A model to simulate medium voltage active networks with an aggregated view of the low voltage ends

Alberto Pagnetti, Gilles Malarange
EDF R&D –France
Alberto.pagnetti, gilles.malarange @edf.fr

Fabrizio Pilo, Simona Ruggeri
University of Cagliari - Italy
pilo , simona.ruggeri @diee.unica.it

ABSTRACT

The integration of Renewable Energy Sources (RES) into distribution networks requires a significant change in the traditional planning and operational approach.
In Medium Voltage (MV) networks, in order to guarantee reliable and secure electricity supply, fostering the connection of new generation, some smart techniques, are based on the integration of operation practices in the set of possible planning alternatives, are being studied.
In Low Voltage (LV) networks, where Distributed Generation (DG), mainly photovoltaic producers, are connected in proximity to existing consumers, similar smart control techniques are being considered, either on the producer side (for instance reactive power control) or on the load side (ADM, Active Demand Management).
One of the main problems associated to the massive connection of DG is represented by to the voltage quality. To this aim, this paper describes and applies a model to simulate MV networks, whilst studying the maximum voltage variations in the underlying LV networks.

INTRODUCTION

The integration of Renewable Energy Sources (RES) into distribution networks requires a significant change in the traditional planning and operational approach Researchers and stakeholders are addressing their efforts on new techniques, the so called “no grid” solutions, based on the control of Distributed Energy Resources (DER) such as DG, controllable loads or energy storage [2] that allow in some cases to postpone, or reduce network reinforcements. These techniques, exploiting the availability of communication, monitoring and control systems, are being studied and implemented both in Medium Voltage (MV) and Low Voltage (LV) networks.
In MV networks, where the capital cost of building underground cables, or upgrading transformers or line sections may be avoided, they include advanced Volt/VAR control schemes, generation curtailment, energy storage system (absorbing some energy in off-load hours and to supply a certain amount of power/energy during peak load periods so reducing transformers and line overloading).

While in LV networks, where DG (mainly photovoltaic producers) are being connected in proximity to existing consumers, similar smart control techniques are being studied, either on the producer side (for instance reactive power control) or on the load side (ADM).
One of the most challenging issues associated to the massive connection of DG is related to the voltage variation, which needs to be studied for different combinations of load and production levels.
In order to consider the most suitable solution, that allows guarantying the interest of the actors involved in the active management, a global vision of the MV network, as well as of the underlying LV hubs is compulsory.
To this aim, a simplified model, which permits to represent LV network at MV level, has been developed.
The paper is organized as follows.
In the first section, the model, with the underlying assumptions is briefly discussed.
In the second section, a compact representation of the LV network data is shown. This representation is based on a number of parameters that describe the network and allow calculating the voltage rises and drops for each of the LV networks without load flow calculations. It is also described, how the model is integrated into an electrical simulation tool that calculates, using load flows, the voltage in all the nodes of an MV network, whilst having an aggregated view of maximum possible voltage rises and drops at the LV level.
In the third section, some techniques proposed to regulate the voltage in distribution networks are briefly described.
Finally, in the last section, a case study is described with the application of the model to a real MV rural feeder with photovoltaic generation on both MV and LV side.

SIMPLIFIED LV NETWORK MODEL

In this section, the simplified model for LV networks that is proposed for MV simulations is described.
The general goals for a model suitable to real size presented are:

- to limit calculation time avoiding load flow simulations of the LV networks;
- to maintain a sufficient detail representing an equivalent model for each LV feeder;
- to have an accurate model for voltage rises and drops.

Usually, in MV planning studies, LV networks are considered as an aggregated load at MV/LV transformer level, without identifying voltage constraints on the LV side. The proposed model allows representing the LV networks analyzed with the maximum voltage variation (rise or drop), considering the contribution of load and generation.

LV feeder reduction

In order to simplify models and calculations, preliminary a reduction process is applied to LV feeders. The reduction process aims at simplifying the network while the most significant information about voltage are kept.
Figure 1 shows the LV feeder reduction from a feeder characterized by two end-nodes, to a feeder with one end-node (red path).
The simplified LV model is defined, individuating the path with maximum voltage drop (considering the maximum load demand on the daily load profile) from the last node of the feeder to the LV transformer bay. This allows determining the equivalent resistance and reactance of this path that is considered for the further calculation of voltage variation.

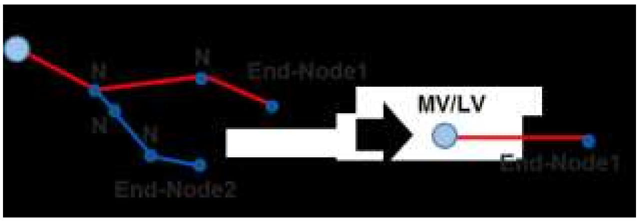

Figure 1 – LV Feeder reduction

When only load is present, the maximum voltage drop will occur in one of the end nodes of the feeder (see Figure 1).

Load

Describing the behavior of a LV distribution network is a difficult issue since, even if the topology is available, the load description may not be accurate.
In this study, for each LV feeder, a term represents the loads as distributed using a uniform distribution.
This is an approximate term, equivalent to considering the total load of the feeder as lumped in the middle of the equivalent line; but it allows evaluating with reasonable accuracy the maximum voltage drop in a feeder.
Eq (1) has been used for the calculation of the maximum voltage drop in a feeder with uniform distributed load.

$$V_{drop-max} = \frac{1}{2} \cdot \frac{P_{load} \cdot R_{eq} + Q_{load} \cdot X_{eq}}{V_N^2} \quad (1)$$

The equivalent load used in the formula (P_{load} , Q_{load}) is evaluated by summing only the loads in the relevant portion of the feeder. Resistance R_{eq} and reactance X_{eq} are those of the equivalent feeder to the final load. V_N is the nominal voltage.

Production

The production is inherently lumped. This is important, since producers can inject more power than the one absorbed by loads and are less distributed throughout the feeders. Their connection to a feeder represents an additional source of power, which can revert the power flows from the customers to the secondary or primary substation. This determines a change in the feeder's voltage profile, namely a reduction of the voltage drop or even voltage rises.
In the example shown in Figure 2, three producers are connected to the same feeder. Each producer contributes to voltage rise with its injected active/reactive power P_i / Q_i, and upstream resistance / reactance R_i / X_i, that is the impedance of the line connecting the producer to the secondary sub-station transformer.
Eq. (2) allows calculating the maximum voltage rise caused by the three generators.

$$V_{gen-rise-max} = \frac{P_1 \cdot R_1 + Q_1 \cdot X_1}{V^2} + \frac{P_2 \cdot R_2 + Q_2 \cdot X_2}{V^2} + \frac{P_3 \cdot R_3 + Q_3 \cdot X_3}{V^2} \quad (2)$$

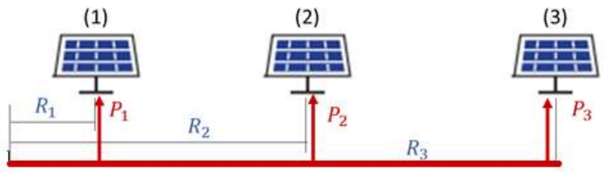

Figure 2 – Producer connected at different nodes of the same feeder

The precision of (1) and (2) is smaller than ±2 V (in 400/230 V LV networks), when compared to precise load flow calculations executed with commercial tools, considering a sample of around 120 real LV feeders.

Unbalanced calculations

The formulas discussed before consider a three-phase balanced equivalent model. To take into account the inherent unbalance of LV networks, a coefficient is considered, that is evaluated from the distribution of loads on their respective phases. To do this, we evaluate the voltage formulas for each phase separately, considering the share of load on each phase. Finally, we consider the worst case (highest voltage drop/rise).

The maximum error calculated on the sample of network used before is 4V.

METHOD PROPOSED

To implement the method into a MV simulation software the different terms needed for the calculations are summed up within a matrix (one per LV network) that gives the term for evaluating voltage drops / rises with the formulas described before.
Figure 3 shows an example of an LV matrix referred to a LV network with a total load installed of 55 kW and characterized by two feeders with one PV generator (18kW) each.
The LV network model has been integrated in a probabilistic electrical simulation tool that simulates all the nodes of the MV network level [2].
After building the LV matrices (one for each underlying LV network) the following steps are executed:

- solve the MV network (the LV is represented with aggregated loads/generators in each MV/LV node);
- calculate a realistic voltage value at the LV side of each MV/LV transformer by using the current off-load tap changer position, transformer impedance, MV voltage and LV load/generation;
- calculate the expected maximum voltage drop and rise in each LV network by using the LV matrix.

Figure 3 – LV matrix with the parameters used in the model

	36	0	55.3	28.4	2 (feeders)	0	0	0
	18	0	39.8	20.4	1 (generator)	0.47	0.52	0.08
	18	0	23.6	12.1	0.277	0.47	0.12	0.03
	18	0	15.5	7.9	1 (generator)	0.55	0.22	0.09
	18	0	8.2	4.2	0.292	0.55	0.08	0.03

The LV model has been integrated into DigSilent PowerFactory® and the MV planning tool in [2][7] with suitable scripts that allow automatically build the LV matrix from the DSO database. The power of the simplified method is self-evident. Several MV planning alternatives can be developed, evaluated and compared without losing information about voltage regulation in all LV feeders. With acceptable accuracy this is obtained without running cumbersome and not always easy to converge load flows of an entire MV/LV network.

VOLTAGE REGULATION WITH DG

Different techniques have been proposed to regulate the voltage rise/drop in distribution networks. In opposition to classical solutions, e.g. limits/bands for demand and generation connection/operation, generation tripping and capacitor banks), smart techniques are proposed such as coordinated Volt-VAr control through DERs' inverter, static VAr compensators and coordinated dispatch of DER [1].

Reactive power control from generator inverter

Although the reactive part of the grid compared to resistive part is less important in LV than in MV, simulation and real experimentation have demonstrated that one of the most promising techniques is allowing the generator to participate to the voltage regulation through the inverter, particularly when overhead lines are present.

Such voltage regulation technology can include different control laws like *fixed* $\tan(\phi)$, $\cos(\phi)=f(P)$, Q=*constant*, $Q=f(U)$, etc., that can be used in local or centralized mode.

Nowadays, in France the power generation on LV networks is interfaced by inverter, but is not allowed to inject or absorb reactive power.

Enedis investigates the reactive power management of DG [3-4].

In other countries (e.g., Germany, Italy and England) the ever-growing amount of RES has led to change the regulation of DG: PV inverters must be able to absorb or inject the reactive power according to DSO's requirements. For instance, in Italy, as stated in the Italian standard CEI 0-21 [5], DSO could impose regulation of voltage on active users. The standard proposes two control solutions in which the reactive power can be modulated following local measurements of either voltage or real power injected. Also in Germany, in the new evolution of the German technical guideline for LV networks, rules for generators connection are provided: fixed power factor method and the power factor as a function of the real power generation method [6].

CASE STUDY

The simulation is carried out through MV LoadFlows using DigSilent PowerFactory®.

The case study is an MV rural feeder, having a total peak load demand of around 2 MW and many LV photovoltaic generators totaling an installed power of around 3 MW. Although the network topology and the distribution of loads and low voltage generators has been obtained from a real MV feeder, the PV production has been increased by 50% (from 2 to 3 MW) to simulate a future situation. Furthermore, a 5 MW MV producer has been connected to the feeder.

The tool could also employ profiles (as described in [7]), but in this case the analysis is performed considering two conditions, namely:

- max load and no generation (this allows obtaining the minimum voltages)
- min load and max generation (this allows obtaining the highest voltages).

The limits for the voltage (on the LV side) are Un±10% (where Un is the nominal voltage). A security margin of 2,5%, that is 1% for the uncertainty due to the HV/MV transformer's tap changer, and 1,5% due to the low voltage connections has also been assumed.

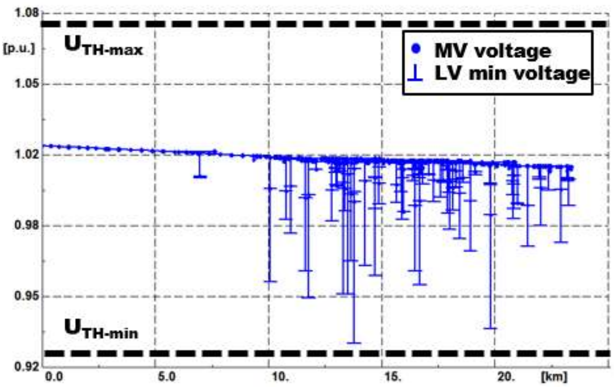

Figure 4 – MV Feeder voltage profile (with min voltage on the LV side) obtained with max.load and no generation.

Figure 4 depicts the case with maximum load demand and no generation. All LV networks (vertical blue lines in Figure 4) are within the allowable voltage band ($U_{th,min}$ and $U_{th,max}$ in dashed bold black line).
The MV/LV transformers have three off-load taps that allow modifying the transformer ratio: these values have been optimized and set statically as high as possible to respect the lower (Figure 4).
When the minimum load/maximum generation situation is considered, it can be seen that in some LV networks the limits are not respected (pink lines in Figure 5).

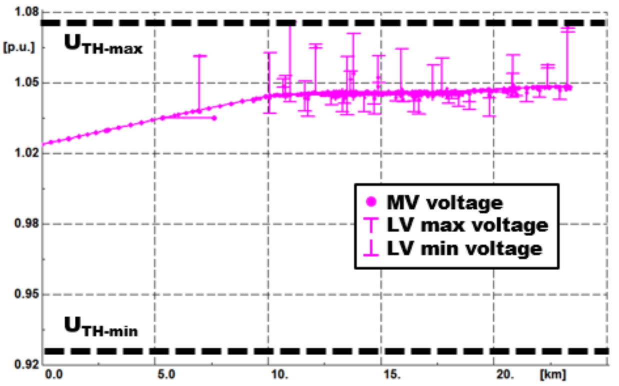

Figure 5 – MV Feeder voltage profile (with max/min voltage on the LV side) obtained with min.load and max.generation

Since off-load tap changers of MV/LV transformers have already been optimized, one possibility to fix the high voltage issue would be to implement Volt/VAR regulation. In the paper it is simulated imposing 0.95 inductive power factor, thus asking all LV generators to absorb reactive power, proportionally to their injected active power.

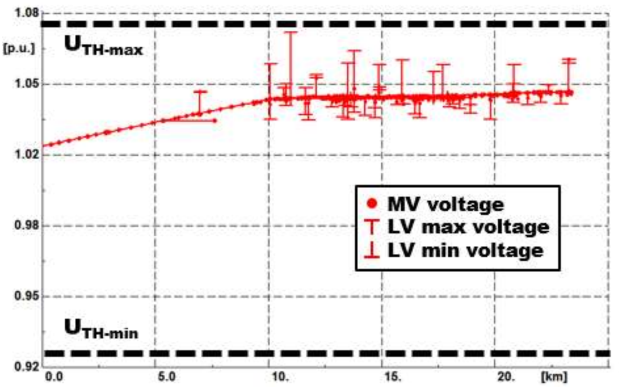

Figure 6 – MV Feeder voltage profile (with max/min voltage on the LV side) obtained with min.load and max.generation using reactive power in the LV generators to regulate voltage.

In the case studied here, it can be seen that the Volt/VAR regulation helps comply with voltage rise constraints (see Figure 6). Indeed, with Volt/VAR regulation all LV networks are expected to have the voltage (red lines in Figure 6) within the allowable regulation band ($U_{th,min}$ and $U_{th,max}$ in dashed bold black line).

CONCLUSION

In this paper, a model has been described, that allows simulating medium voltage active networks, whilst having an aggregated overview of the low voltage ends. This model does not employ load flow calculations of the LV networks, but only uses the results of a load flow on a medium voltage network. It allows to take into account the topology of these networks and the distribution of loads and generators in a simplified way. Despite the approximations, this model allows evaluating maximum voltage drops and rises with an accuracy suitable to planning studies in large real size distribution networks.

The application for the study of off-load taps of MV/LV transformers and for testing the efficacy of Volt/VAR regulation in the low voltage generators is proposed.

Acknowledgments

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