[2]STUDY OF THE HARMONIC BEHAVIOUR OF PWM CONVERTERS UNDER DISTORTED VOLTAGES

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ABSTRACT

The subject of this paper is the analysis of the generation of harmonics of PWM converters connected to a grid with background harmonics. Models of the converters and their control systems were made and the influence of design parameters was analysed.

INTRODUCTION

Traditionally, distorting loads have been considered as pure harmonic current sources, thus not taking into account a possible influence of an existing harmonic voltage distortion. Recent studies show that we can no longer assume this to be true, especially when we are dealing with a large number of distorting loads. This paper focuses on PWM inverters, checking and analyzing their behaviour when the LF background harmonics are increasing.
To do this, a detailed model of the converter and its control system as specified in Figure 1 was used. A single phase converter with an LCL filter was taken into account for our study.

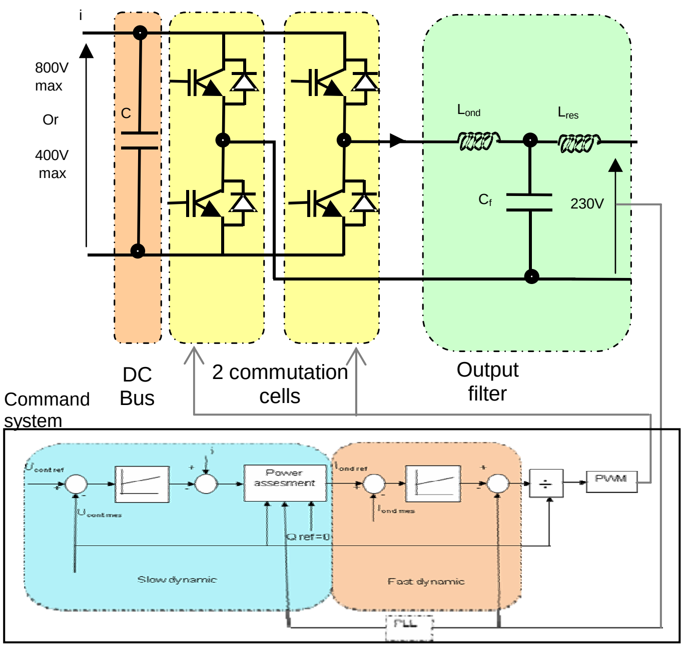

Figure 1: Model of the converter and its control system

In this study the following items are elaborated:
- Inverter topology
- Choice of the PWM modulator
- Dimensioning of passive elements
- Command of the converter
- Modelling and simulation

A single phase converter with an H-bridge was used for the simulations.

FUNCTIONING OF A VOLTAGE CONVERTER IN THE PRESENCE OF HARMONICS

A PWM voltage converter (Pulse Width Modulation) permits the transformation of a DC voltage into one or more alternative voltages and the opposite. To do this, the converter is made up of elementary cells called commutation cells, each containing two commanded bidirectional current interrupters and unidirectional in voltage (association of a commanded interrupter (IGBT) and a diode in anti-parallel).
The commutation cell permits to form the link between the input DC voltage and the output AC voltage. The cell functions as an electronic collector with voltage commutation and the interrupters are only necessary to open the branches in which these cells are inserted. Thus, starting from a DC input voltage, an inverter with voltage commutation allows us to obtain a chopped voltage at a high frequency at the output whose fundamental is an alternative voltage [1].
The voltage commutation at high frequency can be obtained using different methods of pulse width modulation (PWM), this type of modulation was not possible unless a voltage inverter composed of commanded interrupters – as well for opening as for closing - was used.
A PWM voltage inverter is reversible concerning its power. It permits functioning in all four quadrants of the active power – reactive power plan. It can also impose independently the amplitude and the angle of the fundamental of the output voltage(s). The active and reactive power going through this converter can thus be fixed independently of one another [2].e first order headings.

Inverter Topologies

Because of the nature of the networks a single-phase or a three-phase production unit can be connected. This type of connection influences the topology of the inverters. In this paper, the single-phase inverter topologies are investigated

A The single phase inverter must function with a PWM modulator with a fixed frequency and he must assure the functioning in current mode, controlling the alternative output current (network side) and the input voltage (DC-bus side). In contrast with the three phase voltage PWM inverter, two power structures are possible to connect then to the single phase low voltage network: with one commutation cell or with two commutation cells.

Choice of the PWM modulator

The choice of the modulation and of the modulation frequency has an impact on the dimensioning of the passive elements (capacitance, inductance).

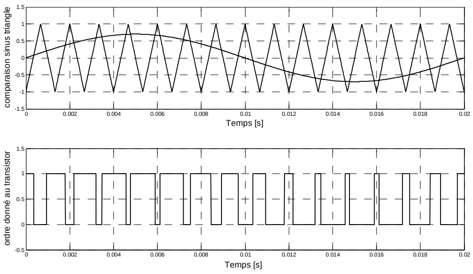

Figure 2: waveforms of a PWM modulation and the command signals of the interrupter

Single-phase inverter

A single phase inverter can be commanded by a PWM modulator using the intersective method shown in Figure 2. There are two types of single-phase converters: with a half bridge and with a full (H- bridge). Following the retained single-phase topology, a supplementary degree of freedom can appear. This is in fact the case for an inverter with a full bridge because it has two branches. This degree of freedom can be used by the modulator to improve the characteristics of the converter. An overview is given in Table 1.

Table 1: Overview of the different inverters

Three-phase inverter	Single-phase Inverter	
	Half bridge	Full bridge (H)
Classical sinusoïdal PWM	Classical PWM	1. Bipolar modulation 2. Unipolar modulation at fdec 3. Unipolar modulation at $2f_{dec}$

Dimensioning of the passive elements

The passive elements necessary for the functioning of the inverter are the DC bus capacity and the output filter (connected to the network). The definition of this filter is identical for the three-phase inverter and for the single-phase inverter. These elements are relatively important as they condition the decrease or the increase of the harmonic content. Their dimensioning is a function of different parameters that have their influence on the global behavior of the inverter and on its price. According to the constructors these parameters do not have the same priorities. It is important to know how they are calculated to fully ascertain how they can influence the creation or the increase of the voltage and/or current harmonics.

The DC bus capacity

The capacity of the DC bus can be calculated so that the voltage at its terminals does not exceed a certain ripple level.

For a single-phase inverter two elements contribute to the evolution of this voltage: the neutral current when the neutral wire is connected to the middle of the capacity and the fluctuating power that circulates between the entrance and the exit of the converter [5].

$$v_{res}(t)=V_{res}\cdot\sqrt{2}\cdot\cos(w_m\cdot t) \qquad i_{res}(t)=I_{res}\cdot\sqrt{2}\cdot\cos(w_m\cdot t-\varphi)$$

After development, this gives us the following equation:

$$p(t)=V_{ond}\cdot I_{ond}\cdot\cos(\varphi)+V_{ond}\cdot I_{ond}\cdot\cos(2\cdot w_m\cdot t-\varphi)$$

When the inverter is connected on the network side to a single-phase network, the choice of the capacity of the DC bus depends only on the inverter; the influence of the source is negligible. To simplify it can be said that the voltage of the DC bus depends on the type of modulation.

The elements to be considered above all are the fluctuating power and the density of the effective current technologically authorized in the capacity

Studies have shown that the single-phase inverter with a half bridge necessitate an entrance filter that is particularly expensive and voluminous. Thus, compared to the price of the modules, this aspect is particularly penalizing. It is al the more penalizing when the ripple on the DC voltage is non-negligible (2.5%), which can have negative consequences for the distortion of the quantities on the network side.

An underestimated capacity can give a THDi that is more penalizing under certain conditions such as the presence of unbalance or harmonics. The presence of the ripple at 2ωm entices the creation of third harmonics for the inverter and can influence the fundamental [6].

Dimensioning of the filter on the electrical network side

The aim of this part is consists in the presentation of the low frequency – or even medium frequency – filter at the output of the single-phase or three-phase inverter connected to the electrical low voltage network.

To reduce the harmonic current next to the switching frequency of an inverter, a sole inductance can be placed in series with each phase of the network. However, when the power is higher than a few kW, this filter becomes expensive and cumbersome because the reactance necessary to filter the harmonics is large. This reactance introduces an important line voltage drop which implies an increase of the DC bus voltage and it limits the band pass width of the current regulators, which in turn degrades the harmonic distortion of the output currents.

On the contrary, to reduce the harmonic currents injection in the network, an attractive techno-economical solution consists in the use of an LCL filter [7]. This solution permits a strong reduction of the total inductance of the filter and the value of the capacity is limited.

Objectives of an LCL filter

The $L_{ond}CL_f$ filter:

- must prevent that the current harmonics generated by the inverter (I_{ond}(hω)) return to the electrical network
- must prevent that the voltage harmonics generated by the network Vres(hω) affect the inverter
- must not have any possible resonances at the encountered frequencies and its elements must be calculated accordingly

The totality of the cascade must have a globally stable behaviour, this is not really a problem, but the study is complex because we are dealing with hybrid systems (continuous and discrete) and the global order of the filter is high.

Command of the inverter – general presentation

In general, the command of an inverter works according to

the principal of a cascade control system with an internal current loop (fast dynamic) and a DC bus voltage loop (slow dynamic) [3].
The voltage of the DC bus is regulated starting from a fixed reference value. The voltage loop control and the compensation of the source current i allow to establish an instantaneous power balance on each side of the inverter.
This power balance (where we normally also fix the set value of the reactive power to zero) asks for measurements. These measurements can contain harmonics, particularly the measurements of the grid voltages.
If these voltages have a harmonic content, they will also be present in the definition of the reference values for the current to be injected in the network. In case of low frequency harmonics (with a rank <15), the harmonics that are thus created will be present in the currents that are injected in the network. As a consequence, the inverter will generate currents and voltages containing harmonics and thus with a higher THD and/or THDi.

Modelling and simulation

A model of a single-phase converter was implemented in Matlab Simulink. The maximum power of this converter is 7.5 kW. To obtain different functioning modes, the power was set to 2.5 kW, 5 kW and 7.5 kW. This was done to have an idea of the influence of the working point of the converter. The L_{ond} value of the filter was also varied, allowing to see how good the harmonics were attenuated in the different cases. These values were set to 0.5 mH, 2 mH and 3.5 mH. In this case the filter is more elaborate, it is in fact an LCL filter. Harmonics were only injected one at a time, with different percentages and with different angles.

- The injected harmonics were 3, 5, 7, 9, 11, 13 and 15
- The percentages were 2%, 4%, 6%, 8% and 10%
- The angles went from 0° to 330° with steps of 30°

The dimensioning of the passive elements led to the following values:
L_{ond} = 2 mH; L_{res} = 0.5e-5; C_f = 7e-6 F; C = 2.2e-3; f_{dec} = 15000 Hz

The injection of the 5th voltage harmonic (250 Hz) provokes a 500 Hz component on the DC bus voltage. This component in turn provokes the components 500 Hz ± 50 Hz on the voltages going to the grid. Thus we can find a 450 Hz and a 550 Hz component on these voltages.
The higher Lres, the lower the current harmonics for the same power and injected Uh.
The higher the converter power, the higher the current harmonics will be for the same Lres, and injected Uh.

There is always a 100 Hz component (and its multiples) present on the DC-bus voltage when we use a single-phase converter. Depending on the harmonic voltage superposed to the ideal grid voltage, other components will also be present on the DC voltage. More precisely, their frequencies will be the injected frequency plus or minus 50 Hz (Figure 3 & Figure 4).

For the injection of the 5th harmonic, we will be able to see 200 Hz (4^{th} harmonic) and 300 Hz (6^{th} harmonic) on the DC bus voltage (Figure 3 & Figure 4).

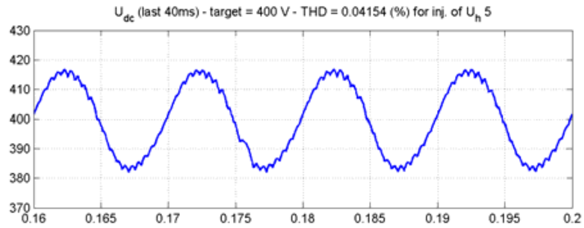

Figure 3: Ripple on the DC bus voltage

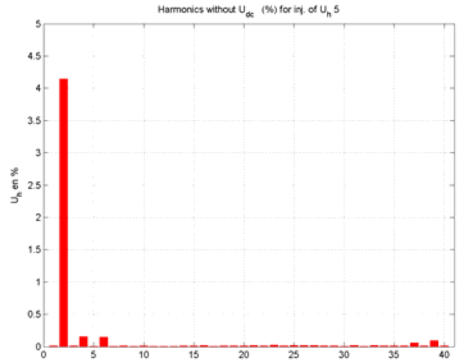

Figure 4: Spectrum of the DC bus voltage

According to the 4 graphs:

- The 3^{rd} harmonic varies little with the amplitude and the phase of the disturbance. The most important effect here is the ripple of the DC bus voltage at 100 Hz.
- On the other hand, the ripple at the multiples of 100 Hz and the presence of the 5^{th} harmonic on the grid voltage provokes a variation of the amplitude and the phase of the 5^{th} harmonic of the grid. This increase depends strongly on the phase of the grid voltage harmonic, but also on the phase shift provokes by the command and the LCL filter, in particular by L_{ond}. These remarks are also valid for the 7^{th} harmonic.
- The variation of the amplitude of the 5^{th} and 7^{th} harmonic remains the same no matter how high the power transiting the converter is. The increase of L_{res} should reduce the amplitude of these harmonics.

CONCLUSIONS

A detailed approach of the elements constituting an inverter allow us to know their contribution in the creation or the amplification of the harmonics that are already present on the grid. The topology of the inverter, whether it be single-phase or a three-phase, and it's type of modulation are the essential parameters for the choice of the passive elements needed for the functioning of the inverter.

- The capacity of the DC bus must manage the fluctuating power during normal operation. This power fluctuating at $2\omega m$ because of the presence of the modulating wave at ωm provokes harmonics of rank h=2k±1 ($\forall k \in [1\ \infty[$, with k an integer). The amplitudes are inversely proportional with the harmonic rank. Nonetheless, harmonics of low rank pose a problem for the positioning of the filter.
- The choice of the modulation also allows to have a set of rays at f_{dec} or at $2f_{dec}$ and their multiples. They are generally easily filtered. They usually do not enter in the calculation of the THDi because their rank is higher than 40.

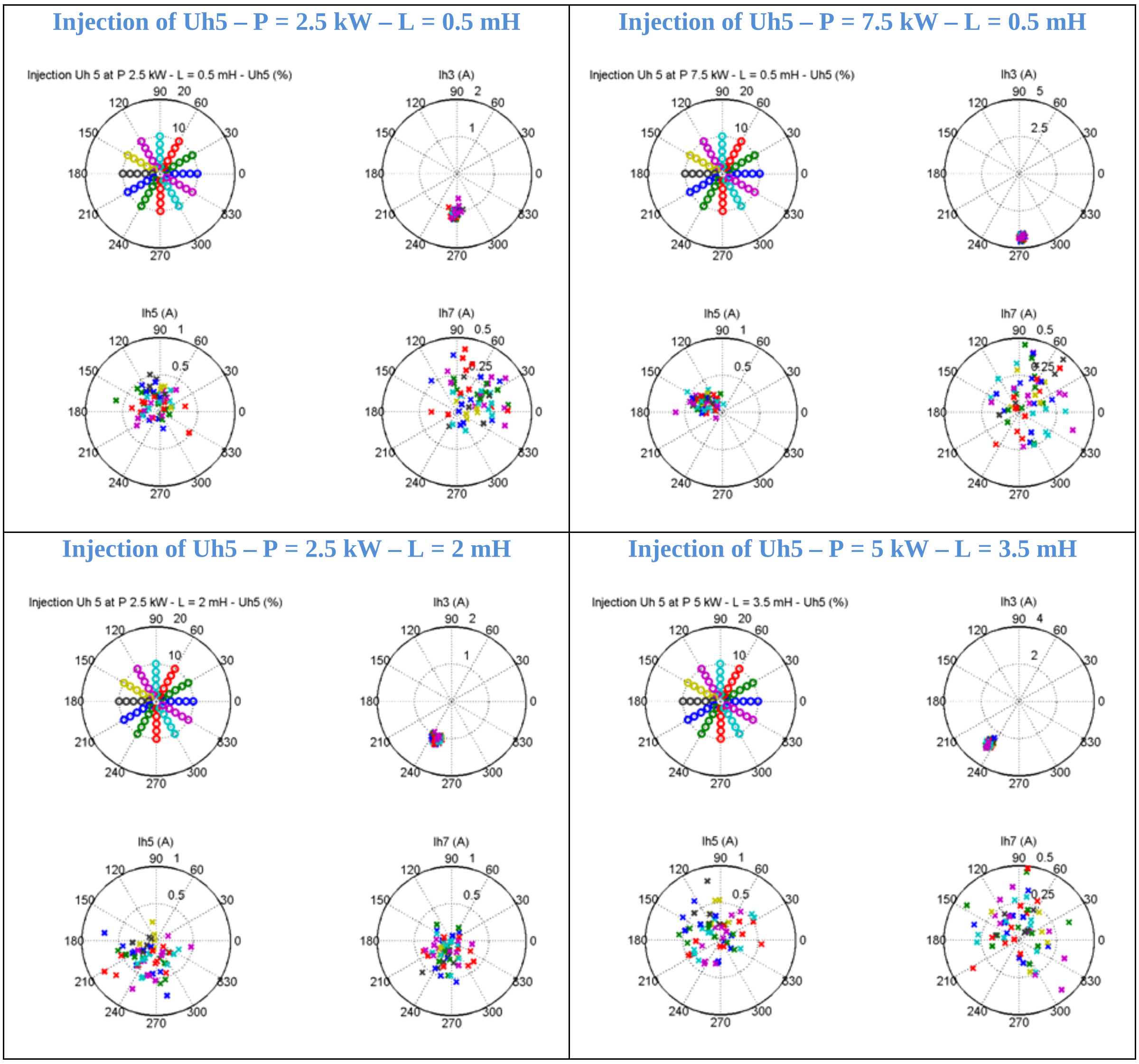

Figure 5: Injection of Uh5

- The LCL filter is a function of the type of modulation and of multiple parameters. The order of this filter accords it a complex behavior. The presence of a resonance can entrail an amplification of certain harmonics created by the inverter or the voltage or current harmonics present in the network.
- The close control of the inverter can be influenced by the disturbances present on the low voltage network. They can be present in the loop control through the measurements en more specific in the measurement of the network voltage. Low frequency harmonics in the currents that are injected in the network (the linear corrector having a limited band pass) are found. The created harmonics are penalizing for the THDi. Generally, the command is not designed to take into account the harmonic disturbances because they are elaborated starting from a linearised model of the system.

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