Evaluation of switching losses effects in multi-level inverters

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Abstract

We propose an alternative approach to characterize a multi-level inverter including a detailed behavioral IGBT model. The Alonso IGBT model, which reproduces accurately in simulation the switching mechanism, is used to demonstrate the influence of the switching losses on the inverter behavior, that induce additional damping in the inverter output filter. Simulation results using the Alonso IGBT model highlight the fact that the IGBT switching properties modify the frequency response of the inverter. Experimental measurements on a 200 kVA multi-level inverter confirm simulation results and therefore prove the theoretical concepts.

IGBT modeling; power inverters; switching losses

1 Introduction

Generally, to design a power converter, an average model of the converter dynamics is built (1). This type of model is dedicated to the behavioral simulation of power converters and is very convenient to design classical controllers such that PID compensators. The simplicity of the model comes from the fact that power components and especially power switches are modeled using a lot of simplifications. For example, a switch is equivalent to a unique variable u, which takes the value $u = 1$ when the switch is turned on and $u = 0$ when the switch is turned off. These binary states are sufficient to establish global dynamical representation in order to describe completely the power system, which can be used to derive an average model for control purpose. Improving simulation accuracy by taking into account real models, which introduce complex physical equations, is a very difficult challenge in power electronics applications. An equivalent electrical circuit representation of an IGBT was proposed in (2) as a good alternative to complex models based on semiconductor physics like e.g. (3), which are difficult to implement in basic simulators. This model, which is referred to as the Alonso model (4), is tuned considering only data-sheets and can reproduce with high accuracy the switching mechanism of real power components. A modified Alonso model was proposed in (4) to optimize the tuning of some internal parameters regarding the representation of the switching losses.

The purpose of this work is to show that switching losses have an impact on the global behavior of a power converter and therefore on the controller design. An NPC multi-level inverter topology will be considered with Semikron 603 GB IGBT (5) and a LC output filter. In this paper, we show that, using the model proposed in (4), the most important effect of IGBT switching losses can be assimilated to an increase of the damping factor of the output LC filter. The rest of the paper is organized as follows. Section 2 introduces the Alonso model and the associated free wheeling diode model. Models are validated in Section 3 based on the efficiency evaluation of simple converter topologies. Simulation results and detail analysis are provided in Section 4. Section 5 discusses the results and concludes the paper.

2 IGBT Model and Diode Model Used to Caracterize the NPC Topology

The Alonso model (2) (4) aims to reproduce with high accuracy transient phenomena that appear during the switching process. It is described as an electrical circuit built only using basic components, which allows the implemention in any circuit simulator. Fig. 1 presents the complete Alonso model for IGBTs and we have developed a complete electrical circuit (4), as illustrated by Fig. 2, which is designed to reproduce the recovery current. The proposed modified Alonso model and its associated free wheeling diode corresponds to the global Alonso IGBT model.

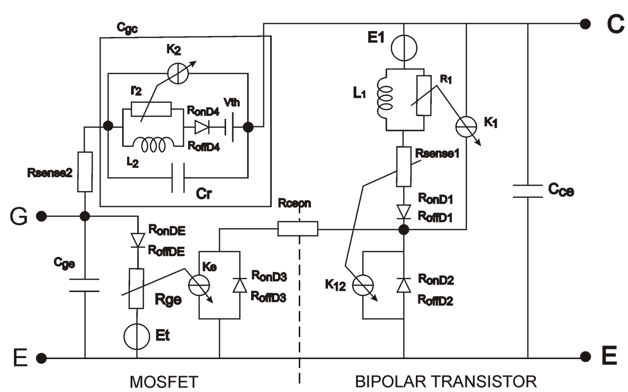
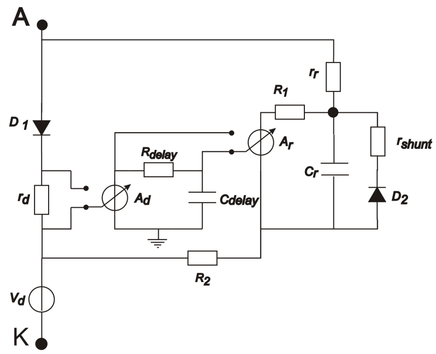


Figure 1: Modified Alonso IGBT model.

According to the IGBT structure, the circuit model can be separated into the MOSFET transistor part and the BJT transistor part. Both are linked and three capacitors C_{ge}, C_{gc} and C_{ce}, whose values depend on v_{ce}, represent the inter electrodes capacitors. Although all these capacitors are nonlinear, it has been shown that only one nonlinear capacitor C_{gc} is necessary to represent the whole capacitor nonlinearities (2). Such nonlinear capacitor is also built from an equivalent electrical circuit (including some



(b)

Figure 2: Associated free wheeling diode model.

nonlinear components such as voltage comparators) in such manner that it can be associated easily within the Alonso model. All the parameters are well defined and a complete process allows calculating them by considering the output $I_c - V_{ce}$ diagram given in the datasheets (the procedure to configure the Alonso IGBT model is described in Appendix **??**). The free wheeling diode of the IGBT component plays a significant role in the switching process.

3 Validation of the Global Alonso IGBT Model

The global Alonso IGBT model is configured from the data-sheet and the goal is to fit the simulated switching losses with the switching losses given in the data-sheet. Although the equivalence between the switching losses of the model and the data-sheet has been obtained via an optimization process, it is relevant to verify the behavior of the model when it is used in normal conditions. In particular, it is essential to verify that the efficiencies of the simulated converter circuits including the global Alonso IGBT model are equivalent to the theoretical results.

3.1 Efficiency of the Buck Converter

Consider a simple buck converter, illustrated in Fig. 3.
It is easy to calculate the efficiency for the buck converter. Define the switching frequency f_c (switching period T_c), according to the IGBT data-sheet, which provides E_{on}, E_{off} and E_w (respectively IGBT turn-on energy, IGBT turn-off energy and diode turn-off energy), the switching energy losses can be written as:

$$W_{switch} = (E_{on} + E_{off} + E_w)\, f_c \qquad (1)$$

Figure 4 presents results of the calculated efficiency in comparison with

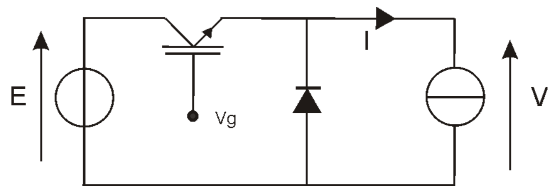


Figure 3: Classical buck converter used to validate the global Alonso IGBT model ($E = 300$ V and $I = 200$ A).

simulated efficiency using the global Alonso IGBT model. In this graph are represented the efficiencies of the buck converter (considering $E_{on} = E_{off} = E_w \neq 0$) calculated using the information given in the data-sheet and simulated with the global Alonso IGBT model. These results prove that the global Alonso IGBT model has been correctly configured and has the same behavior as the real IGBT in the sense of switching losses.

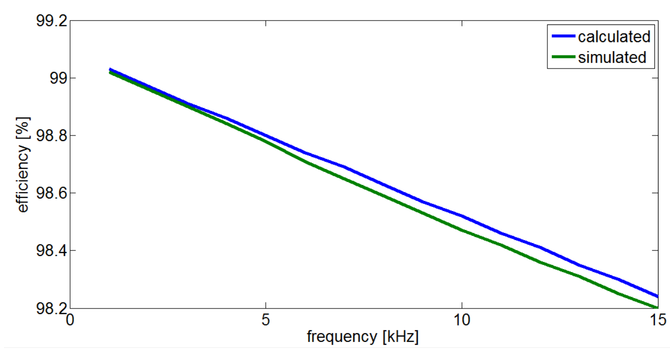


Figure 4: Calculated and simulated efficiency for the buck converter.

3.2 Efficiency of the Half-bridge Inverter

To complete the study, we evaluate the efficiency of a half-bridge inverter, which is represented by the circuit in Fig. 5. The IGBTs are driven by a PWM modulation at the f_c switching frequency and the grid resistor R_g controls the switching mechanism and we consider a resistive load.
Figure 6 presents the simulated efficiency of the topology according to changes in R_g and f_c.
Switching losses increase while R_g or f_c are increasing but conduction losses remain constant. When R_g increases, it takes more time to switch and the switching losses are thus affected. The same principle can be applied when f_c increases because switching losses are proportional to f_c.

This second validation confirms that the proposed global Alonso IGBT model is accurate for any converter type because the efficiency obtained by simulation follows the general rules of the converters.

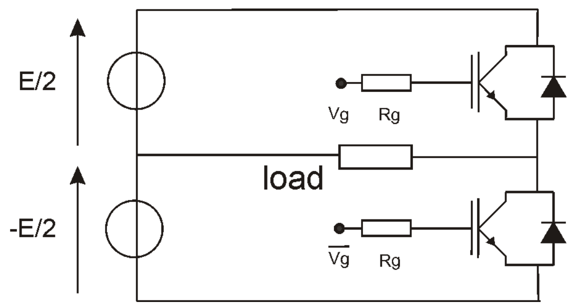


Figure 5: Half-bridge inverter ($E = 630$ V and $R_{load} = 1\ \Omega$).

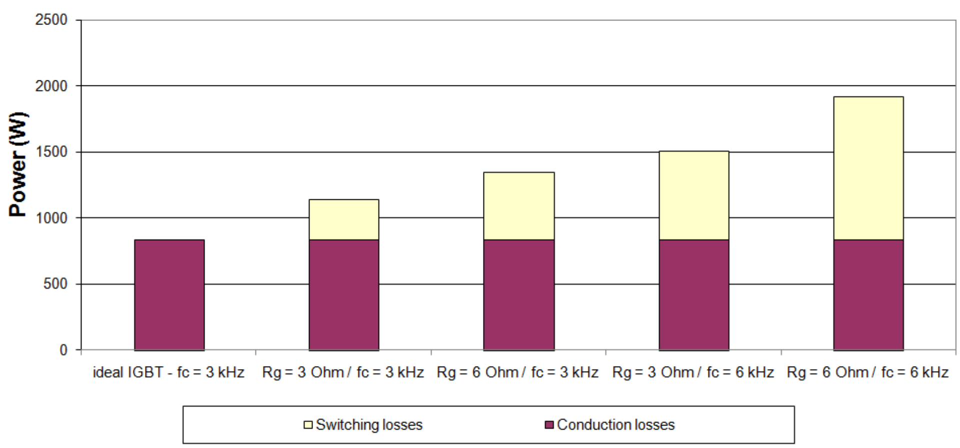


Figure 6: Losses evaluation on the half-bridge inverter. according to f_c and R_g.

4 Effect of Switching Losses on a Multi-level Inverter

Consider an NPC (Neutral Point Clamped) multi-level inverter as shown in Fig. 7. The architecture of the inverter under study comprises the NPC bridge and a LC output filter designed to preserve the fundamental component output voltage at 50 Hz. The DC input voltage of the bridge is set at $E = 400$ V.

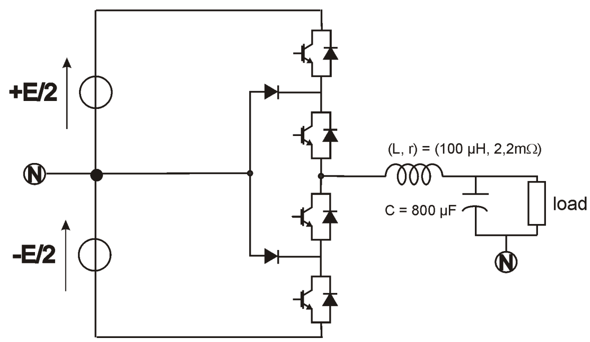


Figure 7: NPC inverter scheme ($E = 400$ V).

It has been shown (6) that this kind of topology is very efficient for high power conversion. Because of the high currents that go through the IGBTs, the losses induced by the IGBTs are consequently very high and cannot be neglected regarding the efficiency evaluation.

4.1 Analysis of the frequency response

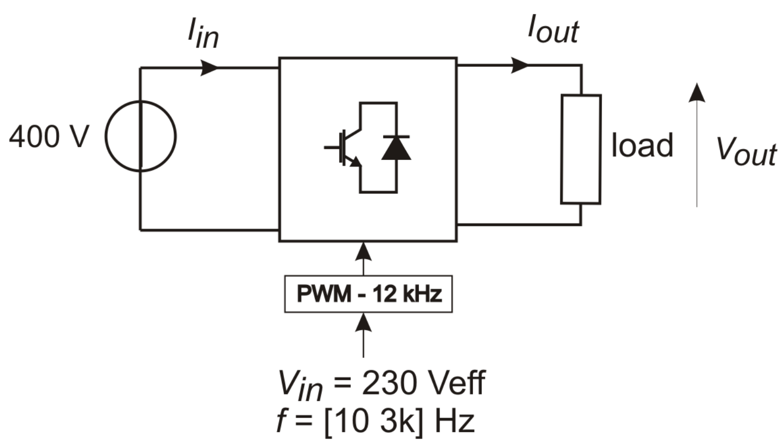


Figure 8: AC analysis principle.

To characterize how switching losses change the inverter output response, a frequency analysis of the bridge is performed and we will show that the switching losses are not only influencing the global efficiency, but they also modify the global behavior of the inverter, and in particular its frequency response. If the IGBTs are considered as ideal, the averaged control variable u is enough to describe the bridge, which is equivalent to the LC filter and is described by the transfer function v_{out}/u. If the IGBTs characteristics are considered as real, the averaged control variable u drives the bridge but the bridge may create some interactions with the LC filter and therefore may change the transfer function v_{out}/u. The method to perform an AC analysis is described in Fig. 8 : an input signal, denoted by v_{in}, which corresponds to the control variable u, is a 230 V AC signal with a frequency varying from 10 Hz to 3 kHz and the corresponding Bode diagram of the inverter corresponds to the ratio v_{out}/v_{in} in the range of frequency defined previously. Figure 9 shows a comparison of the frequency responses between the theoretical transfer function of the NPC inverter (inverter bridge including an LC filter loaded by a resistor R), and the inverter simulated with the global Alonso IGBT model. Although the structure of both transfer functions is similar (second order filter), it proves that the bridge including the Alonso model has a damping effect on the LC filter and this damping effect influences the static gain and the quality factor of the filter.

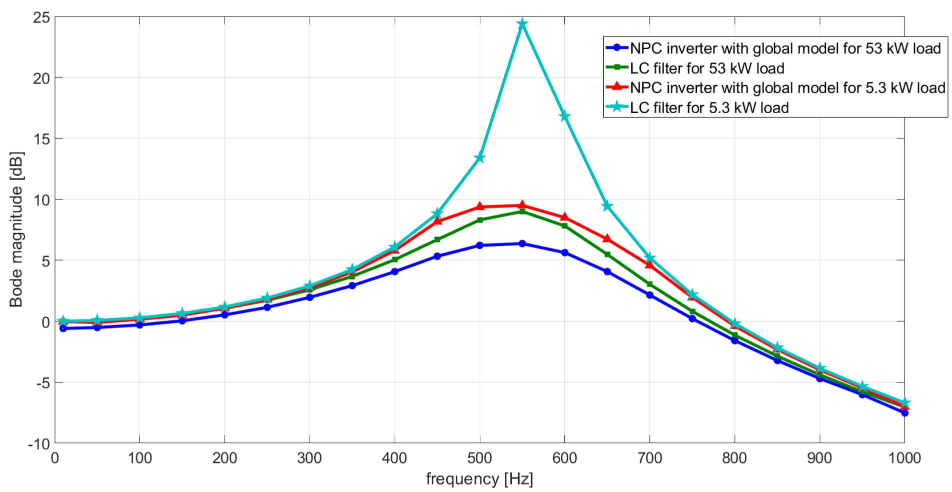


Figure 9: Bode diagrams of the ideal and detailed NPC inverter.

4.2 Experimental results

To validate the simulated results given in Fig. 9, an experimental verification performed on a 200 kVA NPC inverter has been conducted. The experimental results, presented in Fig. 10, have been obtained by the same process considering a resistor load and a dead time of 5 μs that is used to prevent from short-circuits.

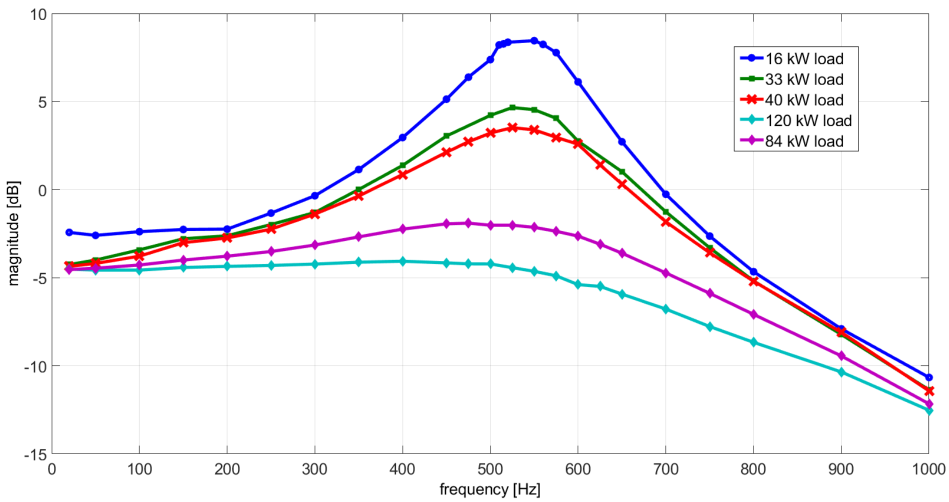


Figure 10: Bode diagram of the experimental NPC inverter.

We assume that the resulting Bode diagram obtained in simulation corresponds to a second order transfer function presented in Fig. 10. Figure 11 and Figure 12 show details about respectively the static gain and the quality factor when the load power changes.
The order of the magnitude of the frequency responses corresponds to the simulated inverter with the global Alonso IGBT model. In particular, we observe a decrease of the quality factor as predicted by the simulations. These curves have been established for the particular input voltage of 400 V. Curves may change if the input voltage changes because the output current depends on the switching losses.
Experimental and simulated results show that the static gain decreases with an asymptotical rate higher than the rate of decrease of the LC filter static gain. Moreover, the nonlinear behavior observed for low output power on the experimental and simulated output gain, is due to the dead time. The constant difference between the simulated and the experimental static gains is due to the discretization effect generated by the electronics which drives the IGBTs. Consequently, experimental static gain is lower than its theoretical evaluation. Regarding the Q factor evolution, as observed in Fig. 12, experimental and simulated bridges are more damped than the LC filter and especially for low output power. It proves that IGBTs introduce a damping inside the output filter. These curves have been established for a particular input voltage. Curves may change if the input voltage changes because the output current depends on the switching losses.

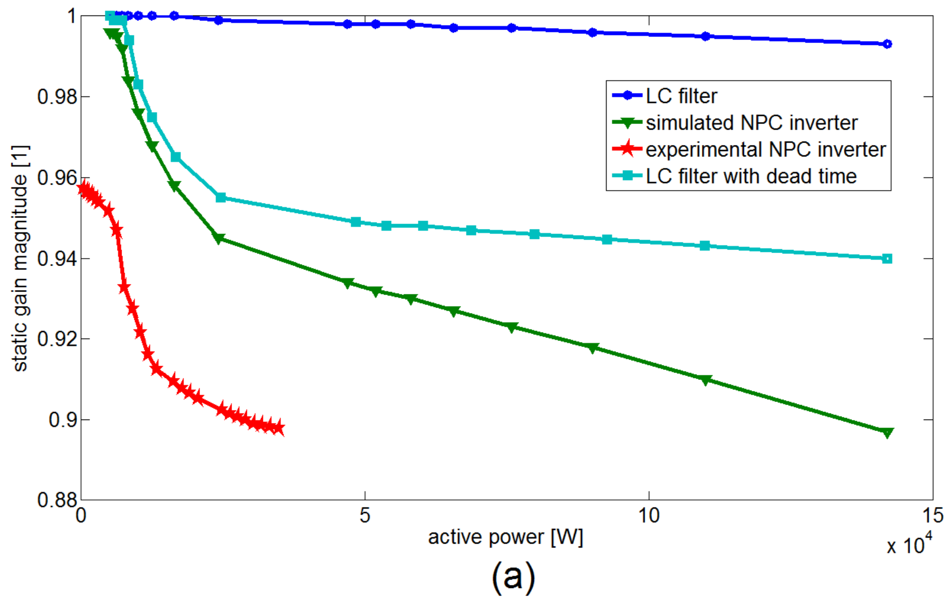


Figure 11: Static gain of the NPC inverter related to power load variations.

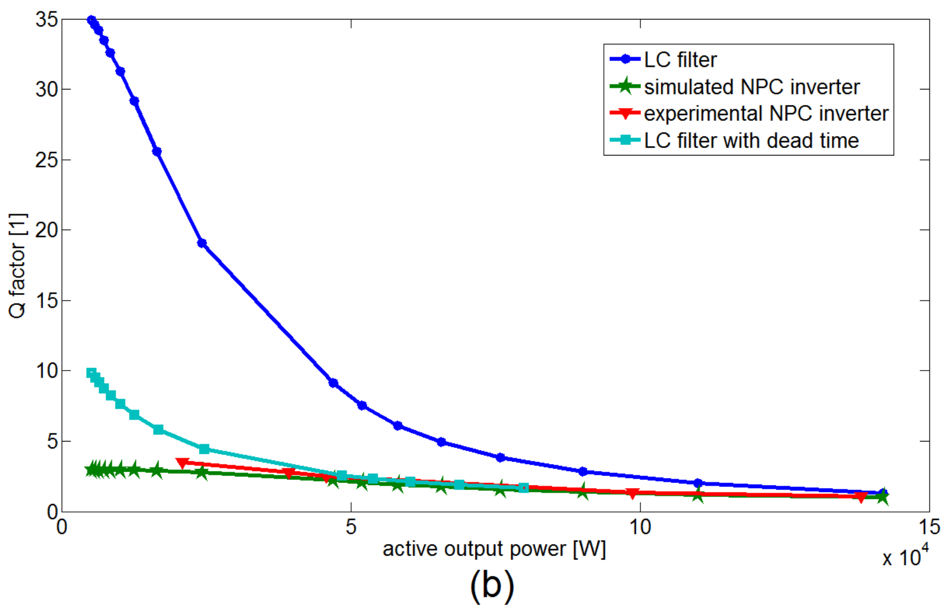


Figure 12: Q factor of the NPC inverter related to power load variations.

5 Discussion

Using the Alonso IGBT model that is tuned using only datasheets and can reproduce with high accuracy the switching mechanism of real components, we have proved that the Bode diagram parameters of an NPC multi-level inverter, which is equivalent to a second order filter, depend on the damping introduced by the IGBTs switching losses. Having a damping factor and a static gain that depend on the current is equivalent to consider the bridge as a non linear resistor in series with the ouput filter; similar approaches have been proposed in (7) without linking losses with the switching mechanism and in (8) where a virtual resistor, included in the controller, allows improving the passivity of power converters. It corresponds very well to the physical interpretation of losses as an equivalent resistor. The proposed model is efficient for the evaluation of the losses in power converters and has the potential to improve design of controllers for power converters.

Future investigations will focus on the design of robust control laws in order to properly control the corresponding uncertain transfer function that is derived from the losses characterization of the NPC inverter.

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