CONDUCTED DISTURBANCES IN THE FREQUENCY RANGE 2-150 KHZ : INFLUENCE OF THE LV DISTRIBUTION GRIDS

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ABSTRACT

For a few years, electromagnetic interference due to conducted disturbances in the frequency range 2-150 kHz has become a real issue in the context of public Low Voltage (LV) distribution grids. This paper is a contribution towards a better understanding of this kind of interference. It deals with the modelling and simulation of LV distribution grids as key elements in the study of interference problems in this frequency range. The first part of the paper will be dedicated to a brief presentation and discussion of some models for various elements such as photovoltaic (PV) inverters. The second part of the paper concerns the presentation of several simulation results. These simulations study the propagation and attenuation of High Frequency (HF) components but also the interaction between several inverters or an inverter and a rectifier-type load.

INTRODUCTION

During last decades, the power grid has changed significantly. The main cause of this change is the increasing number of devices using power electronics. These devices include switches with frequency commutation located between 2 kHz and 150 kHz. Besides, the Power Line Carrier (PLC) is also working in this frequency range. Thus, there is a coexistence of intentional and the so-called “unintentional” emissions in this frequency band.

The problem is that the standardization which is supposed to regulate the emission of the disturbances and the immunity of sensitive devices is, currently, almost non-existent for these frequencies.

However, from the standardization perspective, closing the gap in this frequency range has become a priority. This task progresses slowly for several reasons. The matter is new and very complicated but there are also considerable interests at stake and the initial positions of the parties are very far from each other.

The European committee for electrotechnical standardization (CENELEC) has already published two reports concerning this topic [1][2]. Within the International Electrotechnical Commission (IEC), the maintenance of IEC 61000-2-2 and IEC 61000-2-12 standards was decided in order to define compatibility levels between 2 and 150 kHz. Once compatibility levels have been defined, emissions and immunity levels would easily be deduced. A solution under study to determine compatibility levels could be to divide the frequency range in two parts. In the first part, which concerns lower frequencies (such as lower than 30 kHz), higher compatibility levels could be allowed because PLC usually works in frequencies higher than 30 kHz. In contrast, lower compatibility levels could be allowed in higher frequencies in order to have proper functioning of PLC [3].

One key issue of this maintenance work is, the coordination of PLC systems used for smart grids and smart metering between 3 kHz and 148.5 kHz and the unintentional disturbances produced in the same frequency range by modern equipment connected to public power supply systems such as PV installations, variable speed drives (e.g. those used in heat pumps) or electric vehicle battery chargers.

This problematic being wide, it was decided for this paper to focus on the disturbances produced by a PV inverter. Modelling and simulation are used in order to assess the order of magnitude of disturbances caused by this device and how they interact with each other and with some loads through the grid. Working with numerical simulation has been unavoidable because simple analytical relationships are impossible to use. Indeed, when HF are concerned, phases are coupled because capacitors between phases cannot be neglected.

MODELS

To be able to study that kind of disturbances by simulations, some models have to be developed. The developed models are based on the Matlab/Simulink ® software and its SimPowerSystems library. As PV inverters are usually located in the LV distribution grid, a model for it is also required.

Inverter model

The chosen model is shown in Figure 1. To control the switches, the Pulse Width Modulation (PWM) has been adopted because it is the most common method. Thanks to this method, lower harmonics are obtained in low frequencies but, on the other hand, harmonics in high frequency are higher.

On the DC side, there is just a DC voltage source because it has been proven that the circuit on this side has a rather limited influence on the HF disturbances on the AC side with the chosen topology [4]. The complete circuit is constituted of a boost of which duty cycle varies. Using the complete circuit for the simulations would complicate them and not a lot of precision would be gained.

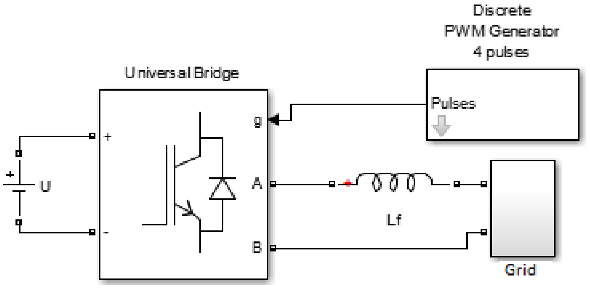

Figure 1 *Inverter model*

The L filter on the AC side has been chosen because disturbances in the frequency range 2-150 kHz are more reduced with this filter than with another one. Usually, filters are designed in order to satisfy standardization concerning frequencies beyond 150 kHz and below 2 kHz because standardization in the frequency range 2-150 kHz does not exist yet.
The values of the different parameters constituting the model in Figure 1 have been studied in order to be as most realistic as possible and they remain unchanged for all the presented simulations. Those parameters are summarized in Table 1.

U	360V
Lf	12.8mH

Table 1 *Parameters of the inverter model*

LV distribution grid model

Having a model for the LV distribution grid is of major importance for the present work because the behaviour of PV inverter in realistic situations has to be observed. Finding such a model is not trivial because most of the time models found in literature are available in low frequencies. Moreover, by using SimPowerSystems, the parameters values have to be fixed and cannot vary.
This model can be divided into two main components. First of all, there is the LV feeder. To simplify, the three-phase Pi section line has been adopted (Figure 2).

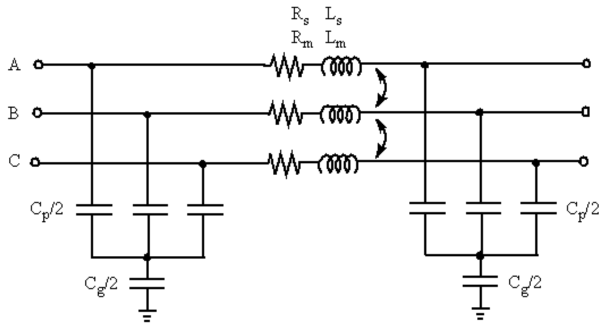

Figure 2 *Three-phase Pi section line [8]*

Concerning the values of the parameters, they have been chosen after comparison of several references (i.e. Laborelec [5], Schneider [6] and Nexans [7]). There are two main differences between a Low Frequency (LF) model and a HF model. Firstly, capacitors are not neglected in HF. The presence of capacitors makes analytical calculations tricky. Then, resistances are higher in HF because of the skin effect. Because of the skin effect, various resistances depending on the frequency should be used. However, in lumped elements models (such as those used in SimPowerSystems), a unique (constant) value has to be fixed.
The parameters appearing in this model are deduced from the positive and zero sequences parameters. These are summarized in Table 2.

R_0	13.77 Ω/km
R_1	3.47 Ω/km
L_0	4.99×10^{-4}H/km
L_1	1.89×10^{-4}H/km
C_0	2.46×10^{-7}F/km
C_1	3.35×10^{-7}F/km

Table 2 *Parameters of the Three-phase Pi section line*

Besides the LV feeder, the other main component of the grid model is the MV-LV transformer. Indeed, in order to have a realistic model, this transformer preceded by a MV grid Thevenin equivalent model has been included. The values of the transformer parameters are those determined experimentally by Laborelec [9]. The upwards MV source is represented by a three phase source from the SimPowerSystems library. Its short circuit power is 150 MVA and the X/R ratio is 4/7, which are typical values.

SIMULATIONS

The purpose of this section is to study by simulation how HF components propagate in the LV distribution grid and also how they interact with other elements present on the grid. All the simulations are based on the models described in the previous section.

Frequency components propagation and attenuation

The attenuation of disturbances in function of the distance has been studied first.

HF voltage harmonics transfer along a LV feeder

As a first general case study, the disturbances are modelled by a voltage source on each phase whose frequency is fixed. Using voltage sources for the injection of HF components is actually not far away from the real physical behaviour of PWM inverters. The simulation simply consists in placing voltage sources with a frequency ranging from 2 kHz to 150 kHz at the end of the considered LV feeder and in observing the value of this disturbance at the LV output of the MV/LV transformer for several feeder lengths (Figure 3). In fact, it means calculating HF voltage harmonics transfer coefficients along a LV feeder. As already mentioned, the LV feeder in Figure 3 is the three-phase Pi section line shown in Figure 2 whose parameters are given in Table 2. It has been noticed that the results were not the same on the three phases. This is due to the parameters of the transformers whose values are not the same on the three phases. This result is normal since the three phases of the transformer are not perfectly balanced from a geometric point of view, certainly for HF concerns.

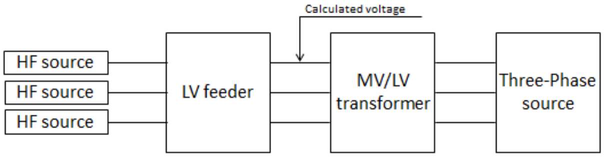

Figure 3 *Scheme representing the simulation used to study attenuation of HF disturbances*

The results for the phase A are shown in Figure 4. The curves for phases B and C are similar to the curve for phase A even if the values are not the same. The diagram represents the ratio of the disturbance after different lengths of LV feeder and the disturbance caused by the sources expressed as a percentage.

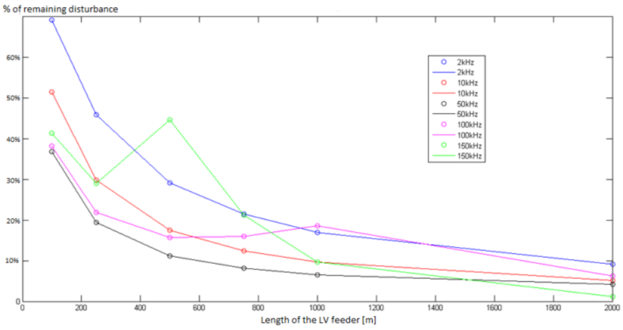

Figure 4 *High frequency attenuation depending on the length of the LV feeder*

One can observe on Figure 4 that 2kHz, 10kHz and 50kHz disturbances decrease monotonically with the length of the LV feeder.

The most favourable frequency seems to be 50 kHz because in Figure 4, the curve in black is below others almost everywhere. On the contrary, the least favourable appears to be 2 kHz.

One can observe that, without any other influence factor, the upwards transfer coefficient for HF components is decreasing in function of the length of the LV feeder for some frequencies, but can be magnified as well. This is due to some resonance conditions that should be further established.

Calculations have been performed for a limited number of frequencies. This could be refined in order to deduce more precise trends and get complete transfer factor characteristics in function of the frequency.

Application to the particular case of PV inverters

The study will now be restricted to the disturbances caused by PV inverters. Thus, the simulation will be similar to the previous one but the disturbance will be injected by a PV inverter and we will limit to only one inverter on one phase. Placing an inverter on each phase would have almost been equivalent to a particular case of the previous simulation since PWM inverters could nearly be modelled by voltage sources, from the perspective of harmonics generation. Figure 5 shows the scheme used for this simulation.

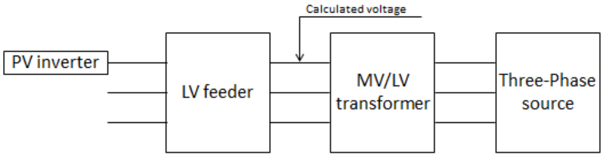

Figure 5 *Scheme representing the simulation used to study the disturbances caused by a PV inverter*

Usually, the commutation frequency of commercially available PV inverters ranges from 15 kHz to 20 kHz [10]. It has been fixed at 17.5 kHz in this study. In these conditions, the highest value harmonic naturally appears to be at rank 699 (34.95 kHz). This harmonic is the most significant one because when the inverter is constituted of 2 arms, present harmonics are located around every even multiple of the commutation frequency. If m is the harmonic related to the commutation frequency, harmonics caused by the inverter will be 2m±1, 2m±3, 4m±1, etc. [4].

By simulation, it has been confirmed that the power generated by the PV panels has no influence on the HF disturbances. Indeed, changing the power provided by the panels means changing the voltage phase angle at the output of the inverter. So, harmonics will have different phase angles but their magnitude remains approximately unchanged.

Figure 6 represents the value of the 699th harmonic of the voltage on the LV terminals of the transformer of the phase the inverter is connected to, depending on the length of the feeder. The phases the inverter is not connected to are also disturbed because the three phases are coupled but the magnitudes of harmonics are lower than for the phase the inverter is connected to.

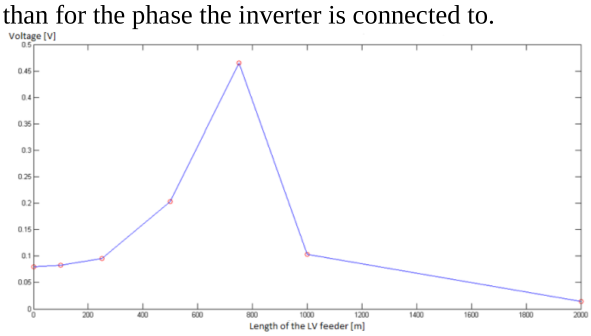

Figure 6 *Harmonic 699 of the voltage on the LV terminals of the transformer of the phase the inverter is connected to, in function of the feeder length*

The curve in Figure 6 has a similar behaviour to the one of some curves in Figure 4. However, it is not easily understandable from Figure 4 that the 699th harmonic has some amplification for several feeder lengths. The major difference between the two diagrams lies in the fact that curves in Figure 4 are established for a balanced three-

phase disturbance whereas the one in Figure 6 is obtained for a single-phase disturbance.
It is easily observed that the length of 750 m appears to be the least favourable. But this result is just applicable for an inverter having a commutation frequency of 17.5 kHz and a L filter having a certain value. Similar results could be found for other parameters combinations.
As mentioned in the previous point, the results could be determined from impedances of the LV feeder and the transformer but we would not obtain simple mathematical relationships because of both inductive and capacitive phases coupling.
It has been mentioned above that harmonic 699 is the highest one but we have to point out that other harmonics can become as high because of resonance. Indeed, the impedance of the LV feeder contains resonance which frequency depends on the length of the feeder. If that resonance frequency is located around harmonics 1400, 2100, etc. (i.e. even multiples of commutation frequency) the magnitudes of these harmonics can become high as well. For example, if an inverter is located on phase C and followed by a feeder of 250m, the harmonics around ranks 1400 and 2100 are higher than harmonics around rank 700, which is due to resonance [4].

Interaction between disturbances from several inverters connected on the same phase

On the LV distribution grid, several PV inverters can be connected not far from each other. That's why we are interested to know how they interact. In fact, to study this interaction by simulation, two single phase PV inverters have been placed on the same phase and different cases have been studied. In order to study the worst case, the commutation frequency of the inverters is the same. The first inverter is connected 1km away from the transformer while the position of the second inverter varies along the feeder which has a fixed length of 1km.
Figure 7 represents the magnitude of harmonic 699 of the voltage calculated in each point of the LV feeder for different positions of the second inverter. (The origin of the x-axis indicates the end of the feeder where the first inverter is connected).

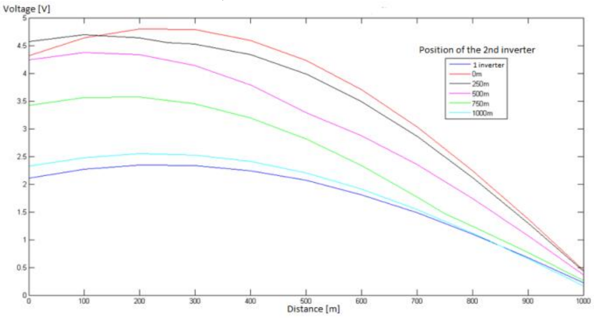

Figure 7 *Magnitude variation of the 699th harmonic along the LV feeder, depending on the position of a second inverter with respect to the first one (connected at the end of the feeder x=0)*

The shapes of the curves in Figure 7 are different from the ones in Figure 6 because we are not computing the same thing. For Figure 6, we were computing the voltage at the terminals LV of the transformer and the length of the feeder was varying. While for Figure 7, we are computing the voltage at different points of the feeder whose length does not vary.
The curve in blue in Figure 7 is the reference case because it is the case where there is just one inverter connected 1km away from the LV side of the transformer. We can notice that the worst case is globally the one with 2 inverters connected 1km from the transformer, that is to say at the end of the feeder. Moreover, the disturbance in that case is approximately double in comparison with the case of one inverter. Therefore, depending on the length of the feeder, if there are several inverters connected not far from each other, the magnitude of the disturbances can become quite high.
Observing the different curves, we can see that the more the second inverter is located far from the first one, the less the disturbance has increased in comparison with the case of a single inverter. It can also be noticed that all the curves follow the same trend.
If the same simulation is performed with more than two inverters, we come to the conclusion that the most unfavourable case happens when all inverters are located at the same place. If all inverters are connected at the same place, the magnitude of the disturbance will be approximately multiplied by the number of inverters. On the other hand, if inverters are sufficiently spaced out, the increasing of magnitude compared with the case of one inverter will not be very high.
However, if the inverters have different commutation frequencies, we will obtain harmonics due to each commutation frequency whose magnitudes are the same order of magnitude as the case of one inverter.

Interaction between inverters and other loads

In previous points, cases where only inverters are connected to the grid have been considered. In reality, the grid contains a lot of other loads of various types. Loads will also have an impact on HF components but they are hard to model. In this paper, the simple case of a single-phase rectifier placed on the same phase of an inverter will be studied. The chosen model of rectifier is just constituted of a diode bridge loaded by a capacitor in parallel with a resistance. Their values have been chosen to be realistic and are summarized in Table 3.

Resistance	105.8Ω
Capacitor	9.45×10^{-4}F

Table 3 *Parameters of the rectifier*

Figure 8 illustrates the performed simulation.

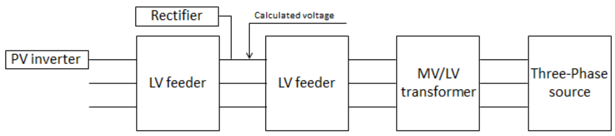

Figure 8 *Scheme representing the simulation used to study the interaction between an inverter and a rectifier-type load*

Several cases have been tested, that is to say different positions of the rectifier and some general conclusions can be highlighted.
At the input of the rectifier, one can observe that the addition of the rectifier has led to the creation of harmonics in low frequencies which were not present in the absence of the rectifier. The peaks around harmonics 700, 1400 are still observed but their values are a little bit lower thanks to the capacitor. The value of the capacitor at the output of the rectifier will have an influence on the magnitudes of the harmonics.
Among the results of this simulation, we have noticed the appearance of secondary emissions. These emissions are not met when just the inverter or just the rectifier are connected to the feeder but they appear when both of them are connected to it at the same time. However, their magnitudes are one order of magnitude lower than those of other emissions.
From these results, it can be confirmed that the presence of a natural commutation converter influences more low frequencies emissions than high frequencies ones. Moreover, the presence of the rectifier can even have a positive impact on HF because we have observed lower values in some cases.

CONCLUSION

The issue concerning HF disturbances in the frequency range 2-150 kHz in LV distribution grids has been dealt with. Knowing that one of the main causes of disturbances in that frequency range is due to power electronic, the case of PV inverter has been thoroughly studied.
Models have been established in order to study these disturbances by simulation.
Thanks to simulations, we have been able to conclude that amplification as well as attenuation are both possible along a LV feeder, due to its natural characteristics.
With a commutation frequency of 17.5 kHz and the specific filter used, the most unfavourable length of feeder appears to be 750m.
It has been confirmed that power supplied by PV has no influence on the magnitude of HF disturbances.
The case of several inverters connected on the same phase has also been studied. It has been demonstrated that if several inverters are connected at the same place, the magnitude of the disturbance will be approximately multiplied by the number of inverters in comparison with the case of one inverter. This result is valid only if all inverters have the same commutation frequency.
Interaction between an inverter and a rectifier has been considered. We have concluded that the presence of the rectifier does not have a negative effect on HF disturbances.
Loads connected to the grid will have an influence on HF but they are hard to model.
All results presented in this paper are based on models which should be checked through experiences on a real grid.
The study concerning the attenuation of HF presented in this paper should be improved by investigating all the frequency range in order to be able to draw more accurate conclusions.
The commutation frequency and the filter parameters of the PV inverter should be modified to test other cases. Moreover, simulations on the three phases should be performed.

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