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DOI
10.1049/cp.2016.0665

Publication date
2016

Document Version
Final published version

Published in
Proceedings CIRED 2016 Workshop

Citation (APA)
Van Westering, W., Van Der Meulen, M., & Bosma, W. (2016). Evaluating electricity distribution network reconfiguration to minimize power loss on existing networks. In P. Soderstrom, R. Prata, & F. Pilo (Eds.), *Proceedings CIRED 2016 Workshop* [Paper 0088] Institution of Engineering and Technology. https://doi.org/10.1049/cp.2016.0665

Evaluating Electricity Distribution Network Reconfiguration to Minimize Power Loss on Existing Networks

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Abstract

This paper applies the distribution network reconfiguration problem to existing networks. The medium voltage distribution network of the Dutch DSO Alliander is operated using a radial topology. By optimizing this topology it is possible to reduce the energy losses caused by the cable impedances. Various solutions algorithms have been compared for this distribution network reconfiguration problem, while taking into account network capacity and voltage levels. A Genetic algorithm combined with a Greedy demeshing starting condition yields the best results. Applying the algorithm on real life distribution networks shows with 226 buses and 406 buses yield a reduction in power losses of 15% and 27% respectively.

1 Introduction

The power loss in power distribution networks is a significant issue, both financial and environmental. Alliander DSO, which operates the electricity distribution for over three million customers in the Netherlands, estimates the total power losses caused by energy transportation in 2014 of 1.1 TWh [12], with a net worth of 72 million euros and equivalent to 747 Gigaton of CO_2 emissions. It is estimated that roughly a third of these losses are the result of the resisitive losses in the medium voltage power grid. Given these numbers, a reduction of a few percent of power loss will already result in a significant benefit.

The power network of the Netherlands operates at three power levels: Low voltage (LV, 0.4kV), medium voltage (MV, 10-50kV) and high voltage (50-300kV). The study conducted in this paper focusses on the MV network and uses the network topology and power consumption data from Alliander DSO. The medium voltage networks which have been evaluated in this paper are shown in Figure 1.

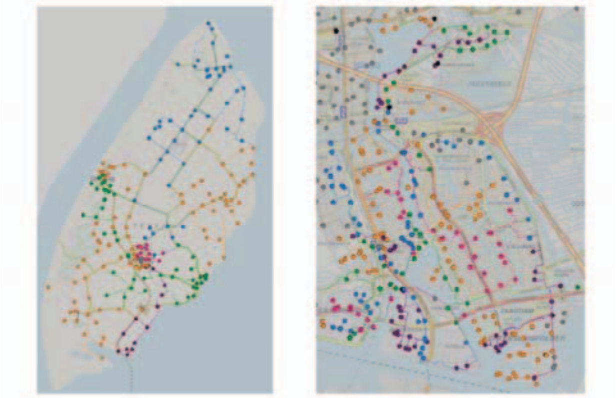

Fig. 1: The medium voltage networks of Texel (left) and Zaandam (right). The distribution networks have 226 buses and 406 buses respectively.

The medium voltage distribution network of the Netherlands is to be operated in a radial tree-like topology for short-circuit detection purposes. However, to ensure redundancy the network is stongly interconnected and the actual radial topology is obtained by disengaging power switches. Since there are many possible switching configurations which yield such a radial topology and the network topology influences the energy losses, it is possible to save energy by finding the optimal switching configuration. The problem of finding the best network topology by changing the switching configuration is known as the Distribution Network Reconfiguration Problem (DNRP).

For this paper, various solution methods for the DNRP were compared, while additional constraints such as capacity and voltage level were taken into account. Studies and theoretical background for the used methods were found in the literature [2]-[7]. These methods were implemented and applied to the distribution network data from Alliander, as shown in figure 1. This paper focusses on the evaluating benefits in these networks and in real distribution networks in general. Full details of this study can be found in [1].

2 The Distribution Network Reconfiguration Problem

The distribution network reconfiguration problem will now be described mathematically. First a definition of the network is given, then the optimization problem and its constraints are defined.

A medium voltage network can modeled as an undirected graph $N = (W, E)$ with nodes W and edges E [11]. The nodes W are the buses of the network. The HV/MV transformers connected to the HV net are the *slack buses*, MV/LV transformers connected to LV networks are the *load buses* and *generator buses*. For the edges E, the set of *optional* edges E_o is defined, which represent the cables and links with switches. These switches can be opened, resulting in a deletion of the corresponding edge in the network. Other edges are *fixed* edges E_f representing those without switches.

A certain open/closed specification of the switches in N results in a certain *configuration* of N. Let $A \subseteq E_o$ be the set of optional edges with closed switches. A is called a *switch specification*, and N_A the corresponding configuration, which is equal to N without the edges with open switches.

Let A be a switch specification for network N. Every node $v \in W$ contains a certain voltage U_v^A, and every line $e \in E_A$ contains a certain current I_e^A. These voltages and currents depend on the power supplies and demands at the nodes in the network and can be calculated by solving the power flow equations [13]. But they also depend on the way N_A is configured, since different connections give different power flow pattern. Hence the index A has to be added to the parameters. Note that when a line $e \in E_o$ is opened, the current through this line will always be zero, hence the current I_e^A is defined for every $e \in E$.

Cables and links in the network have certain impedances. Define line $e \in E$ has impedance $Z_e = R_e + jX_e$. Then the power loss through line e can be calculated as $P_e^{\text{loss}} = |I_e^A|^2 \cdot R_e$. With this, the objective function is described as:

$$L(A) = \sum_{e \in E_A} |I_e^A|^2 \cdot R_e \tag{1}$$

$$= \sum_{e \in E} |I_e^A|^2 \cdot R_e \tag{2}$$

Note that if $e \notin A$, then $I_e^A = 0$, so the second equality holds. Now $L(A)$ is the total power loss in N_A, so the objective is to find A such that $L(A)$ is minimized.

This optimization problem has certain constraints. For policy and safety reasons, the topology of a configuration has the following requirements:

- Every node in the network must be connected to an HV/MV transformer, in order to be able to get demanded power from or withdraw remaining power to the HV net.
- No cycles (loops) are allowed in the network.
- HV/MV transformers are not allowed to be connected to each other. Different transformers constitute different voltage and current frequencies, so when these are connected, an unstable voltage and current will arise as a consequence.

Taking these requirements into account, a feasible configuration must be, in graph theoretical terms, a forest with in each subtree exactly one slack bus $v \in W_n$. This is the definition of a *radial* structure or topology, and it will refered to as the *radiality* constraint.

Due to power supply and demand in the network, a specific power flow pattern occurs. This pattern can be simulated by the power flow equations. This pattern is necessary for loss calculation and capacity checks. Therefore the *demand constraint* is added, which postulates that the voltages and currents in the network satisfy the power flow equations[13].

The *capacity constraint* states that the nodal voltages should be between certain bounds and the line currents have an upper bound, in order to maintain good power quality and avoid overloading the assets. Mathematically, this can be described as:

$$\forall v \in W \qquad |U_v^{\min}| \leq |U_v^A| \leq |U_v^{\max}| \tag{3}$$

$$\forall e \in E \qquad |I_e^A| \leq |I_e^{\max}| \tag{4}$$

where the values of $U_v^{\min}, U_v^{\max}$ for any $v \in W$, and $I_e^{\max}$ for any $e \in E$ are assumed as known.

For network $N = (W, E)$ the complete problem is defined as:

$$\begin{aligned} \text{DNRP :} \; & \min_{A \subseteq E_o} \sum_{e \in E} |I_e^A|^2 \cdot R_e \text{s.t.} \\ & N_A \text{ is a radial network} \\ & (U_{v_1}^A, ..., U_{v_n}^A), (I_{e_1}^A, ..., I_{e_m}^A) \text{ satisfy the load flow equations} \\ & \forall e \in E: \;\; |I_e^A| \leq |I_e^{max}| \\ & \forall v \in W: \;\; |U_v^{min}| \leq |U_v^A| \leq |U_v^{max}| \end{aligned}$$

3 Solution methods and their expansion to multiple slack buses

To find a solution for the DNRP, first a set of solutions has to be defined. Finding the complete set of topologies which satisfy the radiality constraint is not trivial. 5. To construct this set, two methods are proposed using a semi-ear decomposition and a cycle basis [1][10]. As it turns out, the cycle basis method works most efficient, using Hortons algorithm for finding minimum weigth cycles bases [8].

Various solutions methods for the distribution network reconfiguration problem have been considered:

- Brute force random optimization
- Greedy demeshing [3]
- Harmony search algorithm[6] [7] [10]
- Genetic algorithm [4][5]
- Mixed integer linear programming [8]

Since applying all these algorithms to a real world network would require considerable effort, these algorithms have all

Table 1: The power loss in the evaluated MV networks

Optimization method	**Losses in MV network Texel**	**Losses in MV network Zaandam**
No optimization (actual configuration)	89.5 kW	95.3 kW
Greedy demeshing	89.2 kW (-0.5%)	89.6 kW (-6%)
Greedy demeshing + Genetic algorithm	76.1 kW (-15%)	69.9 kW (-27%)

been evaluated on a fictional network with around 50 buses. Using the greedy demeshing algorithm as a starting conditions and then applying the genetic algorithm resulted in the best solution within the fewest iterations and therefore yields the best results [1].

All of the suggested methods, except for the Mixed-Integer Linear Programming, are developed for single slack bus networks. This is undesirable, as it greatly reduces the search space. To modify the optimization problem to allow for multiple slack buses a mathematical defenition is now given. Let $N = (W, E)$ be a network with $W = W_n \cup W_c$, W_n the set of slack buses, and W_c the set of client busses.

Set $|W_n| = n'$, so N has n' slack buses. Set $E = E_f \cup E_o$, the set of fixed and optional lines respectively. Furthermore, assume the input data such as impedances, voltages for the slack busses, powers for the load busses and voltage magnitudes/active powers for the generator busses are present.

Now construct network $\hat{N} = (\hat{W}, \hat{E})$ out of N by adding one artificial load bus a to W_c, and for any slack bus $v \in W_n$, add a fixed line $f_v = (v, a)$ to E_f. For load bus a, set active and reactive power demands equal to zero, so $P_a, Q_a = 0$. And for all added edges f_v, set the impedance $Z_{f_v} = 0 + j \cdot \infty$, so the admittance $A_{f_v} = \frac{1}{Z_{f_v}} = 0$.

For network N, and network $\hat{N}$ constructed out of N, the power flow in N and $\hat{N}[W]$ will be equal. That is, for any $v \in W$, if U_v, S_v are the voltage and power in v in N, and $\hat{U}_v, \hat{S}_v$ are the voltage and power in v in $\hat{N}$, then $U_v = \hat{U}_v$ and $S_v = \hat{S}_v$. Furthermore, the total power loss in N and $\hat{N}$ is equal, which keeps the model mathematically perfectly accurate.

Conceptually, an extra node is added that is connected to every slack bus with a fixed line with infinitely high impedance. As a consequence, no current shall flow through these lines, hence the original power flow is not effected. However, opening every cycle in the new network ensures that any path between two slack busses that does not go via the artificial node is opened at some point. This corresponds to a radial topology of the old network.

4 Results for the medium voltage networks of Texel and Zaandam

The combination of the greedy demeshing and genetic algorithm has been applied to the real networks of Texel and Zaamdam. The results can be found in Table 1. It can be observed that applying only the greedy demeshing already results in some reduction in power transportation losses. However, using the result of the greedy demeshing as starting point for the genetic algorithm results in a far greater reduction of losses.

Table 1 shows a maximum power loss reduction on Texel of 15% can be established and in Zaandam almost twice as much, 27%. This difference is most likely caused by the difference in complexity of the networks. The network of Texel contains one slack bus, where the network of Zaandam contains eight slack buses. Moreover, the network of Zaandam admits a cycle basis of 49 cycles, where in Texel this number is 23. This results in a much larger search space and therefore better solutions.

The algorithms were implemented in the open source programming language ‘R’. The simulations were executed on a laptop computer with an Intel i5 processor and 8 GB RAM. The simulation took several hours to complete.

5 Discussion

While the proposed definition for the distribution network reconfiguration problem and its solution methods are already practically very useful, there are plenty of opportunities for improvement.

For example, the results in Table 1 are based on one specific power demand/supply pattern, namely 25% of the maximal load pattern. With this pattern, a power loss reduction of 15% and 27% can be established, but since the optimal configuration pattern may vary during the day, the actual benefits will most likely be less.

Also, it could be benefitial to develop a better method for constructing the radial configurations of a network. Ideally the method constructs exactly all the radial configurations of the network, no more (as with cycle bases) and no less (as with semi-ear decompositions). It is also probably more efficient to construct a cycle basis of a network that minimizes the sum of the pairwise intersections of the cycles. Horton’s algorithm however, only gives a cycle basis in where the sum of the length of the cycles is minimized. Although an optimal basis for the second problem is often also an optimal basis for the first problem, this is not always the case.

More operator knowledge can still be added to the evaluated networks. For some links or cables it might be preferable/necessary that they are opened, due to unmodeled circumstances such as reliability or location. Using this information narrows the search space and makes it more likely that the output configuration is practically achievable. Operators also do have suggestions for well-performing configurations. Such a guess could be used for constucting the first generation of the genetic algorithmm, as well as the output improving the inner workings of the greedy demeshing algorithm.

If one is not only interested in which configuration minimizes the power loss, but also for instance which configuration is most reliable or has the best power balance, the optization problem can be easily modified. The Genetic Algorithm is very suitable for such a changed the objective function. In case of the Greedy-Demeshing algorithm, this transition to other objective functions is a bit more complex. The idea behind GD is that the situation is at its best if all edges are closed, and by opening the right edges, this situation is effected as little as possible. For reliability and power balance this is not immediately clear and the GD method has to be modified.

The method is also useful for planning future connections in the medium voltage network. If a number of possible connections is present, of which only a small number can be executed, one would like to know which connection has the best impact. By adding all these connections to the input data of the existing network, with realistic impedances and capacities, one could see which of the possible connections is actually used in the output configuration. These are the connections that would make power loss reduction possible.

6 Conclusion

A definition of the Distribution Network Reconfiguration Problem has been given. The problem has been formulated as a mathematical constrained optimization problem. Various solvers have been considered and a genetic algorithm combined with a greedy demeshing starting condition yields the best results.

Applying the algorithm on real life distribution networks shows with 226 buses and 406 buses yield a reduction in power losses of 15% and 27% respectively. Since Alliander estimates the net worth of the total technical power loss on 72 million euros per year, the calculated financial gain is substantial.

The extention of the problem to multiple slack buses helps in finding the most optimal solution and is an improvement over literature. The results of the algorithms will be used as an advice for the network operators at Alliander. A test location will be selected in order to further test the results for their practical value.

Acknowledgements

The authors would like to thank Alliander DSO and the Radboud University for making the DNRP project possible. Thanks to Robin Hagemans for his role in facilitating this project.

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