Versatile LabVIEW-FPGA-based Testbench for Electromagnetic Interference Evaluation in VSDs

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Abstract—This paper demonstrates a testbench system used to assess the conducted EMI measurements of a 3-phase 1 kW Si full bridge DC/AC converter as a variable speed drive (VSD) for 1 HP induction motor under no-load conditions. The control system was developed based on a cyber-physical system composed of a LabVIEW environment and a FPGA-based hardware. The literature review shows that several parameters compromise the inverter’s performance using switching modulation techniques for non-linear loads. This paper presents a case study into four of them, namely dead-time, modulation index, modulating frequency and switching frequency. Yet, considering the standards requirements of harmonics control in VSDs, a second case study is also presented for a proposal of evaluating line inductors EMI filters by using the testbench. Therefore, the testbench can be used to improve EMI-based VSD performance and mitigate the conducted emissions by suppressing levels in the source and along the path, thus, ensuring improved electromagnetic compatibility in the system.

Index Terms—EMC, EMI, FPGA, AC Drives, Induction Motor.

I. INTRODUCTION

Common in most applications for motor controlling, the usage of variable speed drive (VSD) yields electromagnetic interference (EMI) emissions as a drawback in spectrum over a wide frequency ranges [1].

The standard IEC 61000-1-2 describes electromagnetic compatibility (EMC) as the proper functioning of equipment or systems in their intended environment without interfering with other devices used in their intended environment. It implies in that the prediction, design and test of devices are of great importance and are useful to evaluate EMC in development process of a product [2]. Thus, having a cyber-physical that supports such a design process and prototyping is essential to assess EMI from devices.

The studies involving pulse width modulation (PWM) techniques with field-programmable gate array (FPGA), which has been extensively and comprehensively investigated in several studies [3]–[5]. This paper is, however, focused on using a visual programming language to control the VSD with a FPGA in order to reduce the prototyping development time and speed up the tests. The testbench used in the current study has been already proved to be suitable, robust and efficient during PWM tests in DC/DC converters [6]–[8]. In this paper a further investigation expands into the domain of DC/AC converters applied to non-linear loads using sinusoidal PWM (SPWM) technique.

This study proposes a FPGA-based testbench running LabVIEW, as the main objective, to enable EMI tests on inverter-fed induction motor drives using a visual programming language. In addition, four case studies are shown with the following parameters: dead-time (DT), modulation index (MI), switching frequency (SF) and modulating frequency (MF). As contribution, it shows that testbench produced a flexible, stable and robust output, even changing the input parameters, without compromising the EMI tests and using low FPGA computational resources. Furthermore, it enables: 1. The possibility of varying input values during the tests without recompiling and synthesizing the algorithm; 2. the analysis the impact of parameters on EMI during parameters transitions and; 3. the evaluation of filters for different VSD’s settings.

Therefore, Section II describes the setup, components and specification of the system. Section II-B addresses the algorithm, wave synthesizing and carrier generation. Section III describes the case studies for EMI levels of the input parameters.
and proposal for evaluating EMI filters. And finally, Section IV provides conclusion and remarks.

II. METHODOLOGY FOR BUILDING THE LabVIEW-FPGA-BASED TESTBENCH

The EMC testbench assembled is shown in Fig. 1 and all the setup was mounted according to the CISPR-11 recommendations.

The devices and their specification used to build the tests are described in Table I. The FPGA module has Virtex-5LX110 Xilinx family, maximum sampling rate of 750 kS/s per channel and 40 MHz timebase. The EMI receiver provides a frequency range of 9kHz - 6GHz, with 200 Hz IFBW for 9-150 kHz frequency range (CISPR-A) and 9 kHz for 150 kHz- 30 MHz (CISPR-B). The load is a 1 HP, 3-phase, induction motor.

<table>
<thead>
<tr>
<th>Device</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>EA-PSI 91500-30</td>
</tr>
<tr>
<td>LISN</td>
<td>R&amp;S®ESH2-Z5 V-Network</td>
</tr>
<tr>
<td>Inverter</td>
<td>Powersys 80217 P3G 1000W</td>
</tr>
<tr>
<td>Controller Supply</td>
<td>Amrel LPS-305</td>
</tr>
<tr>
<td>EMI Receiver</td>
<td>Gauss TDEMI X6</td>
</tr>
<tr>
<td>3-Phase Induction Motor</td>
<td>Tamel SG80-2A</td>
</tr>
<tr>
<td>PC-based Platform</td>
<td>NI PXIe-1085</td>
</tr>
<tr>
<td>FPGA Module</td>
<td>NI PXI-7854R</td>
</tr>
<tr>
<td>Transient Limiter</td>
<td>Agilent 11947A</td>
</tr>
</tbody>
</table>

In the connection between the LISN and EMI receiver was added a transient limiter to protect the receiver.

A. FPGA

A FPGA-based testbench running LabVIEW was developed in order to overcome low level programming of VHSIC Hardware Description Language (VHDL) - which can increase the designing and prototyping development time for users. Also, as cyber-physical system, it is possible to use NI-PXI IDE (Interface Development Environment) in order to synthesize signals not provided by a conventional FPGA (floating-point number operations only). In addition, FPGA performs concurrent operations in a re-configurable and flexible fashion, allowing programming different PWM techniques with full parameters control.

B. LabVIEW Algorithm

The algorithm flowchart is presented in Fig. 2 and it is divided into two concurrent WHILE loops named “A - Waveform Generator” and “B - Comparator”. The flowchart for the algorithm is presented in Fig. The final LabVIEW block diagram is shown in Fig. 3. This algorithm was adapted from the “Power Electronics Control Application Examples and IP (Intellectual Property) Cores for NI (National Instruments) GPI (General Programming Interface)”.

An explanation of the waveforms generators functions named "SGen.subVI" and TGen.SubVI are addressed in the next subsections according to the flowchart. The extension ".subVI" indicates an algorithm’s separated section file, used to enable modularity and a cleaner and structured visual.

1) Basic Sawtooth Generator (SGen.subVI): The modulating frequency is obtained through user input and is addressed by the subVI called "Basic Sawtooth Generator" (Fig. 3) which produces the three-phase modulating frequency waveforms outputs converted to radians angles. A phase shifting to the
line phases ("SinPhR", "SinPhS" and "SinPhT") is added to the outputs from generator in order to produce the line phases.

2) Modulation Index and Triangle wave Generator (TGen.SubVI): The phase voltage signals (from previous generator) are compared to a triangular waveform synthesized by means the "Modulation Index and Triangle Generator" (Fig. 3, Loop B) using comparator. Dead-time is added to the phase voltage signals just after the comparison step. Thus, half of output values goes through NOT gates (legs’ lower switches) and the another half is sent to upper converter switches.

3) Device Utilization: After compilation and synthesizing, the software returned the utilization as described in Table II. It shows a plausible trade-off between resources used and functionalities presented in the setup.

<table>
<thead>
<tr>
<th>Device Utilization</th>
<th>Used</th>
<th>Total</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Slices</td>
<td>2139</td>
<td>10250</td>
<td>20.9</td>
</tr>
<tr>
<td>Slice Registers</td>
<td>5901</td>
<td>82000</td>
<td>7.2</td>
</tr>
<tr>
<td>Slice LUTs</td>
<td>6695</td>
<td>41000</td>
<td>16.3</td>
</tr>
<tr>
<td>Block RAMs</td>
<td>0</td>
<td>135</td>
<td>0.0</td>
</tr>
<tr>
<td>DSP48s</td>
<td>6</td>
<td>240</td>
<td>2.5</td>
</tr>
</tbody>
</table>

III. CASE STUDIES

This section presents two case studies: (1) assessment of control parameters - in order to assess the performance of VSD under variation of four control parameters (dead-time, modulating index, modulating frequency and switching frequency) while conducted emissions tests are being done. (2) Evaluation of filters for VSDs - with initial objective of testing filters values based on analytical method and from solution-driven COTS (commercial-off-the-shelf) filter.

A. Case Study 1 - Control Parameters Assessment

Based on the capability of parameters, four case studies are analyzed. To accomplish it, EMI levels were assessed after applying 200 \( V_{DC} \) to the inverter, followed by parameter increments. A parameter was changed, in a sweep way, while keeping others parameters at default value. The default values were 500 \( \eta s \) (dead-time), 0.75 (modulation index), 50 Hz (modulating frequency) and 15 kHz (switching frequency). Then, an EMI receiver measured the spectrum of conducted emissions by a quasi-peak (QP) detector. A single test lasted roughly two minutes and the inverter provided power consumption of \( \sim 70 \) W, efficiency of 67% on default values and response of less than 1 s for controller settling time.

The obtained results are presented in a spectrum over the entire range of conducted disturbances (9 kHz -30 MHz). Moreover, the variability of the more significant EMI harmonic peaks with values of 80-100 dB\( \mu \)V, which were located mainly up to 350 or 500 kHz, are also presented.

1) Dead-time - DT: The waveform analysis showed the rise-time and fall-time were up to 190 \( \eta s \) (near the IGBT’s datasheet, part num. IXGH40N60C2D1). The dead-time must be higher than the 190 \( \eta s \) value therefore 500-850 \( \eta s \) was chosen to provide a reasonable transition settlement. The spectrum in Fig. 4-A shows the EMI levels for the highest and the lowest parameter values. The variation of such parameter has almost no impact in the spectrum shape. The obtained differences in the results are below 0.5 dB\( \mu \)V (Fig. 4-B).

2) Modulation Index - MI: It was selected 0.4 (minimum empiric value to run the motor at 200 \( V_{DC} \) input) up to 1.0 (maximum to not achieve overmodulation) for modulation index. As shown in Fig. 5-A, increasing the MI values the spectrum gets narrowed, reducing harmonics below 200 kHz. Between 200 kHz and 1 MHz the effect is opposite.
3) Modulating Frequency - MF: A range of 20 - 70 Hz was chosen for this control parameter. At minimum value, it noted to be the lowest to run the motor at 200 V<sub>DC</sub> input, and for maximum value it was chosen to not stress the machine for short periods (higher power frequency delivered overtime means increasing core loss, over heating, bearing damage, reduction of power factor and audible magnetic noise). According to the theory, the modulating frequency affects the side-bands observed in the spectrum. Because this frequency is smaller than the used IFBW, it may affect a reduction of harmonics peaks in frequencies below 2 MHz (Fig. 6-A).

The worst-case and best-case scenarios were 70 Hz and 30 Hz (Fig. 6-B), respectively, resulting in a reduction of 2.3 dB<sub>µV</sub> (CISPR-A) and 1.2 dB<sub>µV</sub> (CISPR-B) when decreasing frequency (caused by the lower RMS voltage delivered to the motor). Although near 30 Hz’s peak, the 20 Hz’s peak seems to be an outlier data and more tests are needed in lower frequencies.

4) Switching Frequency - SF: In this control parameter, it was considered 10 kHz (higher than the minimum CISPR A lower frequency) up to 30 kHz. Thus, the effects of EMI levels for switching frequencies are shown in Fig. 7-A.

The worst-case and best-case scenarios were 30 kHz and 10 kHz (Fig. 7-B), respectively, resulting in a reduction of 6.7 dB<sub>µV</sub> (CISPR-A) and 9.6 dB<sub>µV</sub> (CISPR-B) when decreasing switching frequency.

It was observed that the (main) reason why the results do not change that much is the very low impedance of the DC source. That means that all switching current is flowing via the DC source. The (relative) small variations of switching parameters will not result in large variations of EMI.
Fig. 6: Spectrum (A) and EMI peak values (B) for MF.

As last parameters comparison, the testbench was set with worst and best parameters values and the frequency spectrum resulted is shown in Fig. 8. Comparing the best scenario (DT=800 μs, MI= 1, MF= 20 Hz, SF= 10 kHz) w.r.t. the worst one (DT=500 μs, MI= 0.4, MF= 70 Hz, SF= 30 kHz) themselves, the peaks reduce 14 dBμV below 150 KHz and 8.6 dBμV above it.

A resulting summary is done in Table III. It shows EMI levels increasing (+) or decreasing (-) for: (1) Incrementing (↑) the control parameters; (2) Worst and best case scenarios w.r.t. default; (3) Comparing passive filters w.r.t. default.

B. Case Study 2 - Evaluating Passive Filters for VSDs

Another possible application for this testbench is the evaluation of filters to control the harmonics components as required by standards, e.g IEEE 519-2014.

1) AC Side - L-filter Line Inductor: This case study addresses a simple L-filter which inductance (L) calculation is based on the maximum current ripple allowed:

\[
L = \frac{\Delta U_L \% \times U_N}{2 \times \pi \sqrt{3} \times f_N \times I_N}
\]

Where $\Delta U_L \%$ is the percentage voltage drop across the inductance of filter, $U_N$ is the rated phase-to-phase voltage [V], $I_N$ is rated current [A], and $f_N$ is rated frequency [Hz]. Thus, $\Delta U_L = 0.01$, $U_N = 200$ V, $I_N = 1.8$ A and $f_N = 50$ Hz, returning 2 mH. Thus, it was used a AC side filter under the value of 2.2 mH. Comparing default values and L-filter (Fig. 9), the filter shows a 13 dBμV lower emission at fundamental component and works properly up to 3rd harmonic component and between 600 kHz and 4 MHz reducing almost 10 dBμV around 2 MHz, although appearing overshoots between 150-300 kHz and 5 MHz.

In addition, a second case study was performed adding a COTS line filter in DC side.

2) AC and DC Side - L-filter and COTS Line Filter: It was used a single-phase line filter, WE-CLFS, 10A, 250V, $L_1 = L_2 = L = 20$ mH, intended to suppress broadband noises in common
and differential mode. In Fig. 10 is presented a comparison between VSD filtered and default value (no passive filter) and shows a reduction of around 10 dB µV on switching frequency, reduction of 27 dB µV in the overshoot region compared to AC side filter (∼300 kHz) and highest attenuation between 1-6 MHz, reaching 34 dB µV (compared to AC-side-only filter case) and 44 dB µV (compared to default).

IV. CONCLUSION

This paper presented: 1. A versatile testbench; 2. Use of the testbench for parametric effects analysis and; 3. Use of the testbench for evaluating filters. The testbench produced a flexible, stable and robust voltage output during change of parameters, without jeopardizing the conducted EMI measurements.

TABLE III: Peak levels from different cases.

<table>
<thead>
<tr>
<th>Control Parameter</th>
<th>CISPR-A</th>
<th>CISPR-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ DT</td>
<td>-0.4 dBµV</td>
<td>-0.4 dBµV</td>
</tr>
<tr>
<td>↑ MI</td>
<td>-7 dBµV</td>
<td>-13 dBµV</td>
</tr>
<tr>
<td>↑ MF</td>
<td>+2.3 dBµV</td>
<td>+1.2 dBµV</td>
</tr>
<tr>
<td>↑ SF</td>
<td>+6.7 dBµV</td>
<td>+9.6 dBµV</td>
</tr>
<tr>
<td>Scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worst Case</td>
<td>+8.1 dBµV</td>
<td>+6.2 dBµV</td>
</tr>
<tr>
<td>Best Case</td>
<td>-5.9 dBµV</td>
<td>-2.4 dBµV</td>
</tr>
<tr>
<td>Filters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-filter</td>
<td>-13.5 dBµV</td>
<td>+17.5 dBµV</td>
</tr>
<tr>
<td>L-filter &amp; COTS Filter Line</td>
<td>-9.6 dBµV</td>
<td>-43.9 dBµV</td>
</tr>
</tbody>
</table>

REFERENCES


