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Combined Medium Voltage and Low Voltage simulation to accurately determine the location of Voltage Problems in large Grids

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Abstract

Distribution Network Operators (DNOs) traditionally treat Low Voltage (LV) and Medium Voltage (MV) networks as two separate entities. Both voltage levels have their own set of assumptions and design policies. This paper proposes a fast load flow algorithm suitable to simulate both the LV and MV network in a single simulation. The algorithm is applied to the grid of Alliander DNO. Using this method, congestion problems in both the LV and MV grid can be determined with greater detail. Using a case study it was shown that identical customer load scenarios produce vastly differently results if the MV network is taken into account. While the absolute number of voltage problems was in the same order of magnitude, the location of these problems overlapped only 20%. The lack of overlap has a severe implication, namely that searching for congestion by only simulating LV networks yields the wrong voltage problems. This conclusion calls for network design using integral MV/LV simulations.

1 Introduction

Distribution Network Operators (DNOs) traditionally treat Low Voltage (LV) and Medium Voltage (MV) networks as two separate entities. Both voltage levels have their own set of assumptions and design policies. For example, Alliander DNO defines the maximum voltage drop in the MV network of 4.5% in internal policies, while in reality only the voltage drop of the customers is required to stay within the legal range of 10%. Simulating both the LV and MV network in a single load flow simulation makes these kind of assumptions obsolete, resulting in a more effective grid management and a calling for a new grid design paradigm.

This paper proposes a novel fast linear load flow algorithm to simulate both the entire LV and MV network in a single simulation. The simulation is applied to the network of Alliander DNO. Alliander DNO is the largest DNO of the Netherlands and operates the Low Voltage (LV) and Medium Voltage (MV) power grid. Subject of this study are both the LV and MV network, which consist of approximately 80.000 km of cable serving over three million customers. It covers over 1/3rd of the total Dutch power grid and is divided in over 24 million

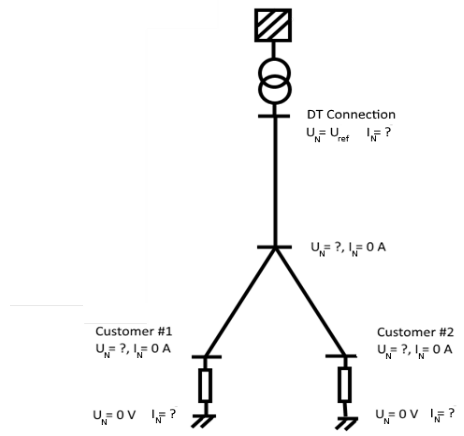

Fig. 1: A small example LV network. The network has two customers modeled as resistors and a single connection to the medium voltage grid by a distribution transformer. In this figure the MV network is simplified as a voltage source with infinite capacity.

cable segments. The network is modeled and a single phase balanced network.

2 Load flow: a fast linear approach

This section describes a fast linear network model, suitable to evaluate very large low voltage networks. It has been used for both strategic studies [1] and network battery storage control [2]. In this paper the model will be applied to calculate voltage problems of a large grid.

2.1 General linear load flow

The standard approach for modeling DNO power grids is formulating a load flow problem and solving it using a Newton-Raphson methodology [3 4]. Usually the load is modeled as a combination of a constant power, constant impedance and constant current [4]. This paper however uses a simple linear load flow approach by only using a ‘constant impedance’ load model. The model is described in greater detail in [2].

The network is modeled as a graph as can be seen in Figure

1. A standard way to define such a graph is by defining graph G as $G = (\mathcal{N}, \mathcal{E})$, where $\mathcal{N}$ are the nodes and $\mathcal{E}$ are the network edges. In case of an electricity network $\mathcal{N}$ represent the network buses and $\mathcal{E}$ are the network cables. The goal of the model is to determine the cable currents $I_{\mathcal{E}}$ and the nodal voltages $U_{\mathcal{N}}$.

The network voltages and currents can be obtained by using Ohm's law:

$$I_{\mathcal{N}} = \bar{Y} U_{\mathcal{N}} \tag{1}$$

Here $I_{\mathcal{N}}$ is the current entering a network bus and $\bar{Y}$ is the so-called admittance matrix. The admittance matrix can be directly obtained from the network lay-out using the following formula [5]:

$$\bar{Y} = A Z_{\mathcal{E}}^{-1} A' \tag{2}$$

Here A is a directional connection matrix. Every row corresponds to a network bus. Every column of A corresponds to a network cable. Each cable should have exactly one starting point denoted by a '1' and and one end point denoted by '-1'. $Z_{\mathcal{E}}$ is a square matrix and has the corresponding impedance of each cable/edge ($\mathcal{E}$) on its diagonal.

To create the 'constant impedance' model as in Figure 1, it is necessary to convert the power use of a customer into an equivalent resistance. This can be done by the following formula:

$$Z_{\text{eq}} = U_{n,\text{ref}}^2 / P_{\text{user}} \quad \forall n \in \mathcal{N} \tag{3}$$

Here Z_{eq} is the equivalent resistance of the customer, P_{user} the real power consumption of the customer, n is a bus which represents a customer connection and $U_{n,\text{ref}}$ is the voltage at the customer location. Since the voltage at the customer is usually not known, the reference voltage is be assumed to be the nominal voltage.

However, (1) cannot be solved directly, because not all elements are known in neither vector $I_{\mathcal{E}}$ and $U_{\mathcal{N}}$. To overcome this problem, it is practical to segment the problem in two equations which can be solved separately. This can be done by sorting the rows of the matrices $I_{\mathcal{N}}$, $\bar{Y}$ and $U_{\mathcal{N}}$ in such a way that all swing buses are $\in U_1$. The segments are then defined as:

$$I_{\mathcal{N}} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \bar{Y} = \begin{bmatrix} K & L \\ L' & M \end{bmatrix}, U_{\mathcal{N}} = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{4}$$

Since at all network nodes no power enters or leaves the network, I_2 is equal to $\bar{0}$. All the voltages on the end nodes, represented by U_1 are known. The voltages in U_1 are zero, except for the transformer voltage. The load flow equations now become:

$$\begin{bmatrix} I_1 \\ \bar{0} \end{bmatrix} = \begin{bmatrix} K & L \\ L' & M \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{5}$$

A natural way to solve for U_2 is:

$$U_2 = -M^{-1}(L'U_1) \tag{6}$$

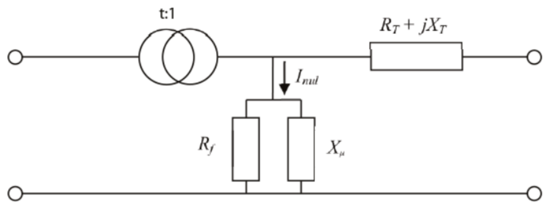

Fig. 2: A schematic representation of the transformer model. [6] The transformer is modelled as an RL network.

However, matrix M is usually too large and too costly to invert. Fortunately, it is not necessary to compute M^{-1}. Instead, it is more practical to solve:

$$L'U_1 = -MU_2 \tag{7}$$

Since this equation is in the form $Ax = B$ it can be solved in many practical ways. Finally after computing the voltages, the cable currents can be directly calculated by:

$$I_{\mathcal{E}} = Z_{\mathcal{E}} A' U_{\mathcal{N}} \tag{8}$$

In addition to be very efficient, this linear model has another distinct advantage. Namely it is not prone to finding unfeasible solutions or numerical difficulties, which can occur in normal load flows [4]. This makes the method more stable and more suitable for increasingly large loads due to the energy transition.

2.2 Adding reactive power

To add reactive power to the load flow simulation, the cable reactances are added to $Z_{\mathcal{E}}$, such that elements of $Z_{\mathcal{E}}$, Y, U and $I \in \mathbb{C}$. To include these efficiently in (1), it can be expanded [7] to:

$$\begin{bmatrix} I_{\mathbb{R}} \\ I_{\mathbb{C}} \end{bmatrix} = \begin{bmatrix} Y_{\mathbb{R}} & -Y_{\mathbb{C}} \\ Y_{\mathbb{C}} & Y_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R}} \\ U_{\mathbb{C}} \end{bmatrix} \tag{9}$$

where the subscripts $\mathbb{R}, \mathbb{C}$ are used to indicate respectively the real and imaginary part of the matrix. Thus, $Y_{\mathbb{R}} = \text{Re}(Y) = A\,\text{Re}(Z^{-1})A'$, and correspondingly $Y_{\mathbb{C}} = \text{Im}(Y)$. Using the same method as before this can be simplified to:

$$\begin{bmatrix} M_{\mathbb{R}} & -M_{\mathbb{C}} \\ M_{\mathbb{C}} & M_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R},2} \\ U_{\mathbb{C},2} \end{bmatrix} = - \begin{bmatrix} L_{\mathbb{R}} & -L_{\mathbb{C}} \\ L_{\mathbb{C}} & L_{\mathbb{R}} \end{bmatrix} \begin{bmatrix} U_{\mathbb{R},1} \\ U_{\mathbb{C},1} \end{bmatrix} \tag{10}$$

which is the complex variant of the equation $MU_2 = LU_1$. By solving this equation, the voltages can be determined. Equation (9) can be used to find the currents through the cable-segments. Then $U_{\mathcal{N}}$ and $I_{\mathcal{N}}$ can be found by:

$$\begin{aligned} U_{\mathcal{N}} &= \sqrt{U_{\mathbb{R}}^2 + U_{\mathbb{C}}^2} \\ I_{\mathcal{N}} &= \sqrt{I_{\mathbb{R}}^2 + I_{\mathbb{C}}^2} \end{aligned} \tag{11}$$

2.3 Simulating MV/LV transformers

To simulate MV/LV transformers, the transformers have been modeled as an RL network[6] as displayed in Figure 2. They

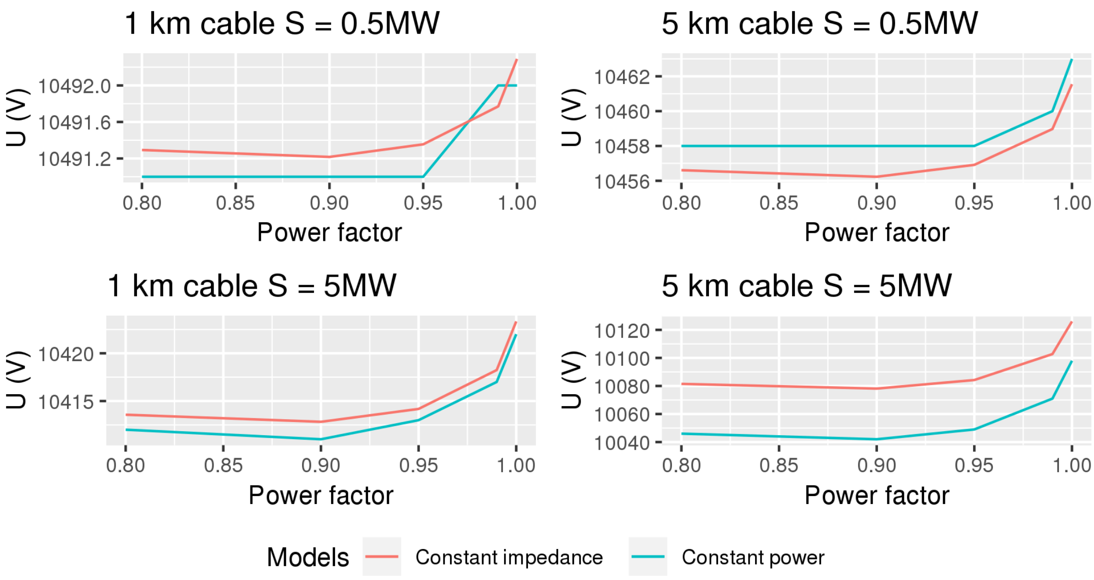

Fig. 3: Sensitivity analysis: voltage at the endpoint as function of the power factor of the load S. Comparison between a linear constant impedance model and the recursive constant power model for an 3x240Al XLPE 10.5 cable with varying length and load.

have been added to the impedance matrix Z from (8), as the link between the MV and LV network. The no-load is added as an extra load to the secondary side of the transformer. To solve the entire network in one matrix equation, an E $\times$ E diagonal scale matrix T is defined using the turns ratio t. For every cable behind the secondary side of the transformer the corresponding value in T is the turns ratio of that transformer. For every cable in the medium voltage network, the corresponding value in the matrix T is 1. The impedance of the links is then scaled using $Z_p = T^2 Z_s$. Here p, s denote the primary and secondary side of the transformer respectively.

After the calculation, the turns ratio is used to re-scale the voltage and current to the LV-regime using $U_s = T^{-1} U_p$ and $I_s = T I_p$, with U, I defined as in (11).

2.4 Motivation for linear modeling

The be able to solve the load flow equations for very large networks in a very short time span, a linear method is used. To ensure this method is sufficient for the applications it is designed for, the network model used in this paper has been validated in various ways. For both models a sensitivity analysis has been performed. The LV model was applied to a real world network and compared with measurement data in [8] and [2]. It was concluded that the LV model is sufficiently accurate for network control purposes. The MV network model has yet to be compared with measurement data.

A sensitivity analysis for the MV model has been performed by comparing the results for a standard (Dutch) cable with varying lengths and loads, to results from a Newton-Raphson load flow calculation performed using the network design tool Vision [9], assuming a constant power load. The cable used is an 3x240Al XLPE 10.5, where the properties used are $R = 0.162$km, $X = 0.089$km, with the length l set to 1 or 5km. The apparent load S was set to 1 or 5MW and the power factor between $0.8 - 1$.

In Figure 3 results from the comparison are plotted. It can be seen that the behaviour for the voltage as a function of the power factor is comparable, but the difference in voltage at the endpoint between the two models increases from 0.3V to 35V for increasing length and load. Respectively, this is a difference of 0.003% to 0.3% with respect to the source voltage of 10500V and 0.03% to 8% with respect to the voltage drop over the entire cable.

The bottom-right situation in Figure 3 is an extreme; it describes a single long cable with a heavy load. The voltage drop itself is 4.2%, which is slightly less than the very maximum Alliander policy allows. The constant impedance model leads to a small underestimate of the voltage drop. However, this error is so small that it is negligible in the case engineering applications.

It is the author's expectation that adding the High Voltage (HV) network to the simulation will not alter the results significantly, since the secondary voltage level of the HV/MV transformer is controlled.

3 Case study: Voltage problems in a large Dutch power grid

To demonstrate the impact of integrally simulating the MV/LV grid, a case study has been assembled. The case study focuses on voltage problems since their locations stay the same between the MV/LV and LV simulations, making the results easy to compare.

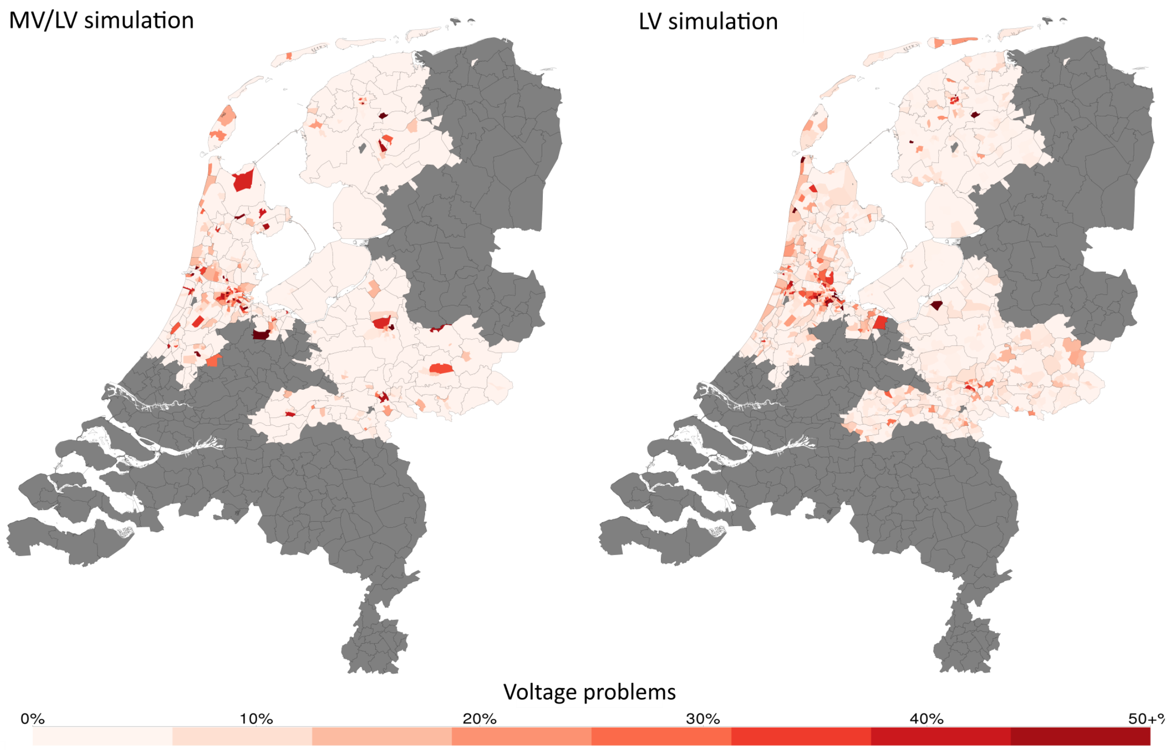

Fig. 4: The geographical distribution of simulated voltage problems in the Alliander service area on a postal code level. The area depicted is the entirety of The Netherlands of which Alliander services the non-grey area. The problems in the MV/LV simulation are more concentrated, which can be logically explained by the fact a LV network with high loads influences neighbouring networks.

3.1 Data and implementation

The models described in the previous sections have been implemented in the *R* programming language. All linear algebra is implemented using the *Matrix* package which is a C wrapper for the BLAS and Lapack matrix computation libraries.

To assess the voltage and current problems, asset data from Alliander DNO has been used. Their data sets consisted of all cable segments, their connectivity and impedance. Furthermore, the connectivity, voltage ratio and impedance of all transformers was used in the simulation.

While the MV network of Alliander DNO consists of 100,000 segments, the LV network consists of over 24 million cable segments. Combining these networks resulted in a $\bar{Y}$ matrix with dimensions of 24 million by 24 million. To cope with these enormous matrix dimensions, sparse algebra implementations have been used. The resulting matrices were not larger than 800 MB which can be easily handled by a modern computer.

Solving load flows for grids the size of the one of Alliander DNO is computationally very expensive. However, by applying the linearized algorithms proposed in this paper, the load flow problem is solved within 60 seconds for the entire network on a single processor core.

3.2 Simulation results

To run the simulation, all three million end users have been given a load of 1.1 kW with a power factor of 0.95. The power consumption of 1.1 kW is the design peak power for regular households for LV grids containing over forty households.

Applying this load to the entire grid is not too realistic and normally the loads would be modified using the Strand-Axelsson incidence factor [10] or by using a power consumption time-series. It is however sufficiently realistic to prove the main point of this paper, namely that an identical load configuration will result in a very different layout of voltage problems, if the MV/LV network is simulated integrally or only the LV network is taken into account.

In line with Alliander policy, a voltage problem was defined as a voltage drop of 4.5% on the LV grid from the distribution transformer to the customer. This implies a 4.5% voltage drop on the MV level and is supposed to be a worst case situation. For the integral MV/LV simulation the allowed voltage drop was set to 9% from substation transformer to customer.

The absolute number of voltage problems that was found in the MV/LV simulation of voltage was 150 thousand, 5% of the total number of customers. The absolute number of voltage problems in the LV simulation was 180 thousand, 6% of the total number of customers.

While these numbers are in the same order of magnitude, the locations of the problems were found to vastly different. The voltage problems overlapped only 20% between simulations as can also be observed in Figure 4. The lack of overlap has a severe implication, namely that searching for congestion by only simulating LV networks yields the wrong voltage problems. It calls for network design using integral MV/LV simulations; a new design paradigm.

4 Conclusion

A fast linear load flow model was proposed, validated and applied to a large real world network. Using a case study it was shown that identical customer load scenarios produce vastly differently results if the MV network is taken into account.

The fast linear load flow algorithm was applied to the entire grid of Alliander DNO. Differences in problem location between the regular assumptions on voltage drops was assessed. The regular assumptions are 4.5% voltage drop on MV and 4.5% on LV networks. The new set of assumptions investigates a 9% voltage drop from substation to customer. While the absolute number of voltage problems was in the same order of magnitude, the location of these problems overlapped only 20%.

This paper motivates a new design paradigm for DNO networks. Instead of designing MV and LV networks separately, it is more effective to design MV and LV integrally. This way voltage problems can be mitigated more efficiently.

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