techniques have been proposed to minimize the power loss, making this objective function the most common in the literature. However, the reconfiguration may also be performed for other objectives, such as, maximizing reliability, and load balancing. Also, the reconfiguration must comply with the system constraints [2][3], such as: radial network configuration; supply all loads;

all buses connected; technical limits of lines and transformers; among others.

The high combinations number of the NO points location, along with the discrete nature of the switches, require advanced computational techniques. Most of the algorithms used in the literature are based on heuristic methods, characterized by processing times that can be used in real time. The use of deterministic methods is limited due to high processing time, but, unlike heuristics, these ensure the optimal solution. Currently, it is possible to find deterministic methods applied to the reconfiguration problems with good computational times. A good example is presented by Khodr et al. [4], for reconfiguration of distribution networks to minimize the power losses. The author uses a technique based on Benders decomposition, which divides the problem into two sub-problems: the first one is formulated as a mixed integer quadratic problem (MIQP), and determines the radial topology of the distribution network. The second one, called the slave problem, is formulated as a nonlinear programming problem and determines the feasibility of the main problem solution by means of a OPF. Dias et al. [5], presents an identical technique, modeled by a multi-objective problem, minimizing the costs associated with power losses, reactive power and energy not supplied. Ajaja and Galiana [6], present a deterministic technique for reconfiguration of distribution networks, modeled by a mixed integer linear programming problem (MILP). The authors use, the linearization of the OPF and power losses.

This paper proposes a deterministic technique for the optimal location of NO switches in a real distribution network, located in north of Portugal. Initially it is considered a meshed network topology without the existence of switches. The objective is to find the optimal radial topology that minimizes power losses. Four feeders are considered (three feeders of the substation 1 and one feeders of the substation 67), ensuring the N-1 criterion in case of supply failure. The method is developed in TOMLAB software, and is formulated as a mixed integer quadratic problem (MIQP). Given the current characteristics of the network, the method is based on OPF through the DC model. The power loss is given by the Joule effect, calculated according to each distribution lines.

This paper is organized as follows. The problem formulation is presented in Section II. Section III presents the case study. Finally, the paper concludes with several main points in the section IV and also the future work in section V.

II. Problem Formulation

The proposed reconfiguration method is based on the technique proposed by Khodr et al. [4] and Dias et al. [5]. Initially is considered a meshed network topology without existence of any switches and with the possibility to open all lines. The optimal radial topology is ensured by calculating an OPF minimizing the power losses.

The Portuguese distribution networks have voltage regulators and capacitors banks carefully positioned in order to keep the voltage and reactive power between the desire limits, thus the problem can be approximated as a DC model. Furthermore, the voltage stability is at the HV/MV substations level and not at MV/LV level. Moreover, the MV/LV transformers also have voltage regulators.

The objective is to minimize the total power losses of the network. The active power losses is given by equation (1) [7][8][9][10].

- Objective function

$$\text{Minimize} \qquad \sum_{ij=1}^{NL} R_{ij} \times S_{ij}^2 \tag{1}$$

The calculation of reactive power losses is given in the same way, but replacing the resistance by reactance. The objective function is shown in equation (1) and it is subject to the following technical constraints:

- Power balance

$$\sum_{i=1}^{NB} Sgen_i + \sum_{ji=1}^{NL} S_{ji} - \sum_{ij=1}^{NL} S_{ij} - L_i = 0 \tag{2}$$

- Generation limits

$$Sgen_i^{min} \leq Sgen_i \leq Sgen_i^{max} \tag{3}$$

- Thermal limits of distribution lines

$$S_{ij} \leq S_{ij}^{max} \times y_{ij} \tag{4}$$

The constraint (5) must be applied in order to avoid the double direction of the power flow in the lines.

- One direction for the power flow

$$y_{ij} + y_{ji} \leq 1 \tag{5}$$

- Radiality condition

$$\sum_{j \in NB} y_{ij}^{j} = 1 \tag{6}$$

The constraint (6), shows that the number of distribution lines arriving to a bus must be equal to one, ensuring that all buses can only be supplied by one source. Thus, it is ensured the radial topology of the distribution network. Moreover, constraint (6) also guarantees the minimum number of NO switches to be installed in the network. This constraint also ensure that all loads are supplied.

With the active power peak losses, it is possible to determine the energy losses (equation (7)).

$$W_{Losses} = \beta \times T \times P_{PeakLosses} \tag{7}$$

Where β expresses the proportionality between the annual energy losses and active power peak losses.

To better understand the proposed methodology, Figure 1 shows a flowchart, indicating all stages of the developed algorithm.

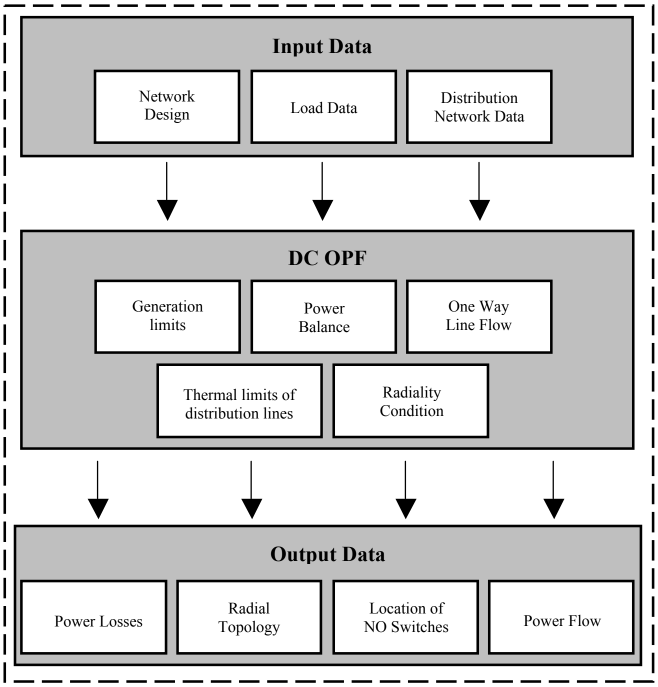

Figure 1. Flowchart algorithm.

III. Case Study

The objective is to make the reconfiguration of a real network in order to find the optimal location of NO switches that minimize the active power losses. In order to prove the method developed in TOMLAB, several comparisons are made with a software used by Portuguese operator for the network planning. It is important to note that the authors don't have the permission of the Portuguese distribution operator to identify the software name.

A computer with one processor Intel Core i7 1,7GHz, 8GB of Random-Access-Memory (RAM) and Windows 8.1 Professional 64-Bit Operating System was used for this case study.

A. Testing distribution network

The proposed method is tested in a medium voltage network (15 kV) located in the north of Portugal. The network is supplied by two substations (1 and 67) and have 220 buses, where 143 buses are load buses. The network has 22.6 MVA of load, over 59.9 km of overhead lines and underground cables. The power factor used is 0.928. Figure 2 shows the single line scheme of the network under study. Figure 3, depicts the active and reactive load present in each bus. It is important to note, that the load of each bus is given as a function of load peak registered by the SCADA (Supervisory Control and Data Acquisition) system in 2014.

The network presented in Figure 2 has five loops, thus the installation of four switches it is necessary to allow the radial operation of the network.

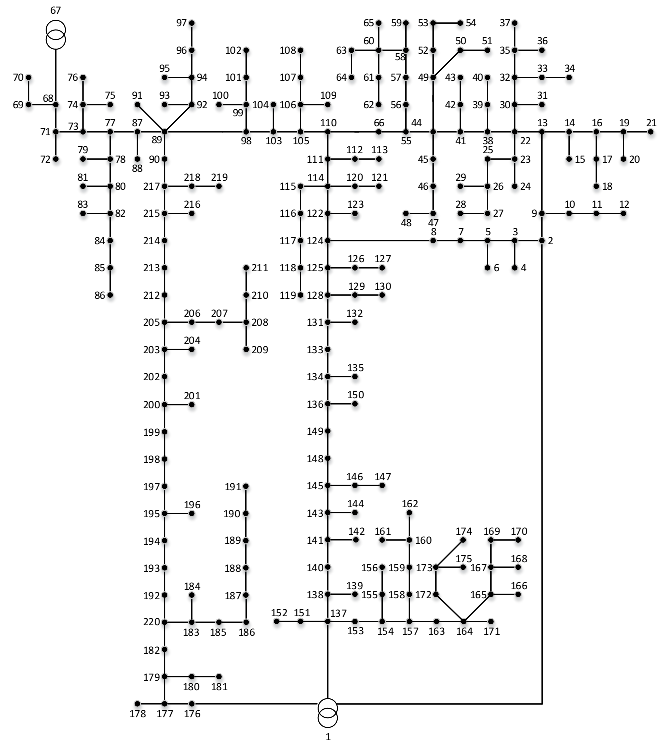

Figure 2. 220 buses distribution network.

B. Implementation

In order to test and prove the proposed method, three scenarios are considered:

- Reconfiguration A - Optimal reconfiguration obtained by the distribution networks planning software;
- Reconfiguration B - Optimal reconfiguration using the proposed method implemented in TOMLAB software;
- Reconfiguration C - Optimal reconfiguration obtained by TOMLAB software, tested in the distribution networks planning software.

Tables I and II present the reconfiguration A, B and C results, including the optimal location of the NO switches and the total power losses of the distribution network. Table III shows the apparent power supplied by substations 1 and 67.

TABLE I. Optimal Location of NO Switches

Rec. A	Rec. B	Rec. C
5-7	44-55	44-55
89-90	111-114	111-114
66-110	125-128	125-128
128-131	214-215	214-215

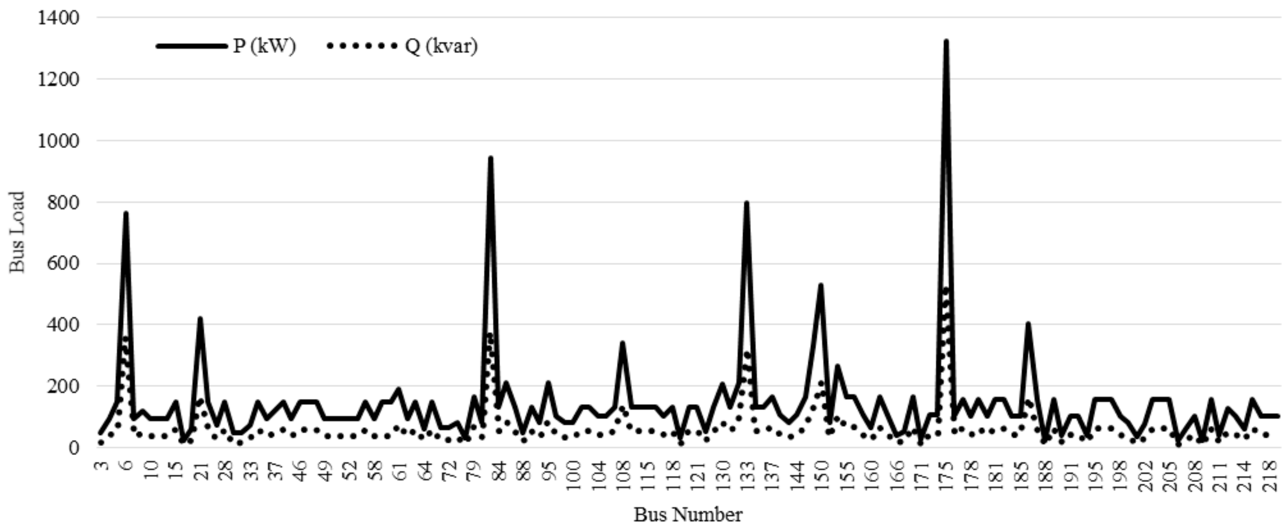

Figure 3. Active and reactive power on load buses

TABLE II. RECONFIGURATION RESULTS

Rec.	Active Losses (kW)	Reactive Losses (kvar)	Energy Losses (kWh)
A	293.6	384.0	674.1
B	301.7	382.3	692.4
C	270.8	339.0	621.7

TABLE III. APPARENT POWER SUPPLIED BY SUBESTATIONS

Substation	Apparent power supplied (kVA)			
	Maximum	Rec. A	Rec. B	Rec. C
1	31.177	16.866	16.858	17.242
67	10.392	6.198	5.797	5.737
Total	41.569	23.064	22.655	22.979

Through the Tables I and II analysis, it is possible to see that reconfiguration B and C are the same, but the losses are different. The different losses results are due to the existence of a difference between the methodologies for distribution networks reconfiguration. The presented method uses the DC model for the OPF calculation, resulting in several simplifications. The reconfiguration C is implemented in a software used for the distribution networks planning, which uses a multi-objective methodology, evaluating losses and reliability. Although the simplifications introduced in the presented method guarantee the global minimum of the problem, which is the topology with lower losses. It is used a quadratic modeling of the objective function, which represents correctly the losses by Joule effect. On the other hand, the DC model induces a slightly different power flow when compared with the full model, however it is far from the lines thermal limit, as can be seen in Table IV. Thus, the optimal solution is not affected.

The proposed methodology is implemented in TOMLAB software and took only 0.83 seconds to get the reconfiguration B. The location of NO switch obtained by reconfiguration B it will be used in reconfiguration C. By comparing the reconfigurations A and C, it appears that the optimal solution of the proposed method shows better results than the solution obtained by the distribution networks planning software. The proposed method also presents lower power losses (22.8 kW).

From Table III, it is possible to see that the substations are far from their limits. The sum of the apparent power of substations 1 and 67 corresponds to the power delivered to the network. The power delivered difference obtained for the different scenarios is related to the apparent power losses, i.e., another error introduced by the distribution networks planning software in the load definition. In reconfiguration B it is not considered the losses because of the nature of the DC model. Thus, the power delivered to network corresponds to network load value.

It is possible to see in Table IV that the distribution power lines have a usage of line capacity above 50%. In reconfigurations A and C, it is not possible to know the exact usage of line capacity of each distribution line. However, the distribution networks planning software indicates that the total usage is below 75%.

TABLE IV. USED LINE CAPACITY OF DISTRIBUTION LINES

Line	Reconfiguration B Usage Line Capacity (%) ≥ 50	Reconfiguration A and C Usage Line Capacity
1-2	62	All lines below the 75%
1-137	60	
71-73	60	
73-77	59	
140-141	65	
141-143	63	
143-145	61	
145-148	57	

Looking to the lines thermal limits, it is possible to see that the most of the lines has a lower usage line capacity (lower than 75%). Thus, it is not expected problems in ensuring the N-1 criterion. The load value used in the network corresponds to the peak load registered by the SCADA system in 2014, in fact, most of the time, the network is operated with a lower supply level, leading to a lower usage line capacity.

C. *Economic assessment*

In Portugal the energy services regulator offers an incentive to the electrical power companies, which is given by the percentage of losses. The incentive is calculated from the reference level of losses (7.8%), as shown Figure 4. The incentive calculation methodology is presented in the reference [11].

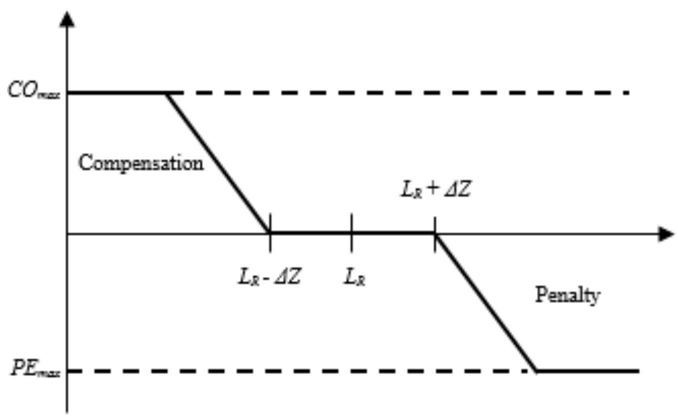

Figure 4. Incentive for power losses reduction.

In addition to the presented incentive, there is also a cost associated with power losses, which in Portugal is estimated at 0.04365 mu/kWh, on the other hand, exists the investment cost associated with the NO switch acquisition. Table V shows the economic balance in both reconfigurations for thirty years of lifetime project.

TABLE V. ECONOMIC BALANCE IN THE RECONFIGURATIONS B AND C.

	Reconfiguration A	Reconfiguration C
Total Cost (mu)	-1,081,974	-1,111,044
IRR (%)	118.2	121.3
RTI (years)	0.80	0.78

As can be seen in Table V, all scenarios are economically viable, presenting attractive economic indicators. However, reconfiguration C maximizes the savings, presenting a greater IRR (internal rate of return) and consequently less RTI (return time investment).

IV. CONCLUSIONS

This paper proposes a deterministic methodology for distribution networks reconfiguration, aiming the minimization of active power losses. The proposed reconfiguration method is based on a OPF supported by DC model. This is a methodology with significant advantages, since it ensures the optimal solution to the problem in real time. The method developed in TOMLAB software presents a computational processing time less than one second. The proposed method has lower losses when compared with the distribution networks planning software, which can result in saving of thousands of monetary units per year. It should be noted that the software for distribution networks planning does not provide the best solution (minimize power losses), but it does not mean that is wrong. The objective function and constraints of the software for distribution networks planning, is different of the proposed method in this paper.

V. FUTURE WORK

A real distribution network is operating and planned considering many factors. Two of the most important factors, are the power losses and reliability, since they can lead to high costs. In this paper, through optimal location of NO switches, a meshed network is transformed in a radial network, where the reconfiguration criterion is the minimization of power losses. A next work is to evaluate the reliability of the network, through the optimal location of normally closed switches, obtaining a network with minimal losses and maximum reliability.

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