

# A Dynamic Reconfiguration Method based on a Deterministic Optimization Approach in Active Distribution Systems

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**Abstract**—This article proposes a method for dynamic distribution network reconfiguration (DDNR) with distributed generation for loss reduction. Advantages and conceptual principles of a deterministic optimization method are exposed, which allows the minimization of technical power losses in distribution systems based on a linear approximation of the loads. In this work is proposed the application of this approach for the modelling of distributed generation sources, obtaining a mathematical formulation that exploits mixed-integer nonlinear programming in solving the optimal reconfiguration problem. The DDNR method is implemented in an automatic tool integrating OpenDSS and GAMS software. IEEE69-Bus test system is considered to demonstrate the effectiveness of the technique. Dynamic results are obtained by implementing the optimal reconfiguration strategy, making the dynamic adjustments of the mathematical modelling in the face of variations in distributed generation and demand profiles. The results reveal schemes that range from one to twenty-four daily control actions.

**Index Terms**—Distributed generation; Mixed-Integer Nonlinear Programming (MINLP); loss minimization; distribution network reconfiguration.

## I. INTRODUCTION

The continuous expansion of urban centres and the growing demand for electrical energy worldwide has led to monitoring and controlling the electrical service quality and the efficiency in transmission and distribution processes. In Colombia, regulatory entities such as the Superintendence of Residential Public Services (SRPS) and the Energy and Gas Regulation Commission realize these monitoring and control activities. For example, the indices SAIFI and SAIDI have been adopted to evaluate the electricity service quality [1], [2]. Also, the efficient operation of electrical systems is assessed by quantifying technical losses and proposing plans for their reduction [3]. SRPS has set a goal of reducing total losses to a value equal to 2% of the annual demand, which would be equivalent to 1,300 GWh, within five years (from January 2018) [1]. These values support the need to implement practical solutions, such as network reconfiguration, where the network operation topology is managed to reduce technical losses [4].

Since Merlin and Back solved the first network reconfiguration problem, many new approaches can be identified. Mainly, the reconfiguration methods can be classified according to the solution approach used: heuristic, metaheuristic, and deterministic [5]. Heuristic and metaheuristic techniques generate solutions from random functions, with the disadvantage that they do not always obtain a single solution, converging on sub-optimal local solutions. The deterministic approach is based on structured rules, and it adapts more precisely to get optimal results [6]. The network reconfiguration problem can be formulated as a mixed-integer nonlinear programming (MINLP), which addresses the nonlinear nature of power losses. Some linearization strategies have been proposed in the literature, such as the linearization of the power flow [7], the power losses [4], [8], or the demand [9].

This paper uses a linearization of the power flow based on a load model approximating the power-voltage relationship to propose a dynamic reconfiguration method for application in an active distribution system. It has also proposed an adaptation based on models of ideal voltage sources for substation nodes and constant impedance for loads and distributed generation [10]. The contributions are two: 1) A dynamic analysis of the distribution system is implemented to obtain a better approximation to an actual scenario, considering the variable nature of the demand and the energy injected by the distributed generation units. The solution to the dynamic network reconfiguration problem is found using the BARON-GAMS solver based on MINLP mathematical formulation. The nonlinearity of power losses and the binary modelling of the opening and closing of power lines are considered. 2) A systematic approach is proposed, integrating OpenDSS and GAMS platforms. OpenDSS provides the electrical modelling using the load forecast and measured generation profiles, obtaining the information required as input to build the problem formulation in GAMS. The analysis of the dynamic results obtained allows a discussion in decision-making to reduce daily energy losses.

This paper is organized as follows. Section II provides the formulation of the used method for distribution network

reconfiguration using a linear current flow approach. In Section III, the automatic tool for DDNR is described. In section IV, the IEEE-69-bus with distributed generation is studied. In addition, the metrics to measure the loss reduction are presented. Finally, conclusions are drawn in section IV.

## II. DISTRIBUTION NETWORK RECONFIGURATION USING A LINEAR CURRENT FLOW APPROACH

In [10] is proposed a model that achieves linearization of the nonlinear power flow for distribution networks. The critical issues of the mathematical formulation are summarized as follows.

### A. Linearization of the Power Flow

The problem is simplified using a model that represents the loads as impedances to the net power consumption at each node with a constant voltage (1).

$$Z_{ci} = \left( \frac{P_0}{V_0^2} - j \frac{Q_0}{V_0^2} \right)^{-1} \quad (1)$$

$V_0$  = voltage at node  $i$

$P_0$  = Net active power absorbed at node  $i$

$Q_0$  = Net reactive power absorbed at node  $i$

Figure 1 shows the single-phase equivalent circuit of a power line and loads. Figure 2 indicates the changes when the substation is connected to node  $i$ . The next step is the calculation of currents in each power line. Kirchhoff's voltage law is applied in Figure 1 in the path formed through the load connected to node  $i$ , line  $k$ , and the load connected to node  $j$ , imposing an arbitrary direction of current flow, as in equation (2).

$$(Z_{ci} + Z_{cj} + Z_{Lk}) \cdot I_{Lk} - Z_{ci} \cdot \sum_{L \in in(i)} I_L + \dots \quad (2)$$

$$\dots Z_{ci} \cdot \sum_{L \in out(i)} I_L + Z_{cj} \cdot \sum_{L \in in(j)} I_L + Z_{cj} \cdot \sum_{L \in out(j)} I_L = 0$$

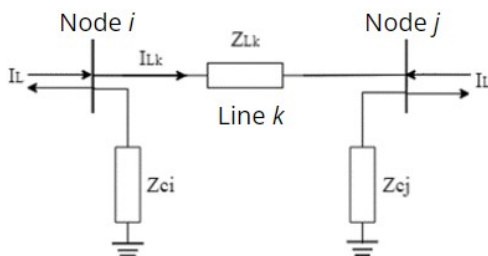


Fig. 1. Single-phase equivalent circuit of a power line and loads.

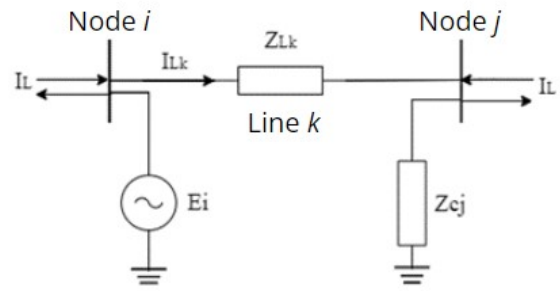


Fig. 2. Single-phase equivalent circuit of a power line, substation and loads.

Equation (3) presents the Kirchhoff's voltage law for single-phase equivalent circuit in Figure 2.

$$(Z_{ci} + Z_{cj} + Z_{Lk}) \cdot I_{Lk} - Z_{ci} \cdot \sum_{L \in in(i)} I_L + \dots \quad (3)$$

$$\dots Z_{ci} \cdot \sum_{L \in out(i)} I_L + Z_{cj} \cdot \sum_{L \in in(j)} I_L + Z_{cj} \cdot \sum_{L \in out(j)} I_L = E_i$$

Equations (2) and (3) can be organized using real and imaginary parts, as in (4).  $m$  is the number of power lines.

$$\begin{aligned} \sum_{L=1}^m (R_L I_L^r - X_L I_L^i) &= E_L^r \\ \sum_{L=1}^m (X_L I_L^r + R_L I_L^i) &= E_L^i \end{aligned} \quad (4)$$

Constraints are formulated based on the following principles:

- Law of current flow.
- Limit the current capacity.
- Minimum and maximum limits of the nodal voltages.
- Law of voltages.
- Radiality is considered for the distribution system operation.

These constraints are discussed in more detail in [10].

### B. Mathematical Formulation for Distributed Generation

Figure 3 shows a distributed generation unit and the location of a meter. This meter registers the generated power, and with the load forecasting is applied the equation (1).

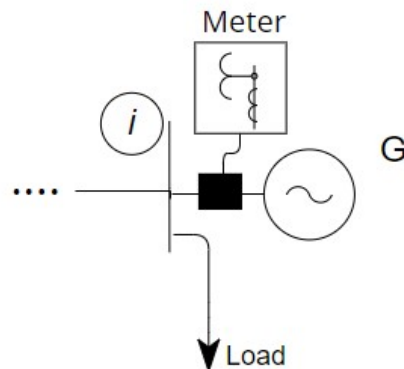


Fig. 3. Distributed Generation Unit connected at node  $i$ .

Therefore, the linearization method can be applied to all distributed generation units. An advantage is the typical installation of meters in the coupling point of the distributed generation. This information can be exploited to implement a linear dynamic model and solve the network reconfiguration problem.

### C. Optimization Problem

The objective function is shown in (5).

$$\min \text{Losses} = \sum_{L_k=1}^m R_{L_k} \cdot (|I_{L_k}^{re}|^2 + |I_{L_k}^{im}|^2) \quad (5)$$

The system reconfiguration implies the connection and disconnection of power lines. Therefore, a binary variable is introduced in the constraints [10].

## III. SYSTEM FOR THE DYNAMIC DISTRIBUTION NETWORK RECONFIGURATION

The proposed system integrates OpenDSS and GAMS platforms. GAMS solves a Mixed-Integer Nonlinear problem using the load forecast and measurement of the power generation profiles. Figure 4 presents the system components.

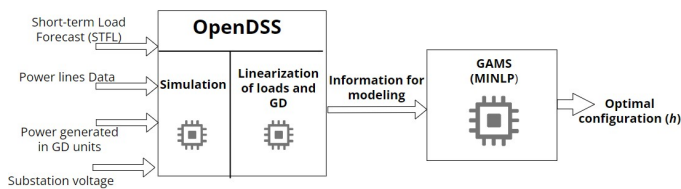


Fig. 4. Process for the dynamic reconfiguration.

### A. Inputs

- Short-Term Load Forecast: this information is used to model the loads as impedance. The STLF can be performed for a time interval of a few hours to a few days. An hourly interval is considered in this work.
- Data of power lines: this data allows to obtain the equivalent circuit of the feeders.
- Power generated in GD units: the measurements are used to model the distributed generation units as equivalent impedances.
- Measured voltage at the substation: a Thevenin equivalent is built with this measured voltage.

### B. Software and processing

- OpenDSS: this software allows to solve the power flow using the load forecast and the measurements of the substation voltage and power generation in GD units. It is an open-source simulation tool for distribution systems, which allows the incorporation of distributed generation, different load models and topology changes in the circuits.
- GAMS: the software builds and solves the optimization problem using an MINLP mathematical formulation importing data from OpenDSS.

### C. Output

- Optimal configuration (h): The optimal status of the tie switches and branches is determined to minimize the losses at interval  $h$ .

The implementation of the proposed method is carried out on a computer with an Intel® Core™ CPU i7 2.80GHz processor and 16GB RAM, mainly using OpenDSS and GAMS to simulate, store, process data, and solve the optimization problems.

## IV. CASE STUDY

### A. Distribution System Test Case: IEEE-69-bus

The system has 68 lines with the ability to be reconfigured. Additionally, it consists of five tie-switches (tsw), which connect non-consecutive nodes. In addition, consistent with reducing losses, distributed generation is implemented in nodes 21 and 61 [11], as shown in Figure 5. A photovoltaic generation profile is also adopted [12], as shown in Figure 6. The rated capacities are 594 kW for the unit connected at node 21 and 1794 kW for the connected at node 61. Figure 7 shows a power demand profile applied to all nominal loads of the distribution system [11].

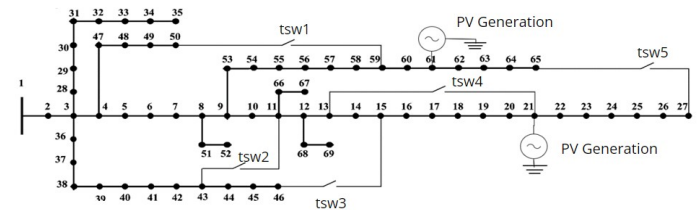


Fig. 5. Illustration of the IEEE-69-bus test system with GD units.

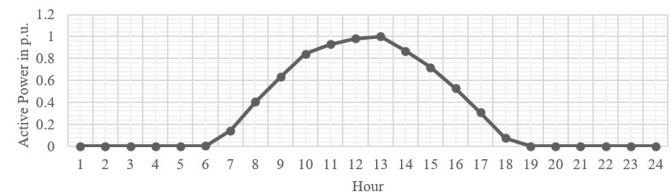


Fig. 6. Active power generation profile in per unit.

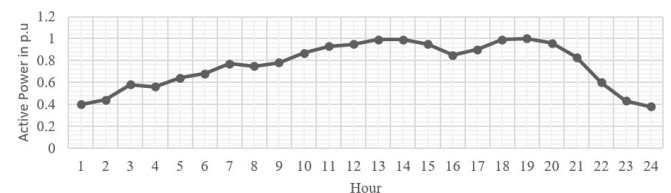


Fig. 7. Active power demand profile in per unit.

### B. Dynamic network reconfiguration per hour

Table I clarifies the ID of the element, which are referenced in this section. Table II shows the results per hour for each calculated optimal reconfiguration. The losses are calculated

by simulation in OpenDSS, solving the power flow with the load profiles, generation profiles, and the calculated optimal configuration without anything approximation. The obtained results allow evaluating the impact of the linearizations used in the mathematical formulation and the solution of the optimization problem.

TABLE I  
ID OF THE ELEMENTS

| Element ID | Sending node | Receiving node | Element ID | Sending node | Receiving node |
|------------|--------------|----------------|------------|--------------|----------------|
| 14         | 14           | 15             | 70         | 13           | 21             |
| 58         | 58           | 59             | 54         | 54           | 55             |
| 61         | 61           | 62             | 57         | 57           | 58             |
| 69         | 11           | 43             | 63         | 63           | 64             |
| 56         | 56           | 57             | 62         | 62           | 63             |
| 12         | 12           | 13             | 55         | 55           | 56             |
| 10         | 10           | 11             | 13         | 13           | 14             |
| 19         | 19           | 20             | 64         | 64           | 65             |
| 9          | 9            | 10             | 20         | 20           | 21             |
| 71         | 15           | 46             | 11         | 11           | 12             |
| 52         | 9            | 53             | 7          | 7            | 8              |
| 18         | 18           | 19             | 41         | 41           | 42             |
| 43         | 43           | 44             | 72         | 50           | 59             |
| 73         | 27           | 65             |            |              |                |

Table III presents a comparison of losses for a day implementing four strategies for the reconfiguration of the distribution system. The base case is operated using the five tie switches open. Case 1 and Case 2 are modifications of the case base where only one tie switch is closed, and another branch is opened. Finally, in case 3, are obtained the losses applying the optimal reconfiguration per hour and for all day. The loss reduction is calculated using as a base the losses of the base case.

TABLE II  
RESULTS OF THE LOSSES PER HOUR

| Hour | Open elements  | Losses | Hour | Open elements       | Losses         |
|------|----------------|--------|------|---------------------|----------------|
| 1    | 14-58-61-69-70 | 13.530 | 13   | 10-14-19-54-64      | 38.072         |
| 2    | 14-54-61-69-70 | 16.683 | 14   | 10-19-55-64-71      | 38.454         |
| 3    | 14-57-63-69-70 | 29.108 | 15   | 10-14-55-64-71      | 37.615         |
| 4    | 14-56-61-69-70 | 26.848 | 16   | 11-52-62-69-70      | 31.827         |
| 5    | 14-58-62-69-70 | 35.610 | 17   | 12-56-62-69-70      | 44.015         |
| 6    | 12-55-62-69-70 | 39.973 | 18   | 12-20-57-63-69      | 80.014         |
| 7    | 14-58-61-69-70 | 39.553 | 19   | 13-56-61-69-70      | 88.664         |
| 8    | 12-55-62-69-70 | 23.824 | 20   | 12-20-52-63-69      | 87.399         |
| 9    | 14-58-61-69-70 | 22.164 | 21   | 10-14-19-58-61      | 64.652         |
| 10   | 12-14-55-62-69 | 28.065 | 22   | 7-13-58-62-70       | 35.516         |
| 11   | 10-13-19-58-64 | 33.004 | 23   | 18-41-43-57-62      | 15.921         |
| 12   | 9-14-20-57-64  | 34.987 | 24   | 10-12-14-55-62      | 12.981         |
|      |                |        |      | <b>Total [kW-h]</b> | <b>918.482</b> |

TABLE III  
COMPARISON OF THE LOSSES

| Open elements                                | Losses kWh/day | Reduction |
|----------------------------------------------|----------------|-----------|
| Case base: 69, 70, 71, 72, 73                | 1863.883       | -         |
| 10, 70, 71, 72, 73                           | 1625.565       | 12.786%   |
| 58, 69, 70, 71, 73                           | 1140.698       | 38.8%     |
| Optimal dynamic reconfigurations in Table II | 918.482        | 52.487%   |

### C. Proposal of other configurations

Additionally, some complementary scenarios are analyzed. Heuristic configurations that are the product of the expert knowledge of distribution network operators can be applied to evaluate the loss reduction. Based on the best results of dynamic reconfiguration in Table II and using heuristic criteria, it is possible to propose an operation based on a smaller number of reconfigurations in the distribution system and where similar results of reducing losses are achieved.

Table IV shows the results of the loss reduction by applying a unique configuration for 24 hours of the day. Case *H1* uses the calculated optimal configuration for the peak demand (solution for hour 19). Case *H2* uses the optimal configuration with minimum daily losses (solution for hour 4).

TABLE IV  
COMPARISON OF THE LOSSES USING HEURISTIC CONFIGURATIONS

| Elements opened         | Losses kWh/day | Reduction |
|-------------------------|----------------|-----------|
| Case H1: 13-56-61-69-70 | 890.193        | 52.240%   |
| Case H2: 14-57-63-69-70 | 889.944        | 52.253%   |

The results reveal schemes that range from one to twenty-four daily control actions, finding similar loss reduction with one reconfiguration per day. It is demonstrated that the losses dynamic calculation using the proposed tool allows making decisions to be made that help the efficient operation of distribution systems.

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### V. CONCLUSIONS

A dynamic reconfiguration method for distributed systems based on a load linearization model and distributed generation has been implemented and evaluated. Its implementation is consolidated into an automatic tool with the potential practical application since it adapts to the variability of demand and generation in actual electrical power distribution systems.

In the performance tests in the IEEE69-Bus, hourly reconfigurations have been obtained, developing a discussion about the results to make decisions to implement the reconfiguration equipment in the distribution network. It is evidenced that the topology changes are made through a limited set of lines. Therefore, the location of switches can be estimated.

In the comparison between the proposed reconfiguration schemes, it is observed that the loss reduction percentage does not vary significantly concerning the number of reconfigurations carried out with an hourly resolution. Therefore, operating schemes that require few topology changes can be viable solutions for a network operator planning to invest in new equipment to minimize electrical energy losses.

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