Modelling of Equivalent Low-Voltage Nodes

Leopold Herman, Mitja Antončič, Boštjan Blažič

Faculty of Electrical Engineerign, University of Ljubljana
E-pošta: leopold.herman@fe.uni-lj.si

Abstract. *This paper presents modelling procedure and simulation results of equivalent low-voltage nodes models. Models were used in a DeCAS project, to define the reactive power of the LV grid as a function of the load, generation and voltage and especially to simplify the modelling procedure of large networks.*

1 Introduction

This paper demonstrates results of the DeCAS project (Demonstration of Coordinated Ancillary Services covering different VoltageLevels and the Integration in Future Markets) [1, 2]. The main objective of the DeCAS project is to research and analyse the coordination of ancillary services such as, aggregated demand response, individual voltage control and reactive power management concepts over traditional boundaries from high voltage (HV), medium voltage (MV) to low voltage (LV) and develop approaches and concepts for a co-ordinated control approach considering the different objective functions of individual voltage levels. It included the integration related monitoring and controls in process control systems as well as to flexibility markets. LV grids are usually not automated yet and there are hardly any measurements available. Thus, the project evaluates promising concepts for LV grid operation tools, processes and how they can interface with MV/HV SCADA DMS [3, 4].
A Passive LV network model development approach that was developed within the DeCAS project is presented in this paper. Whole LV network is to be represented as black box with its inputs and outputs being explained hereafter. For the sake of transparency, we will refer to the "black box LV model" as a "model" through the whole paper.

2 Passive LV Nodes – Black Box Model

2.1 Model description

The purpose of the developed model is to define the reactive power of the LV grid as a function of the load, generation and voltage. It can be written as:

$$Q_{LV} = f(P_{load}, P_{PV}, U) \qquad (1)$$

Conceptual scheme of the developed model is shown in Figure 1.

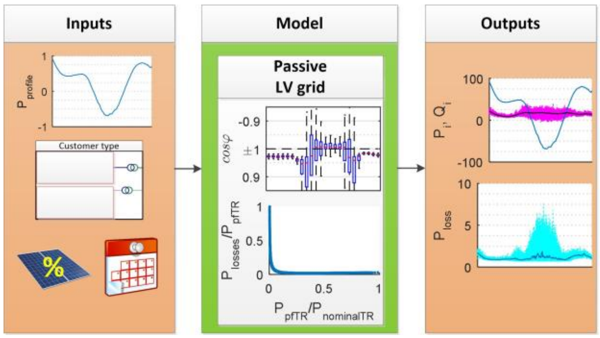

Figure 1: LV network model concept

Input for the model is a normalized active power injection profile of particular LV network, together with the time of the year, the type of the network customers (e.g. residential, commercial, urban, rural…) and the PV penetration as a rate of transformer nominal power.
Outputs from the developed model are active and reactive power injections that can be used for definition of network loading within simulation program (e.g. Neplan). Active power injection definition is based on appropriately scaled normalized load profile. Reactive power injection is calculated using previously defined active power injection and cos(φ_{MODEL}) database. Mentioned database is defined with quantiles in a probabilistic manner. It allows for both deterministic Q calculation using median value of cos(φ) and also for stochastic network simulation using provided probability distribution function for iterative Q definition.
Additionally also network losses are available outputs from the model. They are calculated using provided normalized $P_{loss}(P_{pfTR})$ function.
Input load profiles are distinguished by the season (winter, summer, between) and type of day (weekday, Saturday, Sunday). It consequently leads to 9 different load profiles.
Consequently, also cos(φ_{MODEL}) database has to be developed for the same periods of year as input load profiles are. However, based on our observations, the difference between Saturday and Sunday cos(φ) distribution is negligible, therefore we have merged these two days into a single subgroup.

2.2 Data source

Two sources of data were used to generate the cos(φ_{MODEL}) database. Actually, we have created two different subgroups of the cos(φ_{MODEL}) : cos(φ_{LOAD}) (without PVs) and cos(φ_{PV}) (with PVs) database. Sources of data used for their definition are measurements and simulations respectively.

2.3 Measurements

The cos(φ_{LOAD}) is based on the field measurements of the real MV/LV transformers supplying the real LV grid. Three different subgroups were defined, based on the type of supplied customers, connected to LV grid: residential, commercial and mixed (mixture of both). Additionaly, also a distinction between three different seasons and two type of days was made, which leads to 18 different hourly cos(φ_{LOAD}) databases.

2.4 Simulations

In order to generate realistic cos(φ_{PV}) database and to properly describe the losses for the built model, we did as follows:

I. We have modeled Köstendorf LV network in detail from the provided Neplan data. Load allocation factor for each consumer in this network was also extracted from the Neplan data.

II. For load active power definition we rely on provided customer and transformer measurements from Köstendorf network. Firstly, we have subtracted measured aggregated PV generation and EV consumption of the whole network from the real power injection measurements of the MV/LV Köstendorf transformer. Obtained values were then used for probabilistic transformer active power injection database generation. LV load reactive power is defined using the previously mentioned cos(φ_{LOAD}) database

III. From the PV measurements we have generated PV generation database. Since the reactive power injection of PVs is voltage dependent, we were also provided with the $Q_{PV}(U)$ characteristic. Both databases are further segmented in the same manner as previously mentioned cos(φ_{LOAD}) database.

IV. We implemented Monte Carlo simulations of the modeled network using the databases defined in the previous steps. This step is further explained later in the Simulation details subchapter.

V. Based on the calculated values of interest probabilistic cos(φ_{LOAD}) database was obtained. From the calculated network losses also network losses are defined stochastically, on a per-hour basis, as a rate of consumption of the network loads. It is later used for the model losses calculation.

VI. Now the injection of active and reactive power together with the losses of the network can be defined based on the network power profile and time of the year using cos(φ_{PV}) and losses databases from previous step.

2.5 Simulation details

Following is detailed explanation of the Monte Carlo (MC) simulations from the step IV nad.

Altogether 100 MC iterations of a daily load flow simulation in a 5-minute resolution was performed. Presented are the results for the summer, when the PV generation reaches its peak. It consequently results in a voltage rise in the LV network. Aggregated nominal power of all installed PVs in the network equals 100% of the transformer nominal power.

MV/LV transformer with rated power of 250 kVA is supplied from the grid which provides constant supply voltage to its MV winding at 1.03 pu.

The voltages of the network buses during the simulation are presented in Figure 2. There is a significant voltage rise during the peak PV generation.

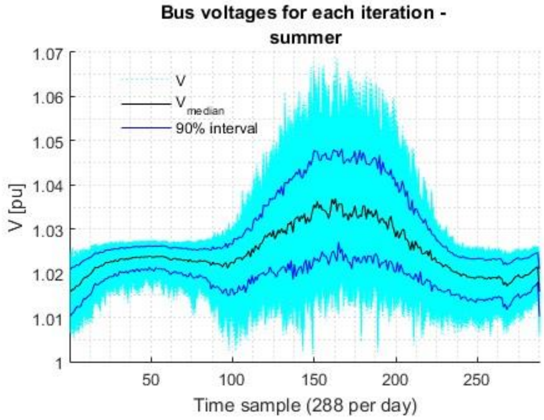

Figure 2: Network voltages

Provided are the results of workday simulation in the summer season. The transformer active power injection, cos(φ_{LOAD}) and PV generation database is chosen in accordance with the chosen simulation period. Three different cos(φ_{LOAD}) databases were defined separately, taking into consideration the type of supplied consumers, for each season and day type. These groups are: households, commercial and mix of both of them.

Aggregated active power of all the LV network loads profile for each iteration $P_{\sum loads\text{-}i}$ is defined from the database. It is also presented in Figure 3, together with its median profile and upper and lower 90% boundaries. Positive power represents power flow into the supplied LV network.

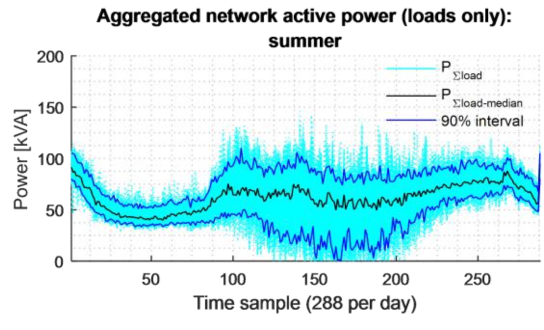

Figure 3: Aggregated active power of LV network loads

Reactive power injection of each PV is voltage dependent. Its dependency is shown in Figure 4.

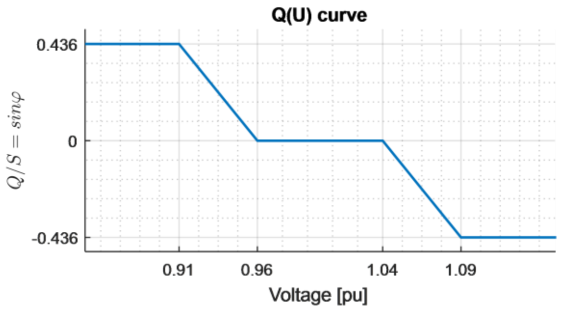

Figure 4: Q(U) characteristic

2.6 Simulation outputs

At the end of the last MC iteration, the power flow through the MV/LV transformer is available for the whole simulation (all MC simulations). Active and reactive power flow of the network is presented in Figure 5, together with its median and upper/lower 90% boundaries. Positive values mean power flowing into the LV network, whilst the negative ones represent the power flowing out from the network, into the MV distribution network.

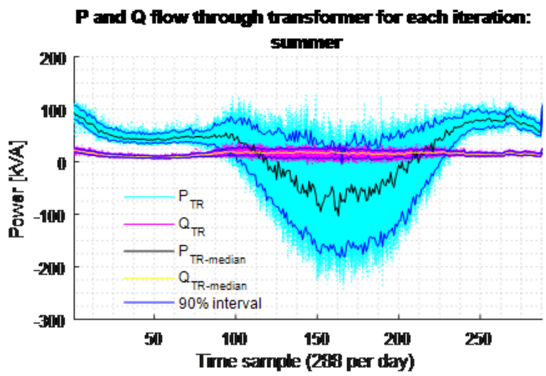

Figure 5: Power flow through MV/LV transformer

Definition of the cos(φ_{PV}) database is of main goal of these simulations, as also mentioned before. This database is derived from the simulated P_{pfTR} and Q_{pfTR} values presented in Figure 5. Due to the high penetration of the PVs in the simulated LV network there is a change in the P_{pfTR} during the day in terms of its direction. On the other hand, the flow of the Q_{pfTR} retains its direction through the whole day. Consequently, when the P_{pfTR} is opposite to the Q_{pfTR} the cos(φ_{PV}) turns out to be a negative value. However the direction, cos(φ_{PV}) is close to the 1 in one case and close to -1 in the other. Therefore we decided to present the cos(φ_{PV}) with a bit unusual approach as can be seen in Figure 6. Presented is a boxplot of values, where values bellow 1 represent the positive cos(φ_{PV}), while the values above 1 represent the negative cos(φ_{PV}).

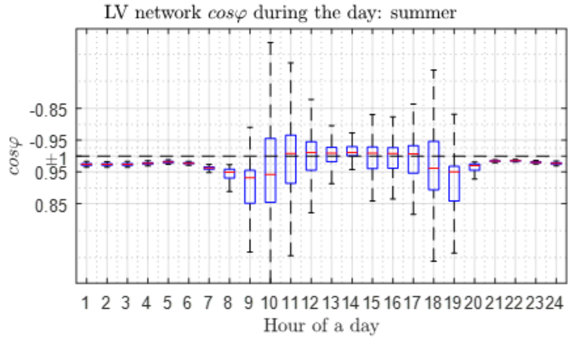

Figure 6: Boxplot of cos(φ_{PV})

Besides the MV/LV transformer power flow data, the network losses measurements are also of interest in our case. These measurements serve as a basis for developed model loses calculation. Network losses, for each iteration are presented in Figure 7

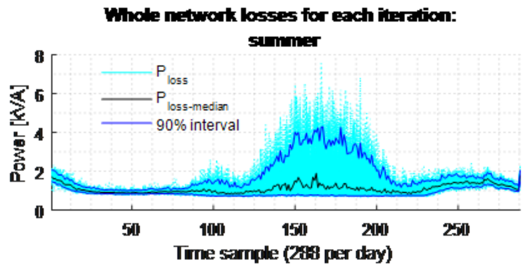

Figure 7: LV network losses (including the transformer losses)

These measurements are then used for investigation of relation between the power flow through the transformer and the losses in the network. The relation in absolute values is shown in Figure 8.

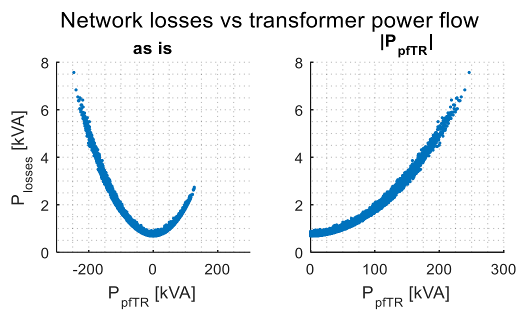

Figure 8: $P_{loss}(P_{pfTR})$ presented with original measurements (left) and with absolute P_{pfTR} values (right)

In order to generalize the relation to different LV networks, the values have to be normalized. Losses are normalized with the aggregated consumption of active power of all network loads only (PV are not taken into account) at each iteration. The variance of values is a bit higher during the PV generation period as can be seen in the Figure 9.

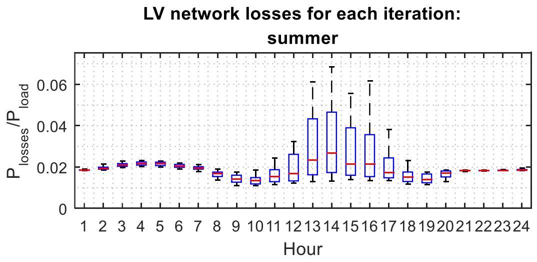

Figure 9: Normalized LV network losses boxplot

For validation of the used method for the losses calculation, histograms of the measured and the calculated network losses are presented in Figure 10. Similarity of the shown histograms is obvious. There is however some discrepancy, which is a consequence of relating the losses only to the consumption of the network (without PVs). The discrepancy can be observed also from the Figure 11, where the daily network losses profile comparisons are shown. Losses calculation is based solely on the network load consumption, disregarding the PVs generation. However, one can see, that mean values fit perfectly.

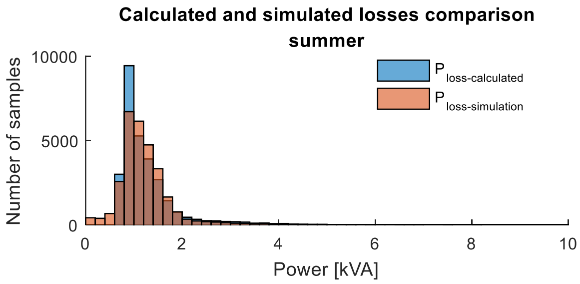

Figure 10: Network losses: histogram of calculated and simulated values

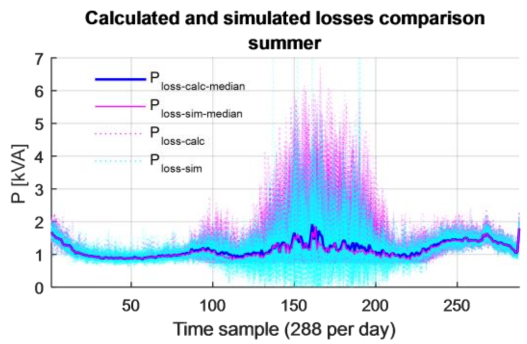

Figure 11 Network losses: daily plot of calculated and simulated values

3 Results

Following is the graphical presentation of the cos(φ$_{MODEL}$) for the summer season. Due to the reasons of straightforwardness only cos(φ$_{MODEL}$) of 3 different consumption types are presented (households-no PV, commercial-no PV, mixed-100% PV) each for both weekday and weekend.

Figure 12 shows a per-hour boxplot of cos(φ$_{MODEL}$) for the LV network supplying a mix of households and commercial users, for the summer season: weekday and weekend. PV penetration rate in terms of MV/LV transformer nominal power equals 100%. This is actually a cos(φ$_{PV}$) database, which is a result of the network simulation described above. One can see, that cos(φ$_{MODEL}$) variance is higher, during the PV generation period of the day. Otherwise, there is no significant difference between the two distributions.

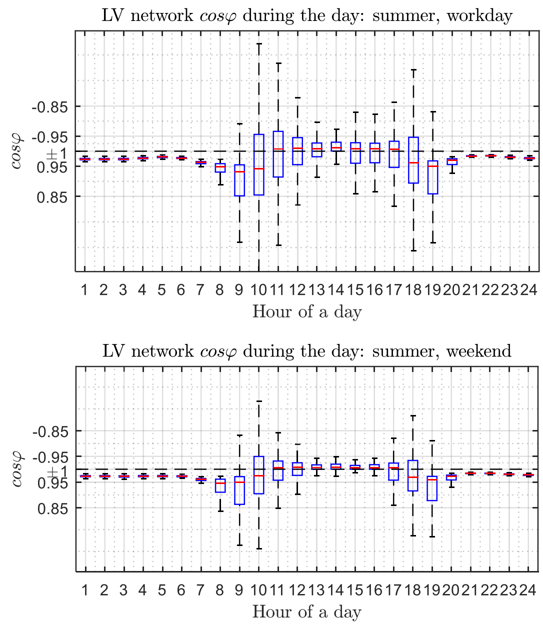

Figure 12: Boxplot of cos(φ$_{MODEL}$) for the summer season, workday (top) and weekend (bottom)

Literature

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[3] EC, network code on requirements for grid connection of generators. 2016.

[4] J. Xie, C. Liang, and Y. Xiao, 'Reactive Power Optimization for Distribution Network Based on Distributed Random Gradient-Free Algorithm', Energies, vol. 11, no. 3, p. 534, Mar. 2018.