

Digital Control of switching converters in renewable sources applications

Keywords: digital control, sliding mode control, switching converters, inverters, FPGA.

Introduction and goals

Switching converters transfer electrical power from energy sources to their loads, while regulating the output voltage and/or current according to the loads' needs: dc converters regulate the output voltage to a constant value provided that the current requirement is within a specified range; inverters produce a sinusoidal voltage at the output. In addition to their control over the output, switching converters are sometimes required to regulate input voltages and/or currents, such as the voltage drop across a photovoltaic panel or the input current of a PFC, which must be sinusoidal and synchronized with the phase voltage. Similarly, the output current of a grid-connected inverter must be sinusoidal and synchronized with the phase voltage.

Switching converters ensure protection against fault conditions, power management in systems comprising multiple energy sources and loads, bidirectional power transfer. The above goals are all met with the help of control algorithms, which can be assessed in terms of their steady-state and transient performance.

The control algorithm can be implemented in analog or digital form. Analog control offers increased bandwidth, but it is affected by component variation, noise susceptibility, it is more difficult to debug and modify than its digital counterpart, it cannot be used in autotuning applications. Digital control allows for the use of more sophisticated algorithms, it is easier to debug and modify, it requires fewer external components, it is less susceptible to noise, it allows for communication with other systems and frequency-domain system identification.

The physical support for the practical implementation of the control algorithm is an Artyx 7 FPGA, which consists of DSP48 stages, similar to those present in DSPs. An interconnection matrix allows for programmable configurations of the FPGA, tailored for any given application. The externally generated clock signal is set at 100MHz, but PLL stages inside the FPGA can synthesize clock signals of up to 800MHz. Therefore, generation of the DPWM signal only requires an FPGA counter circuit.

The goals of the thesis are:

- The control of switching regulators using an FPGA: the design of the DAC, the control circuit and the generation of the DPWM signal;
- The control of a grid-connected inverter in a photovoltaic system.

The design of an analog-to-digital converter

The design of an analog-to-digital converter is part of the first goal of the thesis. The ADC samples and quantizes the analog input signal. Its functionality can be evaluated according to a number of parameters, among which the conversion rate and the absolute resolution. The FPGA circuit used for this application is the Artyx 7, which already features an ADC whose conversion rate is $1\mu\text{s}$ and resolution is 12 bits. In contrast, the designed ADC has a conversion rate of 150ns and a resolution of 8 bits. The downside of the inferior resolution can be alleviated by reducing the full scale of the analog input signal, which is acceptable in a regulator application, where the measured voltage is expected to vary in a narrow range.

The designed ADC uses an intermediate measure – time, which only requires two external components, namely a resistor and a capacitor, and a comparator which is internal to the FPGA. The time-to-digital conversion (TDC) requires the use of serially connected cells whose input to output propagation delays are all the same. This method is not limited by a clock signal, whose frequency might not be high enough. The serially connected cells used for this application are part of the carry chain present in every slice in the FPGA because they offer low and fairly equal propagation delays (according to the specifications). The schematic diagram of the delay chain is presented in fig. 1. In order to design it, a time constraint was necessary.

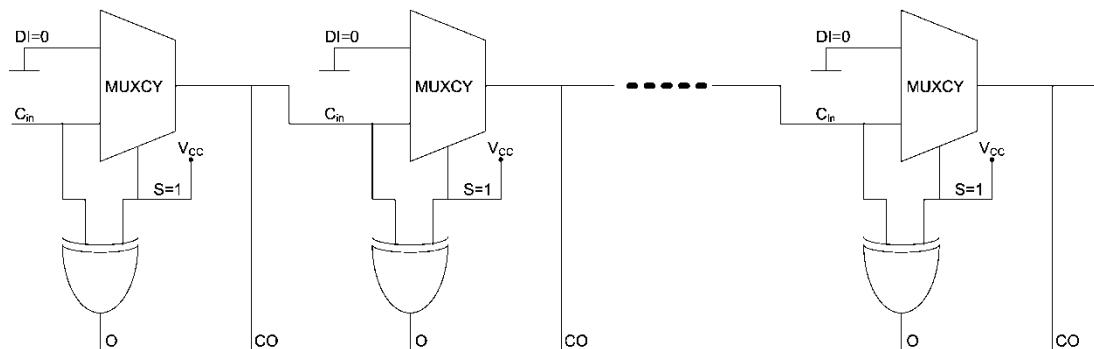


Fig.1 Delay carry chain

Experimental results for various input signal frequencies are presented in fig 2. The color of the input signal is orange, the output produced by the ADC is blue.

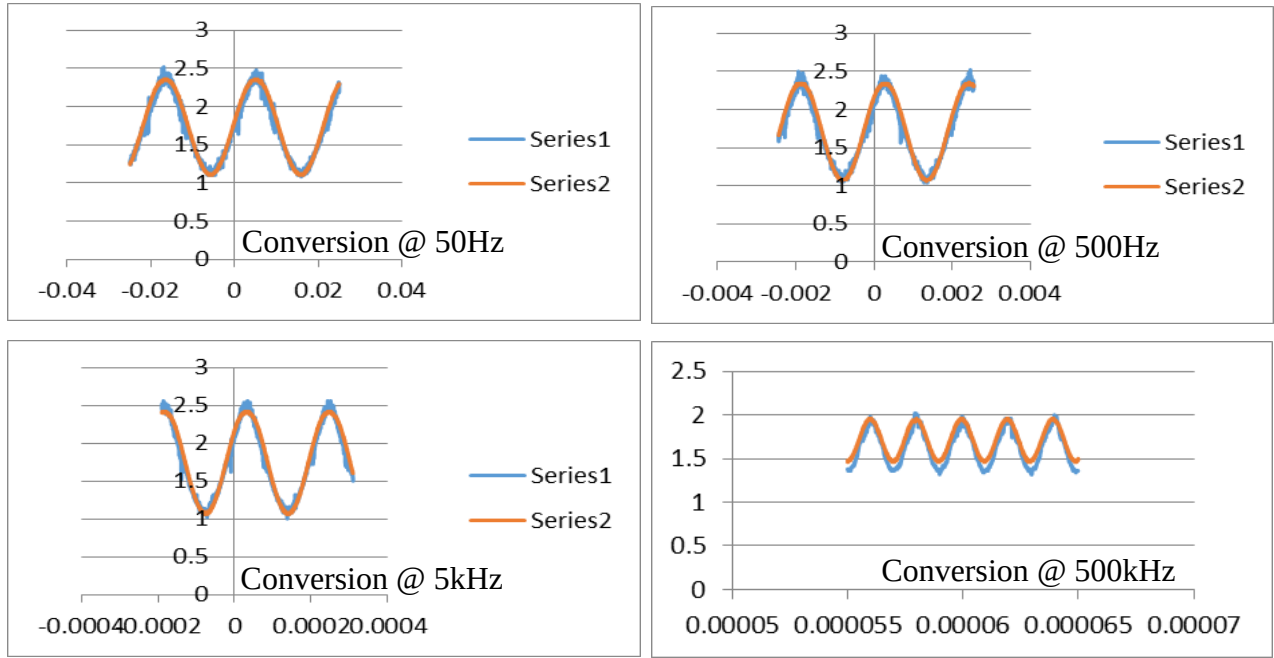


Fig.2 ADC Conversions - experimental results

Frequency-domain system identification

Frequency-domain system identification is part of the first goal of this thesis and it can be used to help autotune the control algorithm. The method consists of the application of a sequence at the input of the system to be identified and the acquisition of the corresponding output sequence. The time domain system equation is

$$y[n] = \sum_{i=0}^N b_i \cdot x[n-i] - \sum_{j=1}^M a_j \cdot y[n-j],$$

where $x[n]$ is the input sequence and $y[n]$ is the output sequence. In order to identify the system as a frequency domain equation, it is necessary to find a_i and b_j .

If n is selected in such a way that the matrix of the above system is square, then the result will only be accurate for that same number of samples n . In contrast to this method, a larger number of samples n can be selected. Although the system matrix is no longer square, the pseudoinverse will return an optimal (minimum squared error) solution. Figure 3 presents the functioning of the method for $n = 100$ samples.

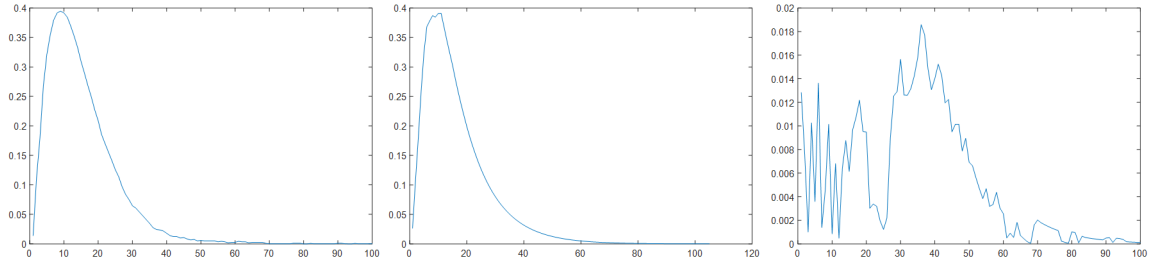


Fig. 3 System output, inferred system output, absolute error - all for 100 samples

The system identified experimentally is a circuit present on the development board used – Nexys 4, which is part of the output signal processing circuitry. The Bode plot of the circuit and that of the identified system are presented in fig 4.

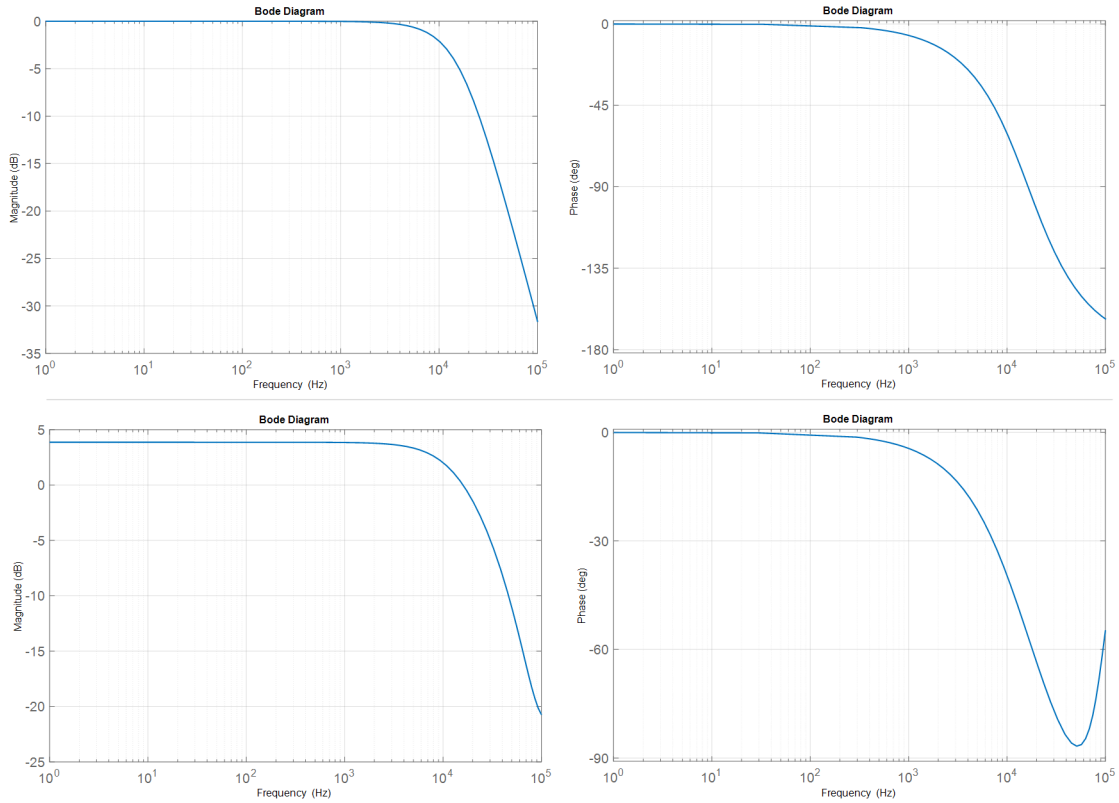


Fig.4 Bode plot of the simulated (top) and detected (bottom) systems

Sliding mode control of a buck converter

The control of a switching regulator is part of the first goal of the thesis. The commonly used control methods are those of linear and invariant systems. However, switching regulators are not linear systems and the application of these methods would require the linearization of the system, good knowledge of its parameters and would function best around the static point of the linearization. The upside of these methods is the possibility to cancel the steady-state error, provided that a zero-frequency pole is part of the control algorithm.

Sliding mode control lends itself to the control of variable structure systems, such as switching regulators, it is simple and does not require accurate knowledge of the circuit parameters. The downside is its inability to cancel the steady-state error. The transient response in SMC comprises two stages: the unconstrained variation of the state measures and the sliding phase. The transient response is presented in fig 6. The sliding phase corresponds to an exponential variation in time.

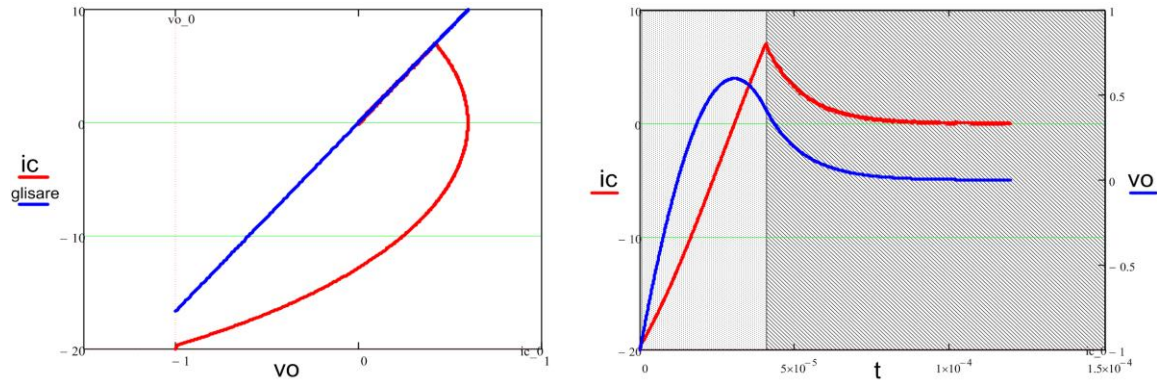


Fig. 5 System response - phase portrait (left) and time behavior (right)

The experimental setup comprises a Nexys 4 development board and a buck converter whose input voltage is 24V, output voltage is 12V, $L=110\mu\text{H}$, $C=100\mu\text{F}$, $R_{\text{load}}=6\Omega$. The output voltage error for a 3A load step is presented in fig 6.

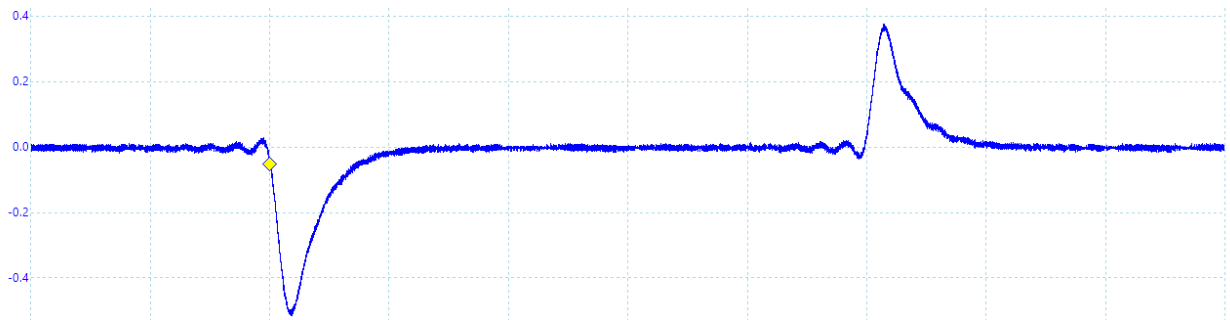


Fig.6 Output voltage error for a 3A load step

Control of a grid-connected inverter

It is possible to use inverters to draw energy from photovoltaic panels and release it into the grid, thus making it available to users which have no direct access to renewable energy sources. The inverter output current must be sinusoidal and in phase with the grid voltage. In order to attain this current, there are several control methods available, one of which is the dq control, as presented in fig. 7.

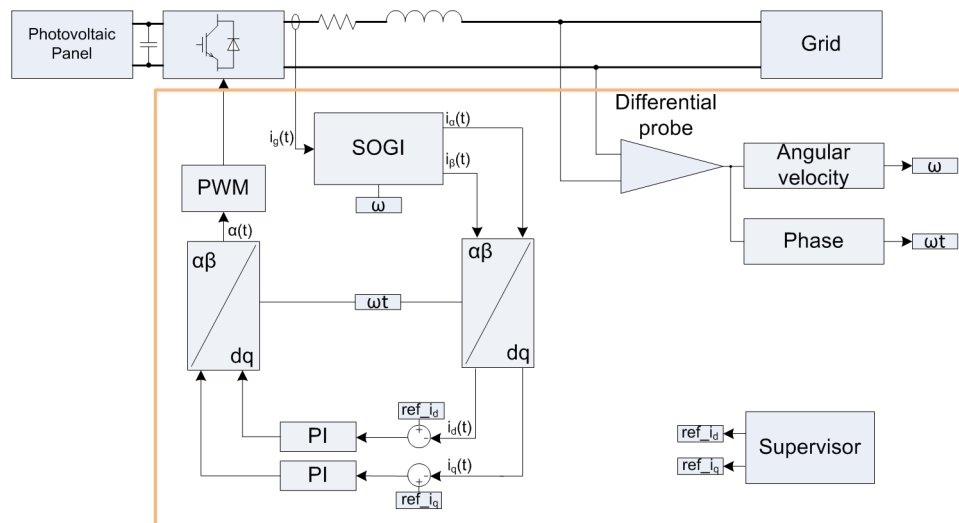


Fig. 7 DQ control of a grid-connected inverter

- PLL – ensures synchronization with the grid voltage; it is also utilized for the successful forward and inverse conversion between time and dq coordinates;
- SOGI – produces two output signals: one is identical with the input, the other is in quadrature with it;
- $(\alpha, \beta) - (d, q)$ transform: it uses the output of the PLL; the dq outputs can be processed using dc methods;
- PI control – applied to the dq measures; the reference values are set by a supervisor circuit;
- $(d, q) - (\alpha, \beta)$ transform: converts the output back to its sinusoidal form;
- PWM generator – modulates the sinusoidal output and applies the command signal to the inverter switches;

One challenge in controlling the inverter is the harmonic content in its output current, which must be sinusoidal and in phase with the grid voltage. Since the powers at the input and output of

the inverter are approximately equal, there is a sinusoidal voltage superimposed on the dc component of the inverter input voltage as follows:

$$u_{dc}(t) = \frac{P_M}{2 \cdot \omega_{grid} \cdot U_C \cdot C} \cdot \sin(2 \cdot \omega_{grid} \cdot t)$$

This ripple voltage is then modulated using the command signal $d(t)$, which follows a sinusoidal signal synchronized with the grid (via the PLL)

$$d(t) \cdot u_{dc}(t) = D \sin(\omega_{grid} \cdot t + \varphi) \cdot \frac{P_M}{2 \cdot \omega_{grid} \cdot U_C \cdot C} \cdot \sin(2 \cdot \omega_{grid} \cdot t)$$

Thus, superior odd harmonics become a part of the inverter output current. Three methods have been used to eliminate these odd harmonics: dq control, proportional-resonant control and repetitive control.

Contributions:

- An analog-to-digital converter was designed using an FPGA;
- The ADC was implemented in Vivado and it was written in Verilog;
- Frequency-domain system identification was implemented on an FPGA and it comprises: the generation of a sequence at the input of the identified circuit; the measurement of the system's output voltage; the inference of the system coefficients;
- The sliding mode control of a buck circuit was modeled in Mathcad, simulated in LTSpice and implemented on an FPGA;
- The control of a grid-connected inverter was simulated and implemented practically;
- The output current of the inverter was regulated to be a sinusoidal by attenuating the higher harmonics, which arise because of the photovoltaic panel at the input; the control methods used are dq control, proportional-resonant control and repetitive control.