Impact of distribution network modelling on harmonic impedance in the HV grid

IMPACT OF DISTRIBUTION NETWORK MODELLING ON HARMONIC IMPEDANCE IN THE HV GRID

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ABSTRACT

Frequency impedance scans are required for the harmonic assessment of new connections in the High Voltage grid. Most of the HV substations are connected to Distribution System Operators (DSO). In the Netherlands these MV grids are cabled with a typical length between 2 to 300 km. These downstream voltage networks may have significant influence on the total system impedance. For the HV network operator, it is almost impossible to model these grids in detail, so a simplification is therefore required. In this paper, a method to derive the simplified model of distribution networks based on a limited number of generalized MV feeders through a clustering process is described. After that, the parameter values (R, L, C's) for equivalent models based on the generalized DSO networks are calculated and compared with other equivalent models found in the literature.

INTRODUCTION

For the harmonic studies in transmission network, the distribution network (the medium voltage (MV) with attached low voltage (LV) networks is generally a complex impedance element, whose impact needs to be investigated further. In the Netherlands, the distribution networks are almost entirely supplied with cable connections and the potential impact of these cables to the harmonic response in the transmission side could be significant due to the aggregated cable capacitance. Therefore, an accurate model of distribution network is required for harmonic analysis. The most accurate one should be the detailed model with each line section including cables, transformers and loads, etc. based on the real topology, components and customer data. It requires the specific information at the locations, which could be difficult for most of the cases and requires tremendous efforts. Moreover, frequency impedance scans need to be executed at the observation bus which calculates the impedance magnitudes and phase angles over a frequency range. When all the distribution networks are modelled in detail, the time consumption in terms of calculating harmonic impedance would also be significantly increased. Therefore, simplified circuits are required to be used as the equivalents of the real distribution network.

Frequency-dependent models for network elements are discussed in [1, 2, 3], which are used for network modelling in the harmonic analysis. Currently a Cigre brochure is foreseen by Cigre WG C4.38 about the network modelling for harmonic calculation. In [4, 5], the harmonic impedance was calculated at the HV side of a 220/70 kV transformer when the distribution system was modelled in either series or parallel load models. Sensitivity studies have been conducted where the impacts of various components are investigated. The simulations have been done when the upstream network (external grid) was represented as an equivalent short-circuit impedance, which can cause large errors for some frequencies, since the external grid impedance is frequency dependent in nature which is more complex than $h \cdot X$. The simplified load models in [4, 5] were calculated with the active and reactive power (*P* and *Q*) given as an *R*, *L*, *C's* circuit when the choice of *L* or *C* is dependent on the flowing direction of *Q*. However, to display *L* and *C* individually would give different response in harmonic domain than just use an aggregated element. Undergrond cables used in distribution network would add more capacitance in MV and LV networks. These capacitive equipment can lead to a move of the resonance to a lower frequency range. Therefore, the Type-2 load model including two capacitances due to MV cables and LV connections, reactance of the downstream transformer and the resistance of the load can be used [6]. Since it is unlikely known the information of each specific distribution network by TSO, the challenge of using Type-2 load model is to determine the parameter values since they are related to component characteristics, feeder length, amount of MV/LV transformers, and so on.

In this paper, an approach based on generalized distribution feeders is proposed to calculate the parameter values for the Type-2 load model. More exactly, the harmonic responses from the generalized extended network are comparing with all other equivalents, where data clustering techniques are used to obtain the generalized network. Then the parameter values for the equivalent models can be calculated with these generalized network.

MODEL OF TRANSMISION NETWORK

The structure of the Dutch power system is shown in Fig. 1. The downstream network (DSOs) is defined from 50 kV to 0.4 kV networks, which involves 50 kV, 20 kV, 10 kV and 0.4 kV networks. The transmission network refers to the rest of the network.

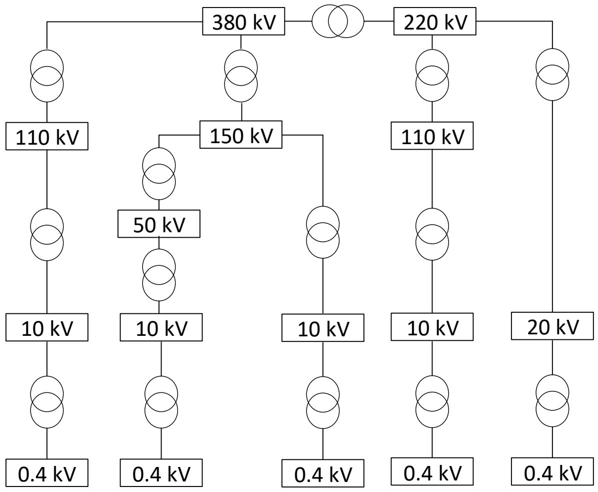


Fig. 1 Dutch power system

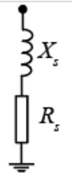
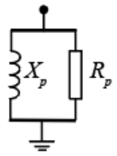
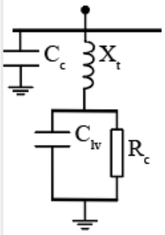
The whole transmission network has been modelled and the network elements include overhead transmission lines (OHL), underground power cables, transformers, and generators and loads etc. The objective of this paper is to add the downstream network parts, including loads, downstream transformers and cables. Accurate models are used in terms of their frequency-dependent (FD) characteristic [1]. Distributed parameter model (equivalent PI) is applied for lines and cables and skin effect is considered as well via Bessel functions. The general FD model of transformer as given in [2] is used. More specifically, the transformer model consists of a resistance in series with a reactance. The reactance is obtained with the leakage inductance and the FD resistance of h_{th} order is considered as $\sqrt{h}$ times the resistance at the nominal frequency. For the generators, the IEEE model is used which gives a FD passive shunt impedance based on the negative sequence impedance [3].

MODEL OF DISTRIBUTION NETWORK

Distribution network models

Load behaviour is becoming more and more important due to the increasing use of power electronic devices and cables in the distribution networks and it can lead to reduction of damping and increase of the load capacitance. In the most previous harmonic studies the distribution network is represented with a fixed PQ load. However, an aggregated harmonic load model, aiming to represent a group of loads at a particular voltage level together with network elements (e.g. cables, OHLs, shunt compensation devices), needs to be used as given as the Type-2 load model. In Table 1, the series, parallel and Type-2 model of loads are illustrated [7]. These are connected to the MV side of the HV/MV transformer.

Table 1 Summary of load models: series, parallel, Type2 and detailed model.

Model	Diagram, Parameters and Description
Series	 $R_s = P\frac{V^2}{P^2+Q^2}$ $X_s = Q\frac{V^2}{P^2+Q^2}$
Parallel	 $R_p = \frac{V^2}{P}$ $X_p = \frac{V^2}{Q}$
Type-2 load model	 C_c: capacitance at the supply bus X_t: transformer reactance C_{lv}: LV capacitance R_c: resistive load
Detailed model	The network from the secondary side of HV/MV transformer to the LV busbar of MV/LV transformer is modelled including all MV cables and MV/LV transformers. The LV network is modelled with an equvilent load model.

The Type-2 model given in Table 1 is elaborated in [6], including the exact definition and calculation approaches. It involves the impedance of the MV/LV load transformer and also contains user definable static and dynamic portions. C_c represents the total capacitance at the grid supply point (GSP) calculated based on the composition of cables in this distribution system. C_{lv} is related to the household electronic devices and cable system at aggregated LV level. The exact definition of each parameter can be given as:

- R_c is calculated with the total active power of loads.
- X_t is constant for 50 Hz and depends on the number of MV/LV transformers
- C_c is calculated by multiplying an approximate length of circuits of the MV distribution network connected to the bus with the cable capacitance.
- C_{lv} is calculated by summing up the capacitance of household electronic equipment and the total capacitance of LV cables.

To get the values of C_c, X_t, R_c and C_{lv}, necessary knowledge about the downstream network should be available which depends on the components, compositions and topology, etc.. Moreover, a detailed load model as described in the last row of Table 1 is required as a reference to compare the performance between the load models of Table 1.

Clustering feeders

As it is difficult for a TSO to obtain the exact information at each HV/MV substation, a generalized method through feeder clustering is proposed here. With the information of approximate 3500 MV distribution feeders and over 80000 LV feeders provided by a Dutch DSO, the necessary data is extracted and a mathematical algorithm has been implemented to describe the MV and LV networks via a limited set of general cases. Furthermore, the parameter values of Type-2 model can be calculated with the characteristics given by the modelled detailed distribution network. In the following subsections, the clustering techniques for distribution network feeder are described and the approach to determine the type and number of each generalized feeder in one substation are illustrated. In Fig. 2, the flow chat of the methodology has been shown.

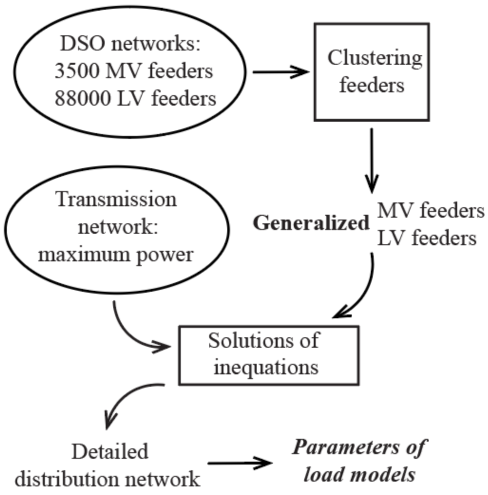


Fig. 2 Flow chart of distribution network modelling

In order to cluster feeders, Gaussian Mixture Model (GMM) has been applied to the MV network information, which is useful both for understanding and suggesting powerful criteria [8]. GMM is a probabilistic model with an assumption that all the data points are generated from a mixture of a finite number of Gaussian distributions with unknown parameters. The details about clustering feeders with GMM can be found in [9]. Some parameters need to be defined for the clustering process.

- Industry substations number (ISN): the number of industry substations among all MV/LV substations.
- LV customers number (LCN): the average number of LV customers in one non-industry substations.

With the input of four different parameters: average POC impedance, the number of POCs, ISN, and the total length of the feeder, all MV feeders have been clustered into fifteen groups, the seven ones with the highest occurrence have been shown in Table 2. For instance, cluster 1 in the second column refers to a group can be represented with a clustered feeder with 7 POCs, an approximate cable length of 4.7 km made of copper, 0 industrial customer and each LV network has around 114 customers. This cluster represents total 13,5% of all feeders. For the LV feeders, the predominant feeder types in the Dutch network is shown in Table 3 according to [10].

Table 2 Generalized type of MV feeders

Cluster	1	2	3	4	5	6	7
Number of POCs	7	19	19	1	11	8	13
Length [km]	4.7	19.5	3.35	3.6	5.4	3.3	6.8
Cable type	Cu 95	Al 150	Cu 95	Al 150	Cu 95	Al 150	Cu 95
ISN	0	5	2	1	5	2	1
LCN	114	117	100	0	27	122	88
Percentage [%]	13.5	12.6	11.3	8.9	7.7	7.6	5.2

*Cu 95: copper cable with a cross section of 95 mm^2
*Al 150: aluminium cable with a cross section of 150 mm^2

Table 3 Generalized type of LV feeders

Cluster	Length [m]	Cable type	Number of customers
1	184	Al 150	17
2	270	Cu 70	24
3	266	Al 95	39
4	218	Cu 50	19
5	362	Al 150	32
6	290	Al 50	26
7	386	Al 95	49
8	683	Al 150	70

Determination of the type and number of feeder

With results obtained from the previous section, the detailed distribution network can be built when the types and the number of each type of feeder are determined. It has be converted as solutions of inequations (1) calculated through nonlinear programming.

$$\begin{gathered}\sum_{i=1}^{15} n_{f,i} \cdot \mathrm{p}_{\mathrm{f,max,i}} \geq p_{s,max} \cdot (1-a) \\ \sum_{i=1}^{15} n_{f,i} \cdot \mathrm{p}_{\mathrm{f,max,i}} \leq p_{s,max} \cdot (1+a) \\ \mathrm{n}_{\mathrm{f,i}} \leq \sum_{i=1}^{15} n_{f,i} \cdot \rho_{\mathrm{i}} \ \& \ \mathrm{n}_{\mathrm{f,i}} \in \mathbb{Z}^{\geq}\end{gathered} \quad (1)$$

where i indicates the type of feeder as shown in Table 2, $n_{f,i}$ is the number of feeder i which is a non-negative integer ($\mathbb{Z}^{\geq}$), $p_{f,max,i}$ is the estimated maximum power of feeder i, $p_{s,max}$ is the maximum power of the target substation, a is a tolerance percentage of the maximum power, e.g. 10%, and ρ_i gives the percentage of feeder i which is shown in the last row of Table 2.

SIMULATION RESULTS

Description of the case study

The theory as described before will be illustrated by a realistic case study. The topology is shown in Fig. 3. The area is with 110 kV supply and the upstream is 220 kV transmission network. The calculation has been executed at the substation of interest. The HV/MV transformer is included in the model and the load model is connected at the secondary side of this transformer.

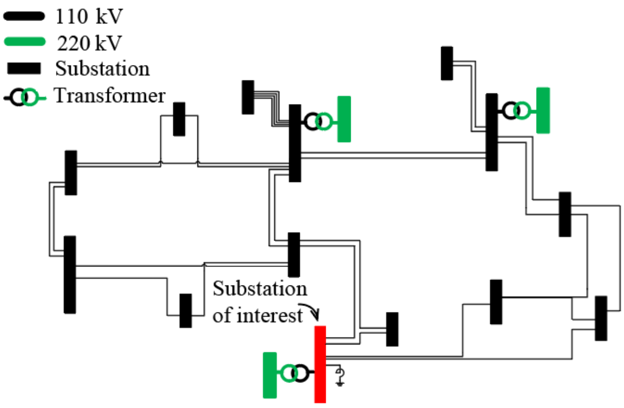


Fig. 3 Local model area

The detailed model as described in Table 1 needs to be built as the reference for model comparison between equivalent load models. DigSILENT Powerfactory provides the platform for these frequency sweep simulations.

Area considered

To use the R/X impedance load model in Powerfactory, either the series or parallel load model of table 1 is chosen depending on the direction of the reactive power. When *Q* is higher than 0, a series model is used, otherwise a parallel model is selected. The abbreviation "R/X" refers to the series or parallel model.

In Fig. 4, different number of substations are modelled in detailed pattern. In the figure, "One substation" indicates only the 110kV/10kV substation of interest is detailed modelled and the rest substations are represented by R/X load models. Label "Five substations" refers that the substation of interest and other four close by substations are modelled in detail. Label "All substations" means the downstream network of every substations in Fig. 3 is modelled in detailed pattern. It can be found that large difference exists between the case of one and five substations, however, the curves of five and all substations are much closer. Although the model with more detailed information provides more accurate results, but the accuracy improvement becomes less significant with increasing distance. Hence, the harmonic impedance when all substations in the local area are in detailed model is used to compare the results with the equivalent load models in the following subsection. Substations in other areas connected with the upstream 220 kV network are not required to be modelled in detail.

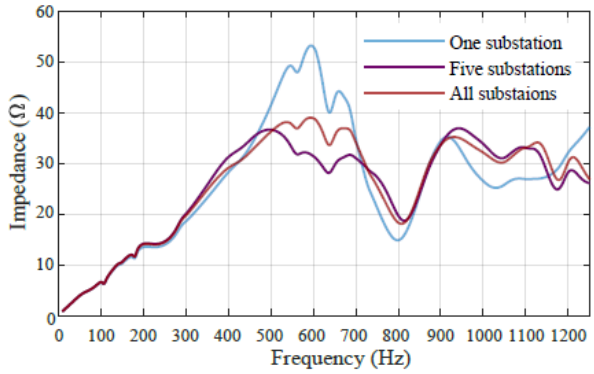


Fig. 4 Harmonic impedance when one, five and all substations are detailed modeled

Comparaisons of load model types

The parameters of Type-2 load model are calculated with the information provided by the detailed model as described above Fig. 5 shows the harmonic impedances from 10 to 1250 Hz at the PCC. It shows that the results of the Type-2 model are much closer to the detailed one rather than the R/X impedance model. The results of all load models are almost the same when the harmonic order is lower than 8. However, the magnitude of the detailed model or Type-2 model at 600Hz is almost double the value of the R/X impedance model, that cause more adverse effect since these peaks of harmonic impedance are critical parts for a harmonic study.

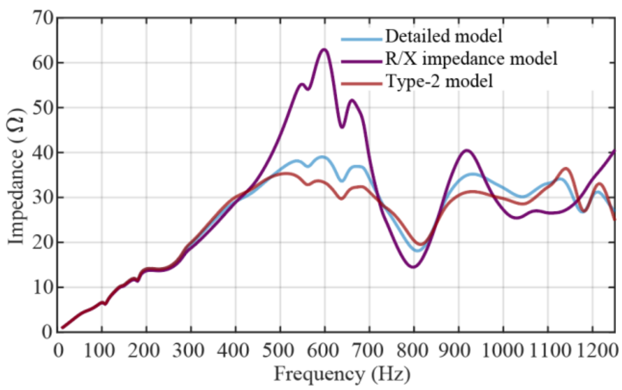


Fig. 5 Harmonic impedances at the HV side at the PCC of the detailed, R/X impedance and Type-2 load models

Fig. 6 (a) and (b) show the magnitudes and phase angles from 10 to 2500 Hz. The phase angle curve of the Type-2 model also matches with that of the detailed model. For higher frequencies resonances occur that are not visible in the R/X impedance model.

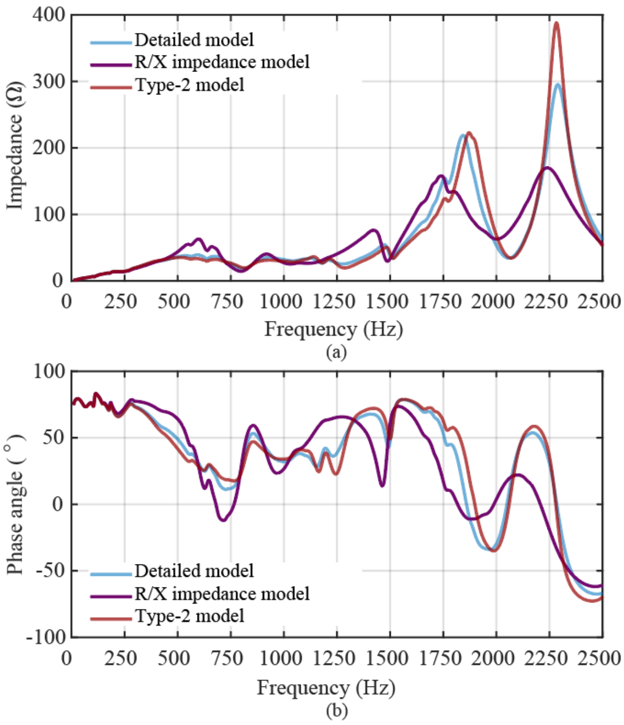


Fig. 6 Harmonic impedances of the detailed, R/X impedance and Type-2 load models: (a) magnitude, (b) phase angle

CONCLUSIONS

The paper proposed a method to model the MV distribution networks in harmonic studies for HV grids. The parameters of equivalent load models are calculated based on feeder clustering with the DSO database. The performance of different types of load models are compared. Significant differences have been found between the detailed and the R/X impedance model. The Type-2 model, as an aggregated load model involving the capacitances of cables and households gives much more accurate harmonic impedance close to the detailed reference case. Especially when the harmonic order is higher than 8, the Type-2 model outperforms the simple impedance model significantly. In addition, to use the Type-2 model takes less calculation complexity than the detailed one. Therefore, the Type-2 load model is recommended to use for harmonic studies since the capacitance values can be calculated with the approach described in this paper.

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