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SIZING OF A POWER ELECTRONICS-BASED VOLTAGE REGULATING DEVICE TO SUPPORT THE INTEGRATION OF PHOTOVOLTAICS AND ELECTRIC VEHICLES IN LV GRIDS

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ABSTRACT

This paper presents a method for sizing a voltage regulation device based on power electronics structures applied to the low voltage distribution grid, in a context of increasing penetration of distributed energy production and electric vehicle charging stations in residential installations. The case studies presented and used in the analyses take into account the scenarios published in Enedis (French main DSO) and RTE (French TSO) reports regarding predictions for the evolution of the French electrical grid up until 2050. The operation mechanism of the power electronics device is diverse and its connection at the secondary busbar of a LV substation can be made both in series or in parallel. In this paper we address the effect of the parallel-connected device, given the similarity of its configuration to the wiring of other power electronics-based elements attached to the distribution grid.

INTRODUCTION

The massive arrival of electric vehicle charging stations (EVs) and the increase in photovoltaic (PV) production connected to the low voltage (LV) distribution grids are likely to cause the appearance of local voltage issues requiring potentially costly grid reinforcements [1].

Among the alternatives to grid reinforcement, the Distribution System Operator (DSO) seeks efficient and less expensive voltage regulation solutions through devices such as On-Load Tap Changers (OLTC) [2] and power electronics-based structures. These are most commonly connected to the grid at the extreme points of the lines [3], far from the transformer and close to the loads under the most severe voltage constraints, while the application of OLTCs requires the replacement of the more traditional MV/LV transformers, with fixed tap-changer.

In summary, LV grid voltage regulation can be performed at different points of the grid and different power electronic structures can be used, from capacitor banks to inverters connected to batteries. And although there are different structures capable of regulating the voltage, the connection of these devices is usually made in parallel with the loads and the MV/LV transformer, because it is easier

to connect and disconnect for maintenance purposes and because it is safer from the point of view of grid protection triggering.

Within this context, the addition of power electronics-based converter devices (PED) at the secondary side of the transformer has been identified as an interesting emerging smart solution for downstream voltage regulation, as illustrated by Figure 1. This solution could be a cheaper alternative to an OLTC or to conventional grid reinforcement solutions.

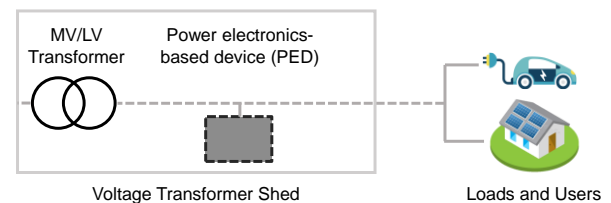


Figure 1: Suggested positioning of the PED in the LV grid.

The PED presented in this paper regulates the grid voltage by manipulating its reactive power while connected in parallel downstream of the MV/LV transformer. This compensator injects and absorbs reactive power to increase or decrease the voltage, respectively.

The goal of this paper is therefore to assess its sizing considering uncertainties related to the future development of EVs and PVs of the French LV distribution grid. To do this, we propose a Monte Carlo based simulation where different scenarios are modelled, representing the evolution of residential PVs and home charging stations for EVs in future LV grids.

We believe that the proposed approach of placing the voltage regulating element right next to the MV/LV transformer is a pertinent way to expand its effectiveness in supplying energy to consumers without having to intervene either in the consumer's end or in the internal connections and structure of the transformer.

METHODOLOGY

For voltage regulation on the LV side, the European standard EN50160 is considered, which stipulates that the

voltage at all points of the LV grid must be within $\pm 10\%$ of the nominal voltage value (400V phase-to-phase, 230V phase-to-neutral). Given these limits and the analysis of the LV grid behaviour downstream the MV/LV transformer, we developed a method to size the PED considering the steps presented in Figure 2 and detailed as follows:

- Elaboration of case studies using scenarios described in Enedis [4] and RTE [5] reports about the behaviour of LV grids in the foreseeable future. These case studies are detailed in the next subsection.
- Application of a Monte Carlo-based simulation that considers various grid topologies with load and generation profiles inspired by the aforementioned scenarios.
- Analysis of the results of the voltage variations that must be compensated and the reactive power that can be injected in parallel beside the MV/LV transformer by a PED responsible for the compensation.

Case Studies

In order to build the simulation models, the following case studies described in Table 1 were created based on the referenced documents. Three case studies are selected, named *stagnation*, *intermediary* and *rupture*, representing different levels of PV and EV penetration in the grid.

These case studies consider:

- Various real LV grid topologies provided by the french project SMAP [6], responsible for the development of the first French rural smart grid. In these rural grids the lines are longer and customers are more sparsely

connected to the grid. We believe that this choice depicts situations where voltage problems may arise more frequently in the LV distribution system.

- LV grid voltage behaviour over a 24-hour period.
- Diverse residential consumption profiles [7] (common peak consumption in the morning and evening).
- Most consumer units have a single phase profile, with a power factor $\cos(\varphi) = 0.928$, corresponding to a limit of $\tan(\varphi) \leq 0.4$ imposed by the french DSO.
- Various electric vehicle charging profiles (recharging terminal power limits between 3kW and 7kW, with charging profiles for both daytime and evening).
- Various rooftop PV generation profiles (single phase between 6kW and 12kW).
- The percentages attributed to the stagnation and rupture cases were extracted directly from the Enedis report [4], while the percentages for the intermediate scenario were obtained using the midpoint between the extreme scenarios.

Table 1: Features of the proposed case studies.

Case	Households with rooftop PVs [%]	Households with EV charging stations [%]
Stagnation	10.3%	33%
Intermediary	55.2%	57%
Rupture	100%	81%

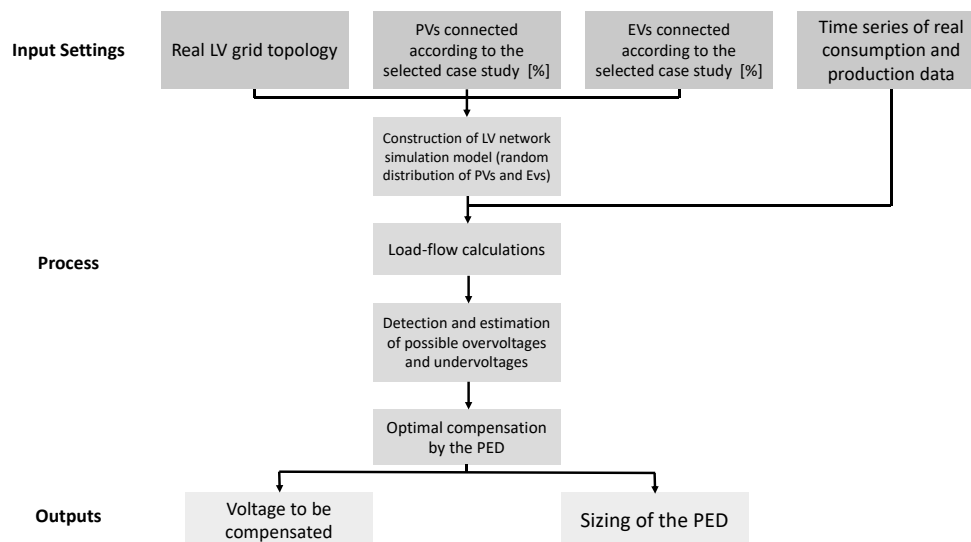


Figure 2: Flow chart of the PED sizing algorithm.

LV Grid Analysis Algorithm

First, the grid topology is selected and then the loads, PVs and EVs are randomly distributed throughout the grid according to the percentages determined for each case study. The consumption and production profiles are mapped throughout one day (24 hours) and a load-flow

analysis is performed in order to estimate the voltage values at the secondary side of the MV/LV transformer for that period at a 30 minutes time step. This method yields an estimation of the voltage value downstream of the transformer.

The load-flow algorithm applied in this context, of an unbalanced three-phase power distribution system, was

based on the Backward-Forward approach [8] to evaluate the voltage at each node, the current in each line and the losses. The result is an overview of the state of the electrical parameters of the grid at each time step.

Once the load-flow algorithm traverses the 24-hour period, a new random distribution of consumption and production profiles is performed throughout the nodes of the grid. This process is repeated for the number of iterations fixed at 100 for the Monte Carlo simulation. This number is chosen as a trade-off between computation time and robustness of the results. By increasing the number of iterations, we ensure that we cover a large representative panel of possible occurrences. Thus, it is possible to determine what is the absolute value of the voltage that needs to be compensated in order to comply with the EN50160 standard, and also the frequency of required actions of the PED.

Optimization of the PED Sizing

From a load-flow algorithm point of view, the modelling of the PED means adding an inductive or capacitive load depending on the desired action.

When a voltage constraint is identified at a given moment, an optimization algorithm will calculate the minimum reactive power that the voltage regulation system must

inject or absorb to stay within the tolerated voltage range. The optimization algorithm is formulated based on the minimization of the variable corresponding to the injected or consumed reactive power in each phase, according to the following equation:

$$f(x_1, x_2, x_3) = \min(x_1^2 + x_2^2 + x_3^2)$$

This equation is subject to the condition that the voltage in each phase across all nodes of the grid is comprised between 0.9 p.u. and 1.1 p.u.. The optimization problem is then solved using a MATLAB® optimization toolbox.

RESULTS

As a result of the complete algorithm presented on the diagram in Figure 2, it is thus possible to observe the voltage constraints, the frequency with which they occur in a day and the corresponding reactive power required for the PED action to be effective, illustrated by the boxplots of Figures 3, 4 and 5. The grid employed in this analysis has 58 nodes and an MV/LV transformer with a rated apparent power of 250kVA.

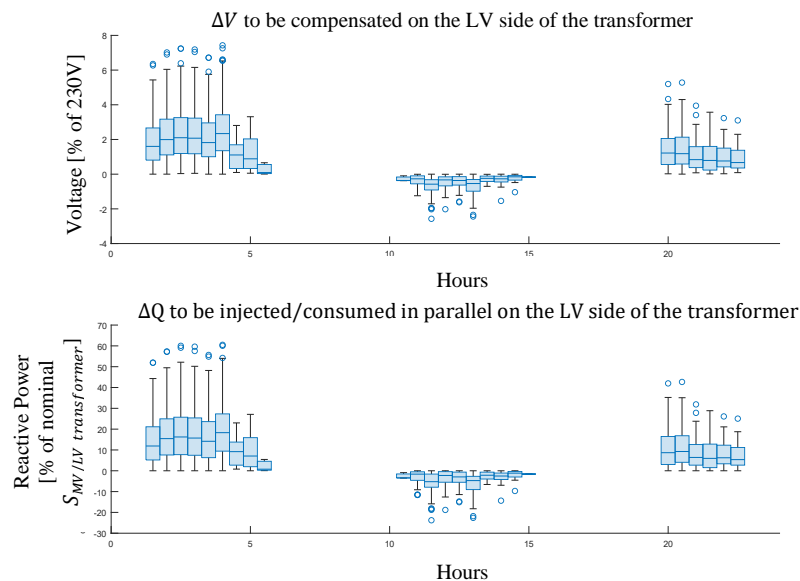


Figure 3: Occurrence of voltage constraints in a 24-hour period – rupture case study.

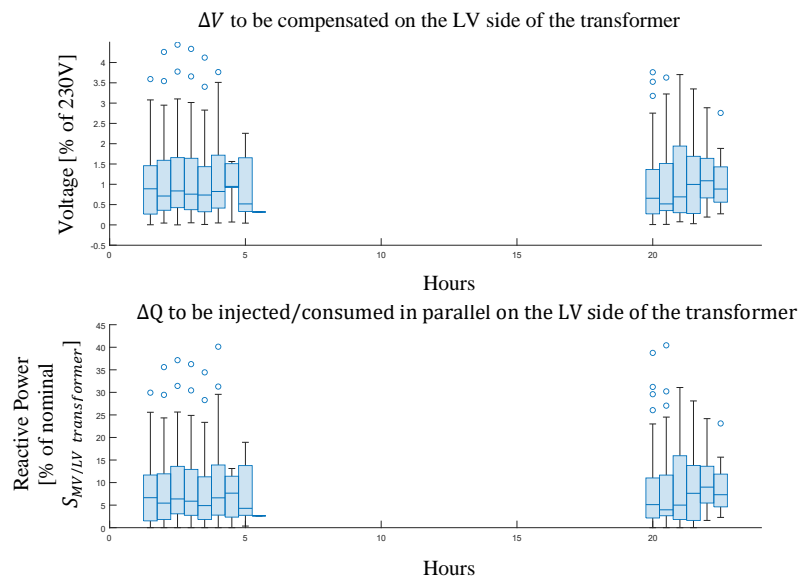


Figure 4: Occurrence of voltage constraints in a 24-hour period – intermediary case study.

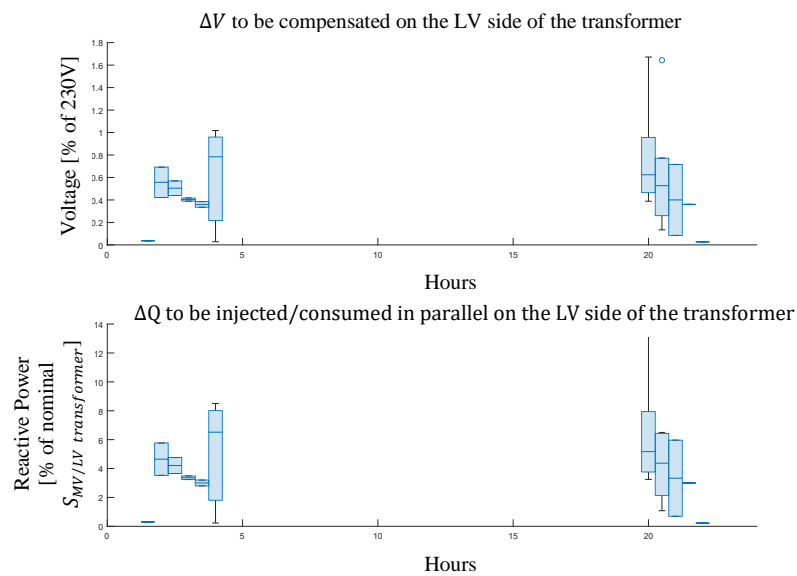


Figure 5: Occurrence of voltage constraints in a 24-hour period – stagnation case study.

The boxplot graphs shown in Figure 3 represent the voltage behavior for a heavily loaded grid (*rupture* case) and show how much the voltage downstream the transformer exceeds the limits ($\pm 10\%$) of the nominal grid voltage.

The voltage values to be compensated are expressed as a percentage of the nominal voltage of the grid (230V phase-to-neutral), while the reactive power values of the PED are expressed as a percentage of the transformer's rated power. The evaluation of the parameters in percentage is interesting in this analysis to estimate the size of the PED in relation to the size of the transformer, since overloading the transformer is unwanted.

The voltage that crosses the limits and needs to be compensated is called ΔV and the blue boxes (quartiles) express how often, for 100 Monte Carlo iterations, a given ΔV needs to be compensated at a certain time of the day. In the case of this simulation result, it is possible to see voltage constraints occurring at the beginning of the day (around 6 a.m.), in the middle of the day (between 10 a.m. and 3 p.m.) and at the end of the day (around 8 p.m.). The early and late day constraints require the injection of a positive ΔV voltage to increase the voltage downstream the transformer. This means that there is an increase in the consumer load that causes this voltage decrease, while the mid-day constraint requires a voltage decrease in the LV

grid. This is due to the power production by the PVs, which has its peak in the middle of the day, where the incidence of sunlight is usually greater.

As for the reactive power equivalent to the ΔV to be compensated, the positive reactive power percentage indicates reactive power injection to increase the voltage, while the negative reactive power injection percentage indicates reactive power consumption to help lower the voltage.

Considering these plots, a PED capable of injecting and consuming around 75kVar (30% of the transformer's rated power) would be able to cover approximately 100% of the occurrences of voltage constraints in this LV grid in a year 2050 scenario for the *rupture* case.

Figures 4 and 5 show the behaviour of the same parameters as in Figure 3, but for the *intermediary* and *stagnation* cases for the same LV grid topology. In these cases, the grid is less loaded with PVs than in the *rupture* case and it is even possible to see that they do not produce overvoltages for this specific grid. However, undervoltages still occur at times of peak consumption as in the *rupture* case.

Besides the purpose of sizing the PED, these analyses also compose a tool to support the LV grid operator in the face of future difficulties in managing the voltage of the LV distribution grid up to the year 2050. This is due to the fact that, by integrating any real grid topology to the algorithm, it is possible to assess its robustness to the arrival of residential PVs and EVs by quantifying the voltage disturbances on the LV grid and the effectiveness of the DSO intervention if done locally only on the secondary side of the MV/LV transformer.

CONCLUSION AND NEXT STEPS

In this article, we have proposed a new methodology for the sizing of a PED used to regulate the voltage at the secondary side of MV/LV transformers under heavy penetration of renewable energy sources and EV charging stations. Different case studies were chosen to represent these conditions. Through a Monte Carlo approach, we are able to identify the reactive power injection and absorption capabilities of a parallel-connected PED that complies with current European standards.

The next step in the development of the PED sizing algorithm is to analyse its behaviour when the device is connected in series with the grid.

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