Power distribution network reconfiguration based on min-cost flow problem

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***Abstract*— In this paper a network reconfiguration model aimed to be used in an industrial context is presented. It is based on a min-cost flow problem (MCFP) and a simplified power flow calculation. Mixed Integer Quadratic Constrained Programming (MIQCP) and Mixed Integer Non linear Programming (MINLP) are used and compared to compute the network reconfiguration with off-the-shelf optimization solvers. Two test cases are presented, a small academic network and a real case study. The paper shows experimentally that simplification on model level can be more efficient than simplification on the solving level for real world problems.**

I. Introduction

This paper presents advances in a joint work between an academic research lab and SRD, the company in charge of the power network in the french department Vienne (431000 inhabitants). Nowadays, the insertion of renewable energy and the future of storage has more and more of an impact on the global energy flow. The aim of this paper is to present an optimization solution of the flow minimizing the loss, which can be applied on a large scale network in a reasonable time. We study the problem of loss reduction in a distribution network by reconfiguration of feeders. This problem has been addressed for a long time [1], and we can separate methods into three main categories: capacitor placement, distributed generation allocation and feeder reconfiguration [2].

The previous problem becomes harder to deal with when capacitor or renewable energy sources must be handled. Also capacitor placement can be efficient when investments are made to improve the network but not in day to day operations, and distributed generation utilization presents a risk because it is hard to predict due to weather uncertainty and cannot be controlled. Moreover large renewable energy sources are usually isolated in the network and the produced power is sent directly to the high voltage to medium voltage transformer so it cannot be used to deliver power directly to consumers. It is for this reason that reconfiguration of the network by modifying switch states is the most accurate way of trying to reduce loss without investing a lot and with less production uncertainty.

The aim of network reconfiguration is to change network topology by modifying the switches state (open/close). Distribution networks are operated in radial configuration, so network reconfiguration transfers loads from one branch to another, and modifies the flow of power in the branch. The discrete nature of such an operation makes the optimization problem of integer type.

Before explaining the way to optimize a network, note that electrical characteristics (voltage, current, phase and power loss) depend usually on a power flow. In the case where the network can be operated in a loop, meaning that a consumer can be connected to different sources, the solution of the non linear equations involved in the power flow has many solutions, one of them inducing a minimum power loss. However in radial configuration where a consumer can be connected to one source only, the power flow has a unique solution and a fixed amount of loss. To solve this second case there are two ways of solving the minimum loss problem: 1) Firstly solve the power flow and then determine which line to open in the network to get a radial configuration or 2) Enumerate all the possible radial configuration and evaluate each one of them to find the best one in term of loss.

Radial configuration is commonly used for distribution networks, the optimization problem of loss reduction can be solved by different techniques presented in [2], such as specific heuristic procedures, meta-heuristics, hybrid techniques or exact optimization methods.

Optimization methods are set for different purposes and due to the huge amount of possible solutions in a distribution network, approximations are made to efficiently solve the problem. This can be achieved at modeling level, or at resolution level. For example, in [3] and [4] the authors use optimization to solve the non linear system of equations involved in the exact power flow with minimum loss, and develop a specific heuristic method to choose the switches to open or close. Therefore, they use approximation at the solving level, that can be efficient as long as a means to search effectively for the solution is known.

In [5] two exact optimization methods are used, one for each stage of the process: one solver for the power flow equations (slave problem), and one solver using the branch and bound method to determine the switch position (master problem).

Optimization can be used to find the best solution among every possible radial configuration in one model. However, with the non linear nature of the power flow and knowing the difficulty of solving a large MINLP (Mixed Integer Non Linear Program), non-linear equations involved in the model can be simplified such as in [6] [7]. Another option is to work on the integer constraints that define the radiality such as in [8].

In the real-world context of distribution network, we usually do not have an exact view of the consumption and production of the nodes of the network and network reconfiguration is not really suited to real-time decision making. Therefore in general worst-case studies are made to define an operational network by this technique. In this paper, we choose to simplify power flow calculations by model simplification to reduce the optimization problem size and complexity. The purpose of this proposed model is to be used in a real network by non optimization and modeling experts and to be easy to plug on off-the-shelf solvers.

The optimization problem defined to solve the network reconfiguration is simplified by a minimum cost flow problem (MCFP) with disjunctive constraints composed by the different operational constraints. This problem is NP-hard [9]. We compare this model to other techniques presented on a small academic test case found in [1], and we then apply our method to a large scale real system.

In section II the model is described and simplifications are explained, in section III, the method used to evaluate the model is presented and in fourth section results are presented and commented.

II. Optimization model

A. Basic concepts of electricity

In the case where the three phase alternating current system is considered balanced and the current and voltage are sinusoidal we can define three sorts of power :

- Active power (real power): $P = u \times i \times \cos\varphi$ where u is the voltage, i the intensity, φ the phase between intensity and voltage and $\cos\varphi$ the Power factor
- Reactive power: $Q = u \times i \times \sin\varphi$
- Complex power (apparent power): $S = P + jQ$ where j is the imaginary unit

In our case, at each point of the network the exact value of φ is unknown but considered constant as is the active power consumption, so we will focus only on the active power. u is also considered constant along the feeders for loss calculation but an approximate voltage drop calculation is implemented and described in II-E and is only taken as an indicator. Furthermore the energy losses on the line to be minimized can be deduced with the active power alone.

B. calculation of energy loss

In this section, we compute the energy loss between two nodes i and j of the power network.

$$P_{loss}(i,j) = R(i,j) \times i(i,j)^2$$
$$i(i,j) = \frac{P(i,j)}{u \times \cos\varphi}$$
$$\text{so} \quad P_{loss}(i,j) = kp(i,j) \times P(i,j)^2 \tag{1}$$
$$\text{with} \quad kp(i,j) = \frac{R(i,j)}{u^2 \times (\cos\varphi)^2)} \tag{2}$$

where $R(i,j)$ is the resistance of the line connecting node i to j and $P(i,j)$ the power flowing between i and j.

In this problem we want to optimize the energy transit into the network by minimizing power loss. Having seen how to calculate losses on a line, we show on Figure 1 how to compute the loss on a network.

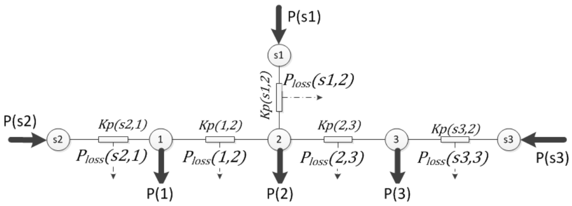

Fig. 1. Simplified electrical network

$P(s1)$, $P(s2)$, $P(s3)$ are the power of the sources s1, s2 and s3 which have to deliver power to the consumption nodes 1, 2, 3, which consume $P(1)$, $P(2)$ and $P(3)$ respectively. We assume that $kp(a,b)$ is equal to $kp(b,a)$.

$P(1)$,$P(2)$,$P(3)$ are known and $kp(s2,1)$, $kp(1,2)$, $kp(2,3)$, $kp(s1,2)$, $kp(s3,3)$ are deduced from material characteristics. However $P(s1)$, $P(s2)$ and $P(s3)$ are unknown and depend on the flow between each node of the network. This flow depends on which consumption is connected to which source.

The aim of the optimization is to minimize the total loss of the network caused by the loss of each individual line.

$$P_{loss\_total} = P_{loss}(s2,1) + P_{loss}(1,2) + P_{loss}(s1,2) + P_{loss}(2,3) + P_{loss}(3,s3)$$

This network can be modeled by a graph, in which source nodes are connected to consumption nodes by edges having a fixed cost, the $kp(i,j)$ value (see Eq. 2). Each line is represented by two edges to represent the two possible directions of the electrical flow. Note that a consumption node may also be a renewable energy source and in this case its consumption has a negative value.

The lines between the power source and the first node are modeled by just one edge, considering that at this connection point the flow goes in only one direction. In reality it is possible to have a flow going up to the power source. This happen when distributed energy produce more energy than what is consumed in the network down to the power source. But here productions are modeled as negative consumption so

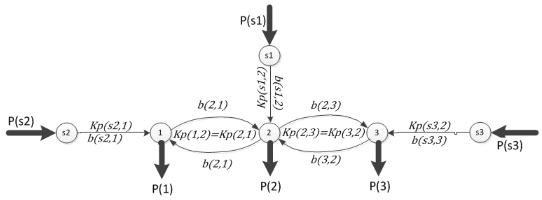

Fig. 2. Simplified network graph

in the graph model the flow going up to the power source will be seen as a negative flow going down.

C. Electrical flow computation

An optimization problem is defined by an objective function and constraints. In sectionII-B the objective function is described and in the following sections the constraints are presented and explained.
Graph theory says that the flow coming into a node is equal to the flow going out, this is a rule applicable to active power flow (Kirschofs law) [10]. Also the graph has to be conservative, so the graph of Fig. 2 is defined as follows:

$$\text{Node 1: } P(s2,1) + P(2,1) = P(1,2) + P1$$
$$P(s2,1) + P(2,1) - P(1,2) = P1 \quad (3)$$
$$\text{Node 2: } P(1,2) + P(s1,2) + P(3,2) = P(2,3) + P(2,1) + P2$$
$$P(1,2) + P(s1,2) + P(3,2) - P(2,3) - P(2,1) = P2 \quad (4)$$
$$\text{Node 3: } P(s3,3) + P(2,3) = P(3,2) + P3$$
$$P(s3,3) + P(2,3) - P(3,2) = P3 \quad (5)$$
$$\text{Conservation : } P(s1,2) + P(s2,1) + P(s3,3) = P1 + P2 + P3 \quad (6)$$

Equations 3-5 give the quantities flowing through the graph, and 6 the conservative flow but we need another constraint to stick to the reality of the electrical network operability.

D. Operational constraint:

A consumption node cannot be powered by two different sources; this constraint is called *radiality* constraint, and is a disjunctive constraint. To model this a new binary variable is defined $b(i,j)$ representing whether an edge connects (i,j) or not. That is the set of b values that gives a "network configuration" by defining where the network should be opened and closed.

Based on figure 2 we can define the following equations:

$$\text{Node 1: } b(s2,1) + b(2,1) = 1 \quad (7)$$
$$\text{Node 2: } b(1,2) + b(s1,2) + b(3,2) = 1 \quad (8)$$
$$\text{Node 3: } b(s3,3) + b(2,3) = 1 \quad (9)$$

Equations 7-9 define the fact that a node can be powered by only one source. Also another important rule has to be implemented, concerning the fact that two opposite edges cannot be active at the same time, which means that the power can only go in one direction through a line.
In the example figure 2 this applies to only two pairs of edges:

$$b(1,2) + b(2,1) \leq 1 \quad (10)$$
$$b(2,3) + b(3,2) \leq 1 \quad (11)$$

In the real test case, equations 10 and 11 are slightly modified to take into account the possibility of opening a line. The condition for allowing a line to be opened is that a switch belongs to the edge considered. If this condition is respected, the constraints are written as in 10 and 11. Whereas in the other case the inequality becomes an equality meaning that at least one of the two edges have to be connected.
Note that $b(s1,2), b(s2,1)$ and $b(s3,3)$ are forced to one.

E. Voltage drop constraint

Voltage drop on a line in a power network must stay between +/-5% of the nominal value. The calculation is defined using the short line pi model Figure 3.

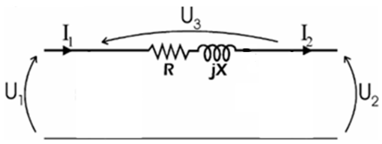

Fig. 3. short line pi model

U1 is the voltage at the beginning of the line, U2 at the end, and U3 represents the voltage drop on the line. Note that $\overline{a}$ is the complex value a and $\overline{a}^*$ is the complex conjugate of a.

$$\overline{U2} = \overline{U1} - \overline{U3} \quad (12)$$
$$S2 = \overline{U2} \times \overline{I2}^* \quad (13)$$
$$\overline{I2} = \frac{P2 - Q2 * j}{\times \overline{U2}^*} \text{ and } \overline{U3} = (R + X * j) * \overline{I2} \quad (14)$$
$$\text{So } \overline{U3} = \frac{(R * P2 + X * Q2) + (X * P2 - R * Q2)j}{U2} \quad (15)$$

To know the value of the voltage drop U3, the absolute value of the complex $\overline{U3}$ has to be calculated. We are interested in the relative voltage drop, because the distribution network voltage drop limitation is defined in terms of percentage of the nominal value. So we divide the obtained value by $U2$. Following these equations, $U2, P2, R$ and X are known.

$$\frac{|\overline{U3}|}{U2} = \frac{1}{U2} \times \sqrt{(\frac{RP2 + XQ2}{U2})^2 + (\frac{XP2 - RQ2}{U2})^2)}$$
$$\text{with } Q = P * \tan\varphi \text{ is known and constant}$$
$$\frac{|\overline{U3}|}{U2} = (\frac{\sqrt{((R^2 + X^2) \times (1 + (\tan\varphi)^2))}}{U2^2}) \times P2 \quad (16)$$

From this is defined the constant coefficient

$$Kc = \frac{\sqrt{(R^2 + X^2) \times (1 + (\tan\varphi)^2)}}{U2^2} \quad (17)$$

which is proportional to the flow obtained by Eq. 3-5.
The particularity of this voltage value is that it is accumulated from the source to the last node of the branch. So, to compute such calculation a third variable $ch(i)$ is defined, which represents the voltage drop accumulated at node i.

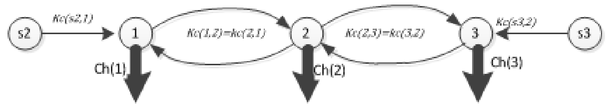

Fig. 4. simplified voltage drop calculation

$$\text{Node 1: } ch(1) = (P(s2,1) * kc(s2,1) + ch(s2)) * b(s2,1) + (P(2,1) * kc(2,1) + ch(2)) * b(2,1) \quad (18)$$

$$\text{Node 2: } ch(2) = (P(1,2) * kc(1,2) + ch(1)) * b(1,2) + (P(3,2) * kc(3,2) + ch(3)) * b(3,2) \quad (19)$$

$$\text{Node 3: } ch(3) = (P(s3,3) * kc(s3,3) + ch(s3)) * b(s3,3) + (P(2,3) * kc(2,3) + ch(2)) * b(2,3) \quad (20)$$

We also set $ch(source) = 0$.
With the constraints described in above sections and knowing that :

$$P_{loss}(i,j) = kp(i,j) \times P(i,j)^2 \quad (21)$$

the optimization model defined in section II-F can be defined with the variables $x(i,j) = P(i,j)$.
Two different equations for energy loss calculation are computed to simplify the computation, one taking into account the square of $x(i,j)$ and the other not.
By taking into account the square of the power in the objective function, the MIQCP problem becomes a MINLP problem, and due to the non-convexity it is harder to solve. We assume that those simplifications do not affect the result of the optimization because during the process, P_{loss_total} will be compared based on the same calculation. However, this could affect the quality of resulting optimization due to computational complexity.

F. Optimization problem definition

1) Glossary:
$x(i,j)$: Real value representing the power flow from vertex i to j
$ch(i)$: Real value representing relative voltage drop at node I
$b(i,j)$: Binary value representing line state (1=edges (i,j) active, 0= edge (i,j) not active)
$kp(i,j)$: Constant loss coefficient from i to j
$kc(i,j)$: Constant voltage drop coefficient from i to j
$up(i,j)$: Upper bound of x(i,j)
$up_{ch}(i)$: Upper bound of ch(i)
nb_{source} : Number sources
$src(p)$: Maximum power that a source p can deliver

a) objective function:

$$Z = \sum kp(i,j) * x(i,j) * b(i,j) \qquad \forall (i,j) \quad (22)$$

b) Constraint:

$$\sum_{i=0}^{n} x(i,j) \times b(i,j) - \sum_{k=0}^{n} x(j,k) \times b(j,k) = P(j) \quad (23)$$

$\forall j$ with $\forall k$ consecutive to j and $\forall i$ incident to j

$$\sum b(i,j) \leq 1 \ \forall j \text{ incident to } i \quad (24)$$

$$ch(i) = \sum (i,j) * (x(i,j) \times kc(i,j)) + ch(j)) \quad (25)$$

$\forall\ j$ incident to i

$$b(i,j) + b(j,i) \leq 1 \ \forall (i,j),\ \forall (j,i) \quad (26)$$

$$x(i,j) \leq up(i,j) \ \forall (i,j) \quad (27)$$

$$x(i,j) \geq -up(i,j) \ \forall (i,j) \quad (28)$$

$$ch(i) \leq up_{ch}(i) \ \forall i \quad (29)$$

$$ch(i) \geq -up_{ch}(i) \forall i \quad (30)$$

$$\sum b(p,i) = nb_{source} \ \forall (p,i) \ i \text{ consecutive to } p \quad (31)$$

$$x(i,p) \leq src(p) \ \forall (i,p) \ i \text{ incident to source } p \quad (32)$$

(33)

III. Performance analysis method

To check the performance of the proposed model, the Matlab tool MATPOWER [11] is used. It is a program developed to calculate power flow of a given network, returning several pieces of information such as voltage at each node and loss in each line. The proposed optimization model does not give the exact loss quantity due to approximations and is used only to find a realistic network configuration that satisfies constraints presented in section II.
In the real-world context, this model is included in a larger application that only handles electrical network data to establish the optimization model, and uses the binary variables assignment to give a network configuration that can be studied on the company state estimator.
In the real network test case, the exact value of $\cos\varphi$ is not known. Moreover we have access to the apparent power for small and medium consumers, and to the real power for large consumers.
Note that small consumers are residential houses, medium consumers are small business and farmers, and large consumers are mainly industrial factories.
However, as input data MATPOWER needs the consumption of each node and the characteristic resistance and reactance of each line. Therefore to get the consumption of each node, a $\cos\varphi$ of 0.95 is used for small consumers and 0.9 is used for medium and large consumers. These values are used to estimate the active and reactive power of each node.
Whereas for the Baran and Wu [1] test case, exact network characteristics are already given. Also each configuration obtained by the optimization process is compared to an initial configuration given by opening s33,34,35,36 and s37 (see figure 5). The loss reduction corresponds to the difference between this initial configuration (loss=202.7kW) and the proposed one.

solver	Energy loss quantity (simple)	Energy loss quantity (square)	loss reduction (simple)	loss reduction (square)	computation time (s) (simple)	computation time (s) (square)
optimum	139.6 kW		31.13%		647	
Alpha_Ecp	181.1 kW	188.8 kW	10.48%	6.67%	14.912	8.78
Baron	161.6 kW	**139.6 kW**	20.28%	31.13%	1.49	19.11
Bonmin	161.6 kW	140 kW	20.28%	30.8%	484	131.43
Dicopt	173.3 kW	**139.6 kW**	14.3%	31.13%	0.105	70.091
Lindo	161.6 kW	**139.6 kW**	20.28%	31.13%	8.805	202.512
Couenne	161.6 kW	**139.6 kW**	20.28%	31.13%	5.251	9.376
Scip	161.6 kW	158.4 kW	20.28%	21.7%	110.05	1000
Sbb	161.6 kW	**139.6 kW**	20.28%	31.13%	3.17	1.345

TABLE I
SOLVERS RESULTS COMPARISON

Our model is mostly developed to be used in planning so computation time is not required to be instantaneous. Nevertheless, it has to be reasonable for practical use (less than 20min), or fast enough to compute a reconfiguration after a blackout.

IV. RESULTS

The proposed model has been tested over Baran and Wu test case [1] composed of 32 nodes, and a real network from SRD composed of 2162 nodes. In the first case no specific limitations are included in the optimization so that every configuration is possible. Whereas in the real case, limitations on the position of the line to be opened are taken into account to simulate the real possibilities of reconfiguration.

The first case study aims at comparing the performance of the result proposed by our simplified model, an optimal configuration, and other proposed methods. The real case study is used to prove the scalability of the model over large networks and studies the trade-off between precision and scalability or rapidity. For the large scale test case voltage drop control is tested. Also taking into account the square of the power is tested for both case study and it corresponds to the annotation "(simple)" or "(square)" in Table I.

The optimization is modeled through GAMS and is computed on NEOS server [12] [13].

A. Baran and Wu test case

Different solvers have been used to look for an optimal configuration. Solutions are given in two columns in Table II: in the first column, we considered a linear loss, while in the second column we consider the loss calculated considering the square of the power.

In the case where the loss is considered linear, the optimal solution proposed on the model does not correspond to the optimal solution for the general loss reduction problem. Whereas in the other case, the optimal solution of the model and the general problem are the same.

In case of square simplification, only two solvers over eight could not find the optimal solution, Alphaecp and Dicopt. SBB found the optimal solution but was not able to declare it optimal.

Whereas in case where the square of the power is computed, three solvers could not find the optimal solution Scip, Alphaecp and Bonmin. Also this time Dicopt, SBB and

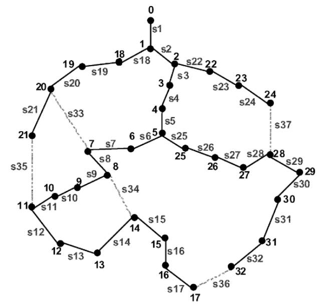

Fig. 5. Baran and Wu network

Baron could not declare the solution optimal even if they found it. Baron found the solution in 19.11s but stopped on the maximum time allowed. An option was used for Dicopt to stop on iteration limit (option: "stop=0" and "iterlim=1000000)). Table I summarizes those results and shows that taking into account the square of the power to optimize energy loss gives better solutions. Also the solver chosen can influence the result, both in quality (energy loss) and speed.

In table II the configurations proposed are compared in terms of line status. We can see that the proposed model reached the optimum configuration.

solver	Line opened (simple)	Line opened (square)
optimum	**s7 s9 s14 s32 s37**	
alpha_ecp	*s9 s24 s32 s33 s34*	*s8 s31 s33 s34 s37*
bonmin	s10 s13 s16 s28 s33	*s8 s14 s28 s33 s36*
baron	s10 s13 s16 s28 s33	**s7 s9 s14 s32 s37**
dicopt	*s10 s13 s16* s27 *s33*	**s7 s9 s14 s32 s37**
lindo	s10 s13 s16 s28 s33	**s7 s9 s14 s32 s37**
couenne	s10 s13 s16 s28 s33	**s7 s9 s14 s32 s37**
scip	s10 s13 s16 s28 s33	*s7 s8 s34 s36 s37*
sbb	s10 s13 s16 s28 s33	**s7 s9 s14 s32 s37**

TABLE II
SOLVERS RESULTS LINE STATUS

It should be noted that With dicopt in the first case without square on the power, the solution returned is different from the optimal one because of one switch (s27).

The proposed model has been compared to other methods of solving the loss reduction problem based on previous work [5]. The author also notes that there is some difference in the value of power loss given by the literature, but to compute the presented value the list of open/closed switches have been used. Table III shows that our proposed method

method	loss Quantity (kW)	computation time (s)
optimum	139.6	647
khodr [5]	139.6	0.11
Gomes [5]	139.6	1.66
Goswami [5]	139.6	0.87
McDermott [5]	139.6	1.99
Ahmadi [14]	139.6	3.2
Proposed	139.6	1.35
Gomes2 [5]	140.2	0.96
Shirohammadi [5]	140.2	0.14
Schmidt [3]	142.4	0.01
Baran [1]	146.8	–

TABLE III
COMPARAISON BETWEEN DIFFERENT METHODE

has the same performance as the best ones proposed in the literature. Nevertheless, our main goal is scalability for real-world networks.

B. Real test case

The Baran Wu test case shows that taking into account the square has a positive impact on loss reduction. However because of computation complexity of a non convex MINLP problem, the time needed to find a solution increased. In the case of a real network with up to 2k variables, the only solver that finds a solution is Baron.

In this part the same tools are used to evaluate their behavior. Nevertheless, since we do not know any optimal solution, the solution is compared to the actual configuration used to operate the network, which is obtained by a manual worst case study. This gives an idea of the energy that could be saved by reducing losses, and we can compare the maximum voltage drop of each configuration. (loss=8.65MW, voltage drop=45.5%).

parameters	total load	total active losses	maximum voltage drop	calculation time
simple	63 MW	4.56 MW	16.4%	410 sec
simple+ voltage	63 MW	4.42 MW	16.3%	405 sec
square	63 MW	4.95 MW	16%	3000 sec
square+ voltage	63 MW	5.13 MW	16.2%	3000 sec

TABLE IV
RESULTS OF REAL CASE

In Table IV, we can see that the model is able to give a solution that reduces the total power loss of the network in any case. We also see that the voltage drop can be controlled even if it the change is small between the two proposed configurations.
In reality, there is a minimum voltage drop under which it is impossible to converge, so trying to control it too much will result in non-convergence. Maybe if we turn off the constraint on the switch position we could control the voltage drop better by allowing more configuration to be evaluated.
But we also see that the complexity introduced by taking into account the square of the real power in the objective function significantly increases the solving time due to non linearity. We also see that those configurations are not better than the one given by the simplified model.
These results show that approximation on the model is more efficient than approximation on the solver. It has to be noted that computation time is reduced in comparison to other methods. In [8] the process takes 14256s on a 417 node network, whereas in [14] it takes 1134s for a 880 node system and [15] relaxes the problem of 880 nodes to have a solution in 874s. So those three examples show that our approach is efficient for a large scale problem.

V. Conclusion

These results tend to prove the possibility of reducing loss in a real distribution network, with network flow problem modeling and show that simplification on model level is better than on solving level. However we can see that MINLP and MIQCP solvers struggle with large scale problems, and that makes the optimization of large distribution network difficult. The proposed method gives good results in comparison to other methods presented in section IV.

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