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ASSESSING THE OPERATION OF TYPICAL DUTCH DISTRIBUTION SYSTEMS WITH LARGE PENETRATION OF LOW-CARBON ENERGY TECHNOLOGIES

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Abstract

Currently, the majority of the available test feeder models are based on the North American type of distribution systems, leaving an absence of representative feeder models for the European (and Dutch) types of distribution systems. Therefore, a standardized set of power flow models for typical Dutch LV distribution networks is developed using real networks and operational data provided by a Dutch DSO. These network models are used to assess if typical Dutch LV distribution networks are ready to operate with large penetration of low-carbon energy technologies (e.g. PV systems, electric heat pumps, EVs). According to the obtained results, simulations of all the modelled networks showed the same behaviour for the power flow at the head of the distribution system and the voltage magnitude level. The changes in voltage magnitude however is dependent on the size of the network, resulting in larger changes in the larger networks. While the voltage magnitude level of the smaller networks stays within the ± 10% range, the larger networks encounter voltage magnitude violations. Thus, it can be concluded that the larger networks are not ready (under the current conditions) for large penetrations of low-carbon energy technologies, while the smaller networks appear to be ready.

1 Introduction

The energy system is currently in a transition from fossil fuel based energy towards a sustainable energy supply. The Climate Agreement, drafted by the Dutch government together with NGOs and key companies in the electricity, industry, built environment, traffic and transport, and agricultural sectors, sets a target to decrease the CO_2 emissions to 49% in 2030 and 95% by 2050, compared to the emissions from 1990 [1]. For the electricity sector, the objective is to scale up the electricity production from renewable sources to 70% of the total generation in 2030. The Dutch government has elaborated on the order of preference for the generation of solar energy, where the first preference is given to solar PV on roofs and facades [1]. The energy transition leads to the increased introduction of low-carbon technologies as solar PV, electrical vehicles (EVs) and electric heat pumps (HPs) for domestic heating in the Dutch distribution networks at the low voltage (LV) level. The implementation of these technologies and the increasing penetration levels, might in the (near) future lead to several technical challenges for the distribution system operators (DSOs) in the Netherlands. To solve such arising technical problems, new control strategies will be required to be developed [2].

The majority of the available test feeder models are based on the North American type of distribution systems, which results in an absence of representative feeder models for the European (and Dutch) type of distribution systems [3]. Therefore a standardized set of power flow models for typical Dutch LV distribution networks is needed, allowing researchers and DSOs to simulate future scenarios in realistic network models.

This paper will elaborate on the development of the network models, the different types of load data and the power flow simulations. The methodology used in the development of the network models, the load profiles and the power flow simulations and analysis will be described. These network models are then used to assess if typical Dutch LV distribution networks are ready to operate with large penetration of low-carbon energy technologies. The selected tool for the power flow simulations is OpenDSS, which is one of the most common open-source power flow simulators, developed by the EPRI in the USA. OpenDSS has a Component Object Model (COM) interface, making it possible to drive OpenDSS using Python to use the features of OpenDSS to perform new types of study cases [4]. OpenDSS does not automatically represent the European and Dutch type of distribution systems, consisting of 3 phase wires and a neutral wire, since the neutral wire is not directly represented in standard OpenDSS models. Therefore, the neutral representation is explicitly implemented in the developed network models. Hereafter the outcome of the study and the results of the power flow simulations will be discussed.

2 Methodology

2.1 Network models

There are several ways to develop network models for distribution systems, one of the most typical ways is a method that clusters several actual networks to represent them in a synthetic network model [3]. This approach is used in the study, presented in [5]. As shown in [5], 94 generic feeders are obtained from clustering more than 150,000 networks models of a Dutch DSO based on main network parameters, such as cable lengths, impedances, the number and depth of the branches and the number and type of consumers connected to the network [5]. From the total of these 94 clustered networks, two of the largest networks and two of the most common networks are used to develop the network models. Table 1 shows the characteristics of the used generic feeders.

Table 1 Overview of the used clustered generic feeders [5]

Network Number	No. Branches	No. Residential Connections	Occurance rate [%]
34	6	74	0.3
41	9	87	0.4
93	2	24	4.5
94	1	18	6.4

From these clustered networks, Network 34 is expected to be the most affected among the selected networks by the implementation of additional PV, EV and HP load in the network. The two most common networks are relatively small and therefore strong networks and the cable lengths in Network 41 are significantly shorter than those in Network 34. Therefore, and for simplicity, only Network 34 will be fully elaborated in this paper. Network 34 consists of 82 network nodes which connect 74 residential consumers, this adds up to a total of 156 nodes in the network divided over 6 branches. A possible topology of Network 34 in a Dutch neighbourhood can be seen in Fig. 1, where it should be noted that some cable lengths are adjusted in the figure to match the underlying topology better.

2.2 Neutral representation

In OpenDSS, a circuit element can be connected with the default connection, without the specification of the node-to-conductor connections. In this default connection, a normal phase sequence is assumed where the phase of the terminal will be connected to the corresponding node of the bus. The neutral in this default connection is connected to ground, which is denoted by Node 0 [4]. When a reduced 3-wire system is used for a 3 phase system, it is assumed that the neutral is grounded at every node. This is however not representative for European (and Dutch) LV distribution systems, which are more represented by the so called TT grounding system, which can be seen in Fig. 2. In this TT grounding system, the neutral wire will be grounded at the transformer and the neutrals of the connected households will not directly be connected to the ground [6]. To include this representative system in the network models, when the MV/LV transformer is not explicitly modelled, the neutral will be connected to ground on the source bus, bus 0. All other busses in the network will be connected to this neutral grounding through the 4th conductor in the line, as indicated in Fig. 2.

2.3 Load profiles

2.3.1 Consumer load profiles: The profiles for the consumers in the networks are based on anonymized smart meter data obtained from a Dutch DSO. The data set contained the load data of 72 consumers with a mean annual energy consumption of 3465.698 [kWh]. Using the Python environment new variables were generated for every consumer in the network containing the load information for the given 15 minute time interval for 1 year, leading to 35040 data points. When the intended network model contains more than 72 connected consumers, the load data is assigned in a loop, where the load data is assigned to the next connected consumer starting again from the first load profile. It can therefore happen that multiple

Fig. 1. A possible topology of Network 34.

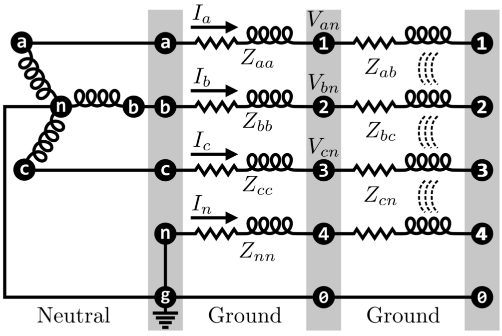


Fig. 2 TT grounding scheme used in the Netherlands in which the neutral wire is grounded at the transformer [6].

consumers will have the same load profile, depending on the number of consumers connected to the corresponding network.

2.3.2 Solar PV profiles: The profiles for the consumers in the networks are based on an annual solar irradiance data set from the Royal Dutch Meteorological Institute (KNMI) which contains the solar irradiance G [W/m^2] in 15 minute intervals. Using Equation 1, the solar irradiance data is converted into the output power of the PV arrays of the consumers P_{PV} [kW] based on the rated power of the PV array Y_{PV} [kWp], the irradiance at standard test conditions G_{STC} = 1000 [W/m^2] and the photovoltaic derating factor f_{PV} [7].

$$P_{PV} = Y_{PV} \times f_{PV} \times (\frac{G}{G_{STC}}) \tag{1}$$

The photovoltaic derating factor f_{PV} is a scaling factor for the power output of the PV array to account for the operating conditions that are not included in the standard test conditions under which the PV module was rated, such as inverter and wiring losses, module mismatch, system downtime and weather conditions as high dust concentration [7][8]. The derating factor in this research is assumed to be 0.77, to account for the lowest possible mean efficiency [8]. Since the temperature data corresponding to the irradiance data is not derivable, the effect of temperature of the PV system is not included in the simulation. The rated power of the PV array Y_{PV} for every consumer was scaled based on their annual power consumption and rounded based on the rated power of the average PV module which is assumed to be 300 Wp.

2.3.3 EV load profiles: The profiles for the EV charging demand for the consumers in the networks are based on an open source data set from E-laad containing random transactions from public charging stations [9]. Not all the data in this data set was usable to create a load profile for private charging cycles. Therefore, the data in this data set was filtered to extract the useful charging profiles. The remaining 171 charging profiles were converted into 24 or 48 hour (when the EV is charged during the evening and night) profiles which were used to create annual profiles for all the consumers. The 24 and 48 hour profiles were appended to the data set for each consumer in a random order until a data set for 1 full year is created, ensuring that all consumers have a different annual profile.

2.3.4 Heat pump profiles: The profiles for the electric heat pumps are based on anonymized smart meter gas usage data obtained from a Dutch DSO. From the total data, 54 usable consumer profiles are used. Since the gas demand is measured on an hourly basis, it is converted into 4 equal 15 minute intervals. The total gas demand does not only cover the domestic heating demand, but also the gas that is used to heat tap water. It is assumed that 70% of the total gas demand is used for the domestic heating [10]. Based on the heating value of natural gas, H = 31.56 [MJ/m^3][11] (where 1[MJ] = 1/3.6 [kWh] = 4/3.6 [kW] for 15 minute intervals), the gas demand Vgas [m^3] is converted into a heat demand expressed in kW. The efficiency rates for boilers η_{boiler} and the coefficient of performance (COP$_{\text{HP}}$) of the heat pumps will convert the heat demand in the actual electricity demand for heating using a heat pump installation P$_{\text{HP}}$ [kW] using Equation 2 [12]. The efficiency of the boilers is assumed to be 90% and the COP of the heat pumps is assumed to be 3.

$$P_{HP} = \frac{Q}{COP_{HP}} = \frac{V_{gas} \times H \times \frac{4}{3.6} \times \eta_{boiler}}{COP_{HP}} \tag{2}$$

2.4 Power flow simulations and analysis

OpenDSS uses a iterative power flow solution method, where the nonlinear element for the loads an are treated as injection sources [3]. Using the OpenDSS engine in Python, the generated network and load profile files are used to perform a power flow calculation for 1 year with 15 minute intervals in 4 cases:

- Case I: Only the consumer load profiles
- Case II: The consumer load profiles + PV production
- Case III: The consumer load profiles + PV production + EV charging
- Case IV: The consumer load profiles + PV production + EV charging + Heat pump demand

The analysis of the power flow simulations focuses on the voltage level of the bus which is furthest away from the source bus, since this bus has the highest potential to have voltage problems. For Network 34 this study will therefore focus on the connected phase voltage of bus 147, since this phase is where the load is connected.

The analysis on the power flow focuses on the apparent power flowing through line 1 and line 14 of Network 34. Line 1 is connecting the network to the source bus, which represents the connection to the transformer. This connection is expected to have the largest power flow and therefore the highest potential to congestion problems. Line 14 is connecting the branch of the bus which is furthest away from the source bus to the network. Since this branch has a high potential to encounter voltage problems, possible congestion problems due to large power flows are reviewed.

3 Results

3.1 Voltage magnitude level

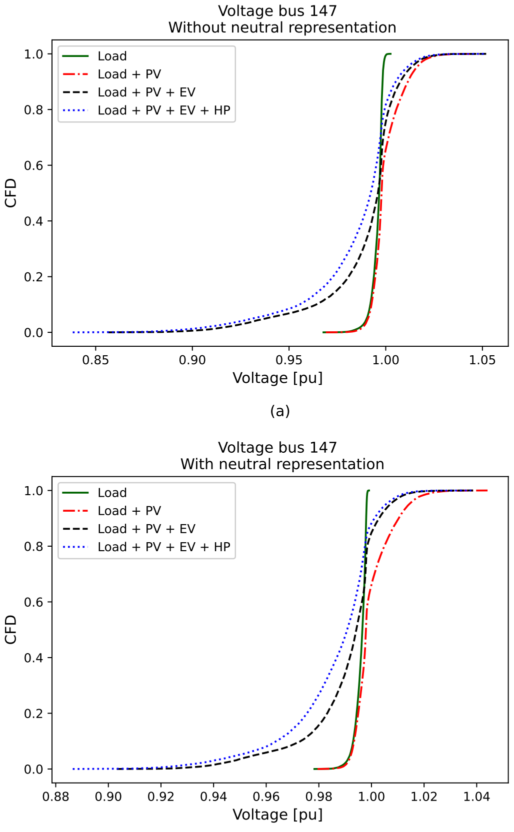
The power flow simulations show that there is a significant difference between the simulations with and without an explicit neutral representation. The voltage magnitude in the network without the explicit neutral representation differs more in contrast to the voltage magnitude with a neutral representation, which resembles the European and Dutch network better. The difference between the different representations is depicted in Fig. 3 a and b, where the cumulative distribution function (CDF) for the phase voltage at bus 147, without and with neutral representation respectively, is plotted for the different implemented loads in the network. It can be seen that the overall effect of the implementation of the different loads is the same for both with and without the explicit neutral representation. However, the voltage magnitude will reach significantly lower voltage levels without the explicit neutral representation compared to the simulation with the explicit neutral representation. For both the situations with and without the explicit neutral representation, no voltage magnitude violations occur in Case I and Case II. This is also the case for the situation with the neutral representation in Case III. For the same Case without the explicit neutral representation the lower voltage magnitude limit of -10% is violated in 0.58% of the time steps which is equal to 51 hours on a whole year. In Case IV, with the neutral representation, the lower voltage limit of -10% is violated in 0.02% of the time steps which is equal to 2 hours on a whole year. For the situation without neutral representation this value is equal to 1.27% which is equal to 112 hours on a whole year.

3.2 *Power flow*

Fig. 4 a shows the CDF diagrams of the total apparent power flow on line 1 for the different implemented loads in the network. As opposed to the voltage level, there is no significant difference between the simulations with and without an explicit neutral representation. The same holds for the power flow on line 14, which is presented in Fig. 4 b. It can however be seen that the amount of power on both line 1 and line 14 increases with the implementation of PV production, EV charging and electrical heat pumps in the network, as it was expected. It can be seen that the power flow on both the lines will increase to around 6 times the maximum value of only the initial load. Assuming a distribution transformer with a nominal capacity of 250 kVA, this would mean that the size of the transformer would have to be increased at least 3 times for normal operation in Case IV.

3.3 *Network analysis*

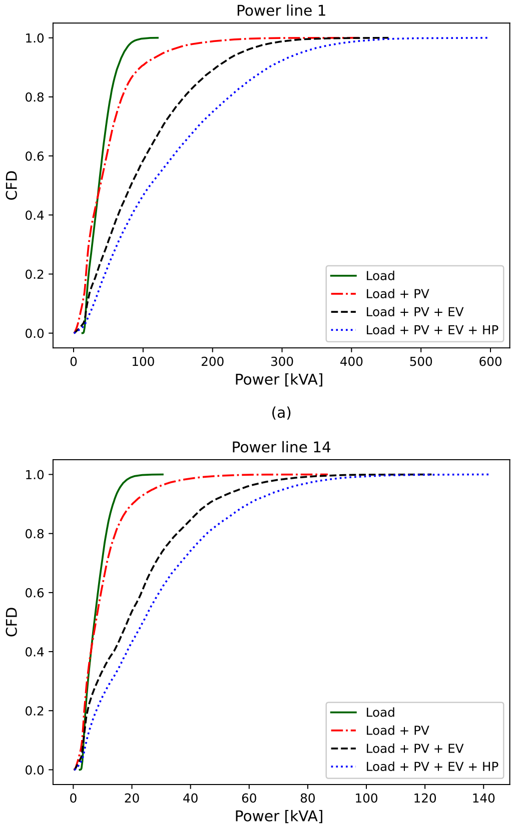
The power flow simulations of all the modelled networks show the same behaviour for both the power flow and the voltage level. The magnitude of the changes in power flow are scaled the same for each of the network models. Regarding the power flow, there is also no significant difference between the simulations with or without the explicit neutral representation. The magnitude of the changes in voltage however are quite dependent on the size of the network and the length of the cables of the network, resulting in larger voltage magnitude changes in the larger networks as opposed to the smaller networks. Table 2



(a)

(b)

Fig. 3 CDF diagrams on the impact of different loads on phase voltage at bus 147 of Network 34 for an annual power flow simulation, (a) without neutral representation (b) with neutral representation.



(a)

(b)

Fig. 4 CDF diagrams on the impact of different loads on the total apparent power flow on line 1 and 14 of Network 34 for an annual power flow simulation, (a) without neutral representation (b) with neutral representation.

shows the minimum and maximum phase voltages at the location of the bus which is the furthest away from the source bus in the feeder, in both the situation with and without the modelled explicit neutral. The minimum values of the voltage magnitude are obtained from the simulations of Case IV. The maximum values of the voltage magnitude are obtained from the simulations of Case II or Case III. Regarding the voltage level, in contrast to the power flow, a significant difference was shown between the simulations with and without explicit neutral representation. It can be seen that the for network 93 and 94, the minimum and maximum voltage magnitude, with and without neutral representation, will not result in a violation of the ± 10% voltage range. This indicates that these networks are ready to operate with high penetration of low-carbon energy technologies. For the bigger networks, network 34 and 41, it can be seen that the minimum voltage magnitude will violate the -10% voltage range in around 0.02% of the time. This indicates that these networks are currently not ready to operate with such high penetration of low-carbon energy technologies.

Table 2 Minimum and maximum voltage at the end of the feeder

Network	Without explicit neutral		With explicit neutral	
Number	Min	Max	Min	Max
34	0.829	1.048	0.888	1.044
41	0.880	1.037	0.917	1.033
93	0.946	1.015	0.967	1.011
94	0.973	1.009	0.982	1.003

4 Conclusion

We developed a standardized set of power flow models for typical Dutch LV distribution networks that can serve as a basis for future scenario simulation studies using realistic network models and context data. The data set is based on four LV grid topologies commonly found in the Dutch electricity grid augmented with realistic patterns of power exchanged with the grid in a realistic future scenario. According to the obtained results, simulations of all the modelled networks showed the same behaviour for the power flow at the head of the distribution system and the voltage level. The magnitude of the changes in voltage however is dependent on the size of the network, resulting in larger voltage changes in the larger networks. Additionally, while the voltage level of the smaller networks stays within the ± 10% range, the bigger networks encounter moments in 0.02% of the time, where voltage magnitude violation exists. Thus, it can be concluded that the bigger networks are not ready (under the current conditions) for such large penetrations of low-carbon energy technologies, while the smaller networks appear to be ready.

Regarding the neutral representation, it can be stated that the models with an explicit neutral representation lead to a better resemblance of the European and Dutch networks. The magnitude of the changes in power flow is scaled the same for each of the network models and show no significant difference between the simulations with or without the explicit neutral representation. The voltage magnitude however, will reach significantly lower levels without the explicit neutral representation compared to the simulation with the explicit neutral representation. It can therefore be concluded that for studies related to voltage problems, it proves to be beneficial to model the network with an explicit neutral representation since it will lead to a better resemblance of the voltage behavior in a European network.

5 References

[1] Nationaal Programma Regionale Energiestrategie, ‘Factsheet Elektriciteit’ (Nationaal Programma RES, 2020), pp. 3-15

[2] Vergara, P.P., Salazar, M., Mai, T.T., et al.: ‘A comprehensive assessment of PV inverters operating with droop control for overvoltage mitigation in LV distribution networks.’, Renewable Energy, 2020, 159, pp. 172-183

[3] Koirala, A., Suarez, L. Mohamed, B., et al.: ‘Non-synthetic European low voltage test system’, International Journal of Electrical Power and Energy Systems, 2020, 118, 105712

[4] Dugan, R.C., ‘The Open Distribution System Simulator (OpenDSS) - Reference Manual’ (Electric Power Research Institute (EPRI), 2018), pp. 1-199

[5] M. Nijhuis, ‘Long-term planning of low voltage networks’. PhD thesis, Eindhoven University of Technology, 2017.

[6] Arboleya, P., Koirala, A., Suarez, L., et al.: ’Impact Evaluation of the New Self-Consumption Spanish Scenario on the Low-Voltage Terminal Distribution Network’, IEEE Transactions on Industry Applications, 2019, 55, (6) pp. 7230–7239

[7] ‘Homer Energy: How HOMER Calculates the PV Array Power Output’, `https://www.homerenergy.com/products/pro/docs/latest/how_homer_calculates_the_pv_array_power_output.html`, accessed 30 March 2020

[8] Gevorkian, P.: ‘Solar Power System Feasibility Study’, in Gevorkian, P. (Ed.): ‘Grid-Connected Photovoltaic Power Generation’ (Cambridge University Press, 2017, 1st edn.), pp. 55–102.

[9] ‘ELaad NL: DOWNLOAD DATA VAN ELAAD - Open datasets’, https://platform.elaad.io/download-data/, accessed 21 April 2020

[10] Ruhnau, O., Hirth, L., Praktiknjo, A., ‘Time series of heat demand and heat pump efficiency for energy system modeling’, Scientific data, 2019, 6, 189, p. 5

[11] Hellinga, D.C., Harmelen, A.K.V.,’Vaststellingsmethodieken voor CO_2 -emissiefactoren van aardgas in Nederland’ (TNO, 2006), p. 6

[12] Conrad, J., Greif, S., ‘Modelling load profiles of heat pumps’, Energies, 2019, 12, (4), 766