Digital Control of Power Converters—A Survey

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***Abstract*—Power converters offer a high capability to efficiently manage electrical energy flows. Until a few years ago, their primary use was in supplying motors in industrial applications and in electric traction systems. Nowadays, in addition to those fields they are employed in a very wide range of low, medium, and high power applications including residential applications, renewable energy systems, distributed generation, and automotive. Since digital control represents a key element of modern power converters, this paper presents a review on digital devices [microcontrollers, Field Programmable Gate Arrays (FPGA)], hardware and software design techniques as well as implementation issues useful for designing modern high-performance power converters.**

***Index Terms*—ADC, digital control, digital signal processors (DSP), field programmable gate arrays (FPGA), industry standards, microcontrollers, power converters, pulse width modulation (PWM), rapid prototyping, real-time control.**

I. INTRODUCTION

BECAUSE of the capability to efficiently manage electrical energy, power converters are employed in a very wide range of low, medium, and high power applications [1], [2]. In fact, while until a few years ago their primary use was in supplying motors in industrial applications and in transportation (trains, trams, forklift, golf-karts ...), in the recent years they are used in home appliances (refrigerators, washing machines, air conditioners, small tools, and in many other applications), electric vehicles, power systems (Flexible Alternating Current Transmission System, or FACTS) and in renewable energy systems (wind, photovoltaic, biomass \ldots). In the latter field, they are fundamental in interfacing electric generators to distributed generation systems, thus providing efficient operations of smart grids even during energy fluctuations.

Modern power converters, summarized in Fig. 1, basically consists of five parts: i) analog-to-digital section, providing signal conditioning and digital acquisition of electrical and mechanical quantities (usually current, voltage, frequency, position, speed); ii) a computational engine, necessary for algorithms implementation (filtering, identification, control, modulation of output signals and others); iii) a power electronic section, governed by the previous stage and operating as a digital power amplifier; iv) a communication section which is more or less complex depending on the final application; and v) a Human-Machine Interface (HMI), useful for setup as well as for monitoring functions. Nowadays, the computation engine consists of a microcontroller, i.e., a Very Large Scale Integration (VLSI) component incorporating a microprocessor core and Input/Output (I/O) peripherals, or, alternatively, an application specific circuit (ASIC), i.e., Complex Programmable Logic Devices (CPLD) or Field Programmable Gate Arrays (FPGA).

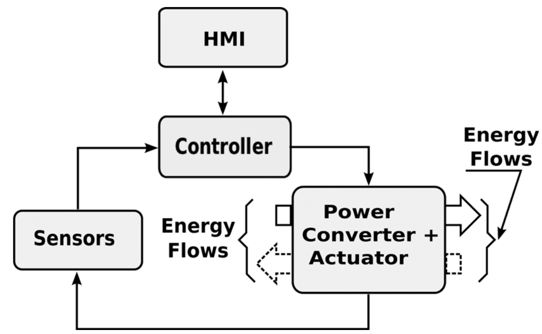

Fig. 1. Block diagram of a typical power converter-based system.

The main challenges for a power converters designer are the following:

- to manage the input/output energy, often with bidirectional flow, so that the whole process guarantees the highest efficiency while satisfying the expected operations;
- to offer a high grade of precision, flexibility, communication capability and reliability to the end user;
- to decrease the overall costs.

Since these goals greatly depend on the adopted computational engine and software, this paper attempts to analyse these strategic parts defining their main specifications, characteristics, performance and the tools needed for their development. As known and already pointed out, power converters may have three distinct uses: i) drive a motor or an actuator; ii) interface DC or AC sources with a load; and iii) improve power quality of a grid. More in detail, in case of drives, they operate the motors in such a way they achieve accurate speed and, or position tracking and disturbance rejection; in case of DC/DC converters they operate a DC to AC and AC to DC conversion, with the scope of adapting the input source with the load and eventually to allow bidirectional power flow, thus obtaining higher efficiency. In case of power quality applications, they improve power factor, reduce or eliminate electromagnetic emissions (EMI) and/or provide interconnection between power systems with different characteristics (usually: frequency, voltage, amplitude). In a distributed generation system (e.g., in a wind or in a photovoltaic system), it is used for extracting the highest amount of energy from wind, sun or another renewable energy resource, or to convert the electrical

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energy produced by fuel cells or electrochemical batteries in some usable forms, typically sinusoidal AC currents at 230 or 400 V, 60 or 50 Hz, and to synchronize the output voltage with the existing grid, in order to inject the produced energy in the grid without or with minimum power losses and maintaining system stability; additionally, they reduce the electromagnetic interferences (EMI) present in the mains.

To achieve the expected behavior in spite of nonlinearities and disturbances, a control system is needed in interacting with the converter on the basis of the sampled inputs and the expected outputs.

Early control systems consisted of analog systems, with many drawbacks including: i) the large number of parts, especially passive components, reducing system reliability and increasing hardware complexity and its space and energy demand; ii) the poor computational capability, often restricted to the implementation of simple proportional-integral controllers (PI); iii) the aging and the temperature dependence; and iv) the difficult reconfigurability of the controller, not possible without changing hardware circuits. However, whatever their limitations, analog controllers still remain a reference in terms of rapidity and bandwidth [3].

Since their introduction during the 1970s, digital control systems have become more attractive as they allow the implementation of complex control strategies with the powerful calculations and math-intensive algorithms. In the field of power converters and drives high-performance digital devices are needed as many or most of the advanced control techniques could not be implemented at all, due to their complexity and the very short control interval. Until the 1990s, power converters were mostly analog and could not handle the complexity of algorithms. The introduction of digital signal processors (DSPs) by Texas Instruments in 1983 [4], was restricted to the realization of expensive power converters with digital control, while simpler microprocessors were used in auxiliary functions, such as HMI, tuning of digitally controlled programmable analog amplifiers and few others. Industrial products with full digital control, instead, were available approximately during the second half of the 1990s. However, during such a long period, in Europe, Japan and USA, high-performance AC drive prototypes were proposed based on DSP, general purpose microprocessors like Motorola 68020 and 68030 [5], parallel processing systems, i.e., transputers and others. The latter were quite popular, particularly in Europe, because of their capability to overcome the limited computational capabilities of microprocessors and DSP by using more processors in parallel and operating concurrently [6]–[11]. But, in spite of their high performance and advanced characteristics, after some years they disappeared from the market.

From the software point-of-view, most of early systems were programmed using assembly language, only occasionally for overcoming complexity, high-level language as "C," Fortran, Pascal were adopted. An exception was the use of *occam* the only language available for the transputers (at least at its introduction as later other high-level languages were available) which was a Hardware Description Language (HDL) and, at the same time, a programming language [12].

Even if a huge number of experimental systems were proposed in the scientific literature, the large-scale diffusion of power converters with full digital control occurred at the end of the 1990s, with the availability of low-cost microcontrollers and DSC.

This paper attempts to present a general overview of digital systems for power converters and their tools, analyzing the main requirements in terms of required/available function and performance, illustrates the evolution and typical performance of current devices, and drawing future evolutions.

In the following, Sections II and III introduce the main concepts on how to develop high-performance power converters using state-of-the-art tools, highlighting the opportunities offered by the so called "Hardware In the Loop" approach. Section IV deals with basic requirements for digital controllers and reviews some current solutions based on microcontrollers. Section V discusses and analysis the opportunities and the use of Field Programmable Gate Arrays (FPGA). Sections VI and VII present a short review about Programmable Logic Controllers and general-purpose industry-standard buses/protocols, and finally, Section VIII discusses current advances and possible future trends.

It is worth noticing that many concepts introduced in this paper are not restricted to power converters and can be extended to many other fields of interest.

II. Digital Control Systems

Real-time (RT) digital control can be implemented using different technologies, basically:

- Microcontrollers μC.
- Digital Signal Processor-Based Controllers (DSC).
- FPGA or Complex Programmable Logic Devices (CPLD).
- RT Rapid Prototyping Systems.
- Programmable Logic Controllers (PLC).
- Industrial Computers based on industrial busses (VME bus, VXI and PXI boards and others).

The last two are only suitable for developing large and/or complex systems but they may not respond to the time constraints typical of electric drives or power systems, moreover, they are very expensive and encumbrant; in short, they appear not suitable for static converters.

Rapid prototyping systems are very useful for designing power converters. Since they may use the same microprocessor of industrial products, in these cases, once a laboratory prototype has been successfully developed, its software can be reused "as-is" on the actual system. This shortens and simplifies the design of complex systems and decrease their development costs.

Microcontrollers, DSC, and FPGA are the core of all present systems including previous categories. Hence, in the following, this paper deals only with them highlighting their characteristics, advantages, and drawbacks.

Table I summarizes the main properties of the above digital RT control applications.

III. Project Development

Because of the high complexity, design of power converters should be done using high-level design environments. A typical development cycle includes system-level simulation, circuit-level simulation, software and hardware development, prototyping, testing, and so forth. At the first step, the whole system

TABLE I
DIGITAL RT CONTROL APPLICATION PROPERTIES (HARDWARE)

Solution	PLC	ind-PC, VME ...	μC/DSC	FPGA
Reliability	high	high	medium	medium
Flexibility	high	high	medium	high
Advanced Algorithms	low	high	low/med	med/high
Costs	high	high	low	med/low
Rapid Prototyping	low	high	low/high	low/high
Power Converter friendly	no	no	yes	yes

is represented in terms of mathematical models which behavior is presently tested using programs like Matlab/Simulink, Octave, Scilab, PSim, PLECS, and so forth [13]–[17]. Hence, hardware development can be refined using Spice [18] or other circuit simulators: they allow a precise study and evaluation of electrical systems, thus optimizing the overall behavior of the power converter. Digital control system can be developed and tested using specific tools, such as Rapid Control Prototyping (RCP) and Hardware-in-the-Loop testing (HIL).

A. Automatic Code Generation

Many years ago when only low-performance processors were available, low-level languages without a specific and standardized design procedure were the only tools to write code for controllers. However, some companies made available tools allowing high-level graphical configuration of peripherals for specific microcontrollers, but they were not useful as expected and disappeared shortly. With the advent of high-performance processors, the design approach has significantly changed. Writing codes in high-level languages such as C or C++ has allowed the introduction of algorithms and test procedures that have improved the complexity, performance and reliability of designs and decreased the development time. In recent years, the trend was toward the environments with a complete set of standard functions, graphic user interface (GUI), ease of operation, and short training period [19].

Nowadays, there are many GUIs for generating codes automatically from preprepared block diagrams. Among them, MATLAB Simulink [13] and National Instrument LabVIEW [20], are the two well-known commercial model-based design tools for modeling, simulation and analysis of multidomain RT systems.

The LabVIEW Embedded Module and LabVIEW Real-Time Module are the add-ons to creating standalone embedded systems with an easy to understand and use graphical programming approach. Block diagrams translated into executable RT or standalone code by built-in "C"-Code generator to be deployed to the embedded platform [20].

Since MATLAB R2011a release, some of the previous tools and features have been merged and improved. Now, using MATLAB Coder, Simulink Coder, and Embedded Coder [13], generating codes for embedded processors to be used in RT and non-RT applications, including simulation acceleration, rapid prototyping, and hardware-in-the-loop testing is possible. For many applications, a design also includes a set of preexisting "C" functions created, tested, and validated outside of a MATLAB and Simulink environment. It is possible to integrate these functions into a model and the generated code easily. External "C" code can be used in the generated code to access hardware devices and external data files during rapid simulation runs. It is also possible to use an ERT shared library target (shrlib.tlc) to build a Windows dynamic link library (.dll) or a UNIX shared object (.so) file from a model. An application, which runs on a Windows or a UNIX system, can then load the shared library file. After that, it is possible to upgrade a shared library without recompiling applications that use it. Using these tools, many microcontrollers can be used in connection with a high-level simulation environment, greatly reducing the development time.

B. Hardware-in-the-Loop (HIL)

HIL simulation is a form of RT simulation which differs from pure RT software simulation by addition of one or several actual devices in the loop instead of their models. The other parts of the process are simulated using a controller board or parallel computers [21]. Indeed, implementation constraints are taken into account such as sensor accuracy, sampling period, modulation frequency, active limitations, and so on. HIL simulation is becoming more prevalent in the development and test of complex RT embedded systems by reducing development cycles, overall costs, and time-to-market. Another benefit of HIL is to validate tests before integrating it into actual processes and test operation and failure conditions that are difficult to physically replicate without damaging equipment. This method, starts from a pure simulation and gradually integrates real subsystems into the simulation loop due to availability and application. This technique is especially valuable when the simulation of a particular device is very difficult or the whole system is not yet built. With this approach there is no need for software developer to wait for a physical plant in order to write and test code [22], [23].

HIL simulation has been used for more than 40 years. One of the first uses of HIL simulation was for flight simulation and testing missile guidance systems; nowadays, its applications spans on power engineering, power electronics, electric grids, robotics, and many other applications. There are three different kinds of HIL simulation for electric drives referring to as signal-level HIL, power-level HIL, and mechanical-level HIL [24].

In Signal-level simulation, only the signal coupling between the RT simulator and hardware is considered. So, power converters, electric machines, and mechanical loads are simulated in RT while, actually, only the real controller board is tested. In power-level HIL, the actual controller board and the power electronics converter are tested and the other parts are simulated in RT. Moreover, to signal coupling, this interface requires power variables as well. Mechanical-level HIL simulation while involving the whole drive just the mechanical components are considered. There must be a link between the mechanical inputs and outputs to the electrical machine under test. Moreover, measurements on the mechanical parts have to be sent to the controller board under test [25].

IV. MICROPROCESSORS FOR POWER ELECTRONICS APPLICATIONS

Power electronic converters basically include: controlled-AC/DC converters (active rectifiers), DC/DC converters, DC/AC converters (inverter), active filters (AF), and power factor controllers (PFC) [1], [26]. Neglecting low-power systems (500 W or less), most of them incorporate a digitally programmable controller, implemented using a microprocessor or an application specific device (ASIC). In the following years, this level of penetration will suddenly increase due to the introduction of more restrictive regulations on energy saving.

A. Microcontrollers and DSC

Microcontrollers (μC) embed I/O capability (analog and digital), CPU and memory in the same chip. Often they incorporate a DSP core specifically designed for control applications rather than a general purpose core [27]–[33]. These chips are usually known as "motion control" microcontrollers, because of their early application in the field of drives, but actually they are suitable for a much larger number of applications, including DC/DC converters and AC converters for renewables.

Modern microcontrollers include a high-performance core (16 or 32-bit wide), a sufficient amount of RAM and FLASH memory (usually some tenths of kBytes, up to 1 MBytes for FLASH) and some peripherals: one or more analog to digital converters (ADC), one or more Pulse Width Modulation (PWM) units, necessary for generating output signals applicable to power converter drivers, two channel pulse counters for interfacing a quadrature encoder or other devices comparing two signals with different phases, a watchdog timer, useful for ensuring correct timing and one or more serial communication ports, for interprocessor communications or HMI. Often, the significant difference among microcontrollers and DSC is the amount of available memory (RAM and FLASH), but generally speaking all these devices are thought for Sistem-on-Chip development.

Current devices have very high computation capabilities, measured in million instruction per second (MIPS) and/or in MFLOPS (Million Floating Point Operations). The latter is specific for processors embedding a floating point coprocessing unit, very useful for increasing the computational performance in power converters which operate on complex numbers represented by trigonometric functions, or using complicated algorithms (e.g., Kalman filter or recursive least square (RLS) algorithm), where floating point operations are needed for obtaining a sufficient level of precision.

Nowadays, typical μC and DSC for "motion control" have throughput higher than 100 MIPS and 300 MFLOPS, respectively, but it is expected to grow very quickly in the future. In some cases, μCs are designed around a Reduced Instruction Set Architecure (RISC) core: single instructions are split among some sequential parts (usually fetch, decoding, execution, and write back), which are then executed concurrently as subunits, thus achieving a parallel pipelining of sequential instructions. Modern devices often use Harward architectures, i.e., two distinct paths for instructions and data flows, respectively. Examples of μC suitable for power electronics are, among the many others: ARM Cortex 3 [34], Infineon 167 [29], Renesas SH2 [28], while examples of DSC are: the Texas Instruments C2000 series (e.g., TMS 320F28069) [27], the Analog Devices series (e.g., ADSP-2199x) [35], and the DSPIC series (e.g., dsPIC30F4012) [36]. The following subsections deal with the peripheral requirements for microprocessors and DSCs for power electronics applications.

B. Digital Signal Processors (DSPs)

DSPs boost their performance over standard cores due to their "multiply and accumulate" (MAC) unit and where among the first single chip solutions used in power electronics. The TMS 320C14 was probably the first component specifically designed for direct digital control as it incorporated a multichannel ADC, some PWM outputs and a 10 MIPS, 16 bit processor [37]. Later, the 32-bit wide floating point DSP (TMS320C30) was introduced in 1988 [38] and used in many high-end systems. Nowadays, many high-performance processors utilize a dual bus Harvard architecture, where one bus is used for data flow and the other for program instructions and MAC units. Such an architecture saves time because the buses work independently and simultaneously. Usually, numbers are represented either as fixed point or floating point in all processors. Input data are obtained by analog to digital conversion using either 12 or 14 bit converters or 16 bit capture units (counters), therefore, 32-bit wide fixed point representation is sufficient for simple computations while floating point does not give any significant advantage. On the other hand, if the implemented algorithm is very complex and with many mathematical operations, errors accumulated during computation could not be acceptable. In this case, floating point representation greatly reduces the problem as it has a higher dynamic range compared to fixed point. Recently, 32-bit DSC incorporate floating point unit [27] at the cost of 16-bit fixed point DSPs, hence it is expected that they will become the new standard, at least in medium-high level systems and they will contribute to significant enhancements in this application field. Nowadays, the development of powerful DSPs have made it possible to use complex control techniques in power electronics converters field [39]–[43].

1) Communication Channels: Modern drives require large communication capabilities, hence μC usually incorporate high-speed serial channels and specific interfaces, like the Serial Peripheral Interface (SPI), suitable either for interprocessor or for high—speed peripheral communications (e.g., ADC, DAC, FLASH memory and others), Controlled Area Network (CAN) bus [44] (very popular in industrial and automotive applications), Universal Serial Bus (USB) [45], Ethernet. CAN, USB and Ethernet instead, are useful for interprocessor communications. Some recent microcontrollers, for instance, STM32W and Stellaris-Texas M3 include Zig-Bee connectivity [46], [47], i.e., wireless capability, WiFi is expected to become popular very soon, too: the first is becoming a standard in short range wireless communications, the latter allow effortless wireless connection with computers and many other devices.

2) Analog to Digital Conversion: Power converters incorporate current and/or voltage feedback, requiring analog inputs. For satisfying such a need, typical microcontrollers embed 12-bit or 14-bit A/D converters with sampling times of some 100 nanoseconds at most. Often, in order to maintain phase correctness among three-phase quantities, two or more ADCs are available in a single μC, eventually with Sample and Hold (S/H) input buffers, thus allowing to sample several input channels at the same instant eliminating phase shifts and delays. Multiple channels are managed through multiplexers. A typical

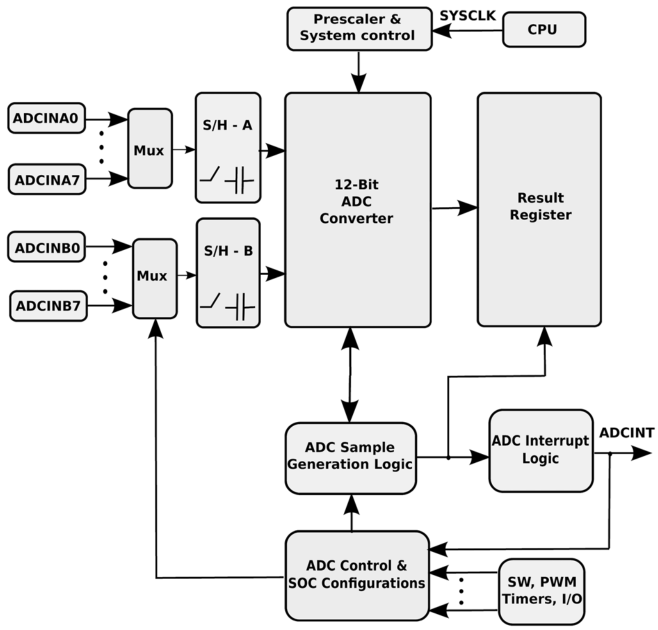

Fig. 2. Typical analog to digital conversion in microcontrollers.

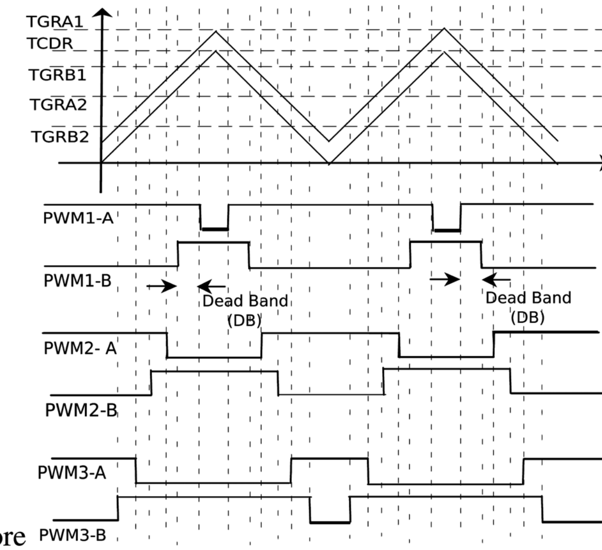

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Fig. 3. Three-phase complementary PWM output waveforms [28] (active low).

configuration is shown in Fig. 2. Sampled data are passed to CPU through interrupts or direct memory access operations implemented through memory sharing mechanisms. The latter eliminates overheads and latencies, typical of interrupts.

Recently, smart sensors providing digital output (e.g., [48]) and high-performance I/O ports (ADC, DAC, serial communication channels, FLASH memory, etc.) with the high-speed SPI or other incoming high-speed serial interfaces (e.g., USB-3) are becoming widely and economically available; it is expected that future high-performance microcontrollers may not incorporate internal ADC but they will be replaced by sufficient number of serial interfaces.

3) Timers Counters: Usually, microcontrollers incorporate timer/counters units, necessary for measuring or generating time intervals. These peripherals allow either to count input events (this function is usually called "capture") or to output signals as a result of a comparison between an hardware count, performed by the timer, and a reference signal, generated by the control algorithm ("compare"). In the past, these units were useful for counting encoder pulses for position or speed measurement, however, with the growing diffusion of sensorless drives [49], this function should disappear in a future; on the other hand, as pointed out in previous subsection, the new smart sensors require timers, hence they will alive but for a different purpose and it is expected that their number and performance will increase.

4) Pulse Width Modulation Peripherals: Pulse width modulator (PWM) is one of the most important μC peripherals as it provides the signals needed for commanding power devices (typically, MOSFETs and IGBTs) through driver circuits, i.e., buffers elevating the output voltage/current of the microprocessor and providing galvanic insulation between processing circuits and power. This unit must be able to generate complex pulse width waveforms with little or minimum CPU overhead, starting from the output signal generated by the general control algorithm. They need high programmability and flexibility, and they should be easy to understand and use. Present μC and DSC mostly include a six output, 16 bit-wide PWM, for direct interconnection with a three-phase inverter/rectifier and some additional units, which may be useful for driving an additional DC/DC converter, a Power Factor Controller (PFC) or another electronic power converter. In some cases, a second six-output or higher number of outputs PWM is available, too, thus enabling the command of a second inverter or of an active rectifier or a complex converter with a high number of switches. Usually, the operating frequency is scaled-down by the main microprocessor frequency and allows output signals in the range of some kHz, with resolution around some hundreds of nanoseconds. Recent DSPs include high-resolution pulse width modulator (HRPWM), operating at nanosecond level resolution. The PWM modules can operate independently (standalone) or they can also possible to chain them by synchronizing clocks, in order to operate as a single module. This allows either a higher number of outputs of higher resolution; the last allows either higher precision or a longer interval counting.

Usually, each PWM module has its own timer that determines all of the event timing, allowing three modes of operation: Up-Down, Up, and Down-Count. Moreover, specifying the output rising-edge and output falling-edge delays, suitable dead-band values can be imposed to inverter legs, thus avoiding short through between power devices during commutation without the need of external hardware. As example, two different approaches to generate three-phase complementary PWM output from [28] and [27] are shown in Figs. 3 and 4. Microcontrollers incorporate PWM-chopper submodules allowing a high-frequency carrier signal to modulate the PWM waveform. This function could be useful for decreasing the conduction losses.

PWM modules usually generate CPU interrupts at any event or trigger the ADC module start, thus allowing a fixed operational speed, very useful for achieving high precision control.

It is also expected that future μC will incorporate more powerful PWM units, for instance, with a higher number of independent digital outputs (e.g., 24 or 48), thus allowing a great simplification in multilevel or matrix converter design [50], [39].

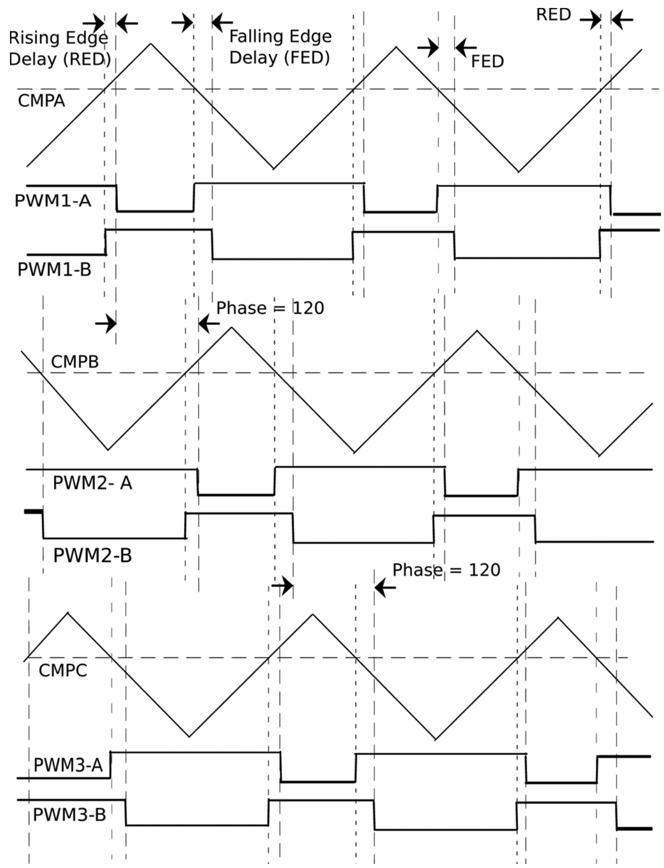

Fig. 4. Three-phase complementary PWM output waveforms [27] (active low).

Programmable phase-control support for lag or lead operation relative to other ePWM modules is also available in most μC.

V. Field Programmable Gate Arrays (FPGA)

ASICs represent another large family of devices which can be used in the development of high-performance power converters. CPLDs and FPGAs are the most common technologies used in ASIC.

Generally speaking, the FPGAs have more facilities than CPLDs to design more complex digital systems. CPLDs provide gate cells that can do all kinds of logic algorithms useful for digital control applications with fewer delays and lower cost than FPGAs. CPLDs are EEPROM based which can be activated at power-up by itself, while most of the FPGAs need to boot from nonvolatile storage because they are SRAM based. The design security is lower in FPGA and in some cases the designer might not have enough time to boot up the device.

On the other hand, FPGA in addition to more logic flexibility and much higher complexity, could also contain more sophisticated system features such as on-chip RAM, MAC unit, on-chip microprocessor/DSP, Multi-Gigabit Transceivers (MGT), etc. Implementation of FPGAs using computer aided design (CAD) tools is also possible.

FPGA usually consists of two-dimensional arrays of logic blocks and flip-flops with an electrically programmable interconnections [51]. They can be used to integrate large amounts of configurable logic blocks in a single Integrated Circuit (IC), which is entirely reprogrammable. Some of the major disadvantages of the conventional microprocessor or DSP controls could overcome by using FPGA, because it can be designed to perform any application and is not specific to a particular function. Also, the written code is almost independent from the architecture of the device and the hardware is reconfigured easily. Other advantages over other traditional devices are different and probably shorter design cycles, low-power consumption, and higher density for implementing digital control system [52]. The FPGA is suitable for systems which require relatively simple computation and fast processing time; complex control algorithms with complicated computations could be easier implemented by software in the FPGA, as they may embed a true microprocessor. The results of this co-design is increasing the flexibility of the designed system and reducing the development time [54]. The speed, size, and the number of I/O pins of a modern FPGA far exceeds that of a microprocessor or DSP.

When FPGA was introduced by Xilinx in 1984 [55], it provided only peripheral interface to main processors. Today, they allow the design of very complex and high-performance digital control systems, incorporating all necessary functions (computational capability, input and PWM output). Altera and Xilinx are two main vendors, also a well-known names. Lattice, SiliconBlue, and Actel are other brands [56]–[59]. Making high-performance processors to implement complex parallel arithmetic architectures could be easily done using FPGA. The Fusion family from Actel was the first FPGA integrating ADC and other basic analog devices, thus allowing system-on-chip applications [60]. Recently other firms have introduced mixed signal (analog and digital signals) technology. A detailed schematic of the FPGA-based digital platform is depicted in Fig. 5. As shown in this figure, the interface board provides all the usable I/O lines as well as the ADC input and DAC output lines from the FPGA board. For communicating with the PC, RS232 or USB or Ethernet could be used on the interface board. For standalone working in RT without the intervention of a main PC, the keyboard and LCD might be used [61].

As mentioned before, each of the analog and digital controllers have some advantages and drawbacks. Cumulating the advantages of both, it is obvious that a quasi-analog controller by digital means that could execute a control algorithm quasi-instantaneously, should be of great interest. FPGA is a good candidate for this kind of controllers [62].

In recent years, motion control and power conversion using FPGA technology are receiving increased attention because of their complex modulation scheme ability and high-speed switching requirement. The first application of FPGA in motor control was started in 1994 and continued rapidly after that [63]. Now, they are used in various tasks from the main controller in motor control applications, to control the whole system. FPGAs have already been used with great success in power converter control such as PWM inverters, power-factor correction [64], DC/DC resonant converters [65], multilevel converters [66], matrix converters [67], soft switching [68], and STATCOM [69]. In the field of motion control, they have vastly used in Brushless DC motors, induction machine drives, switched reluctance machine drives, fuzzy logic control of power generators, speed measurement, and so on [70], [71].

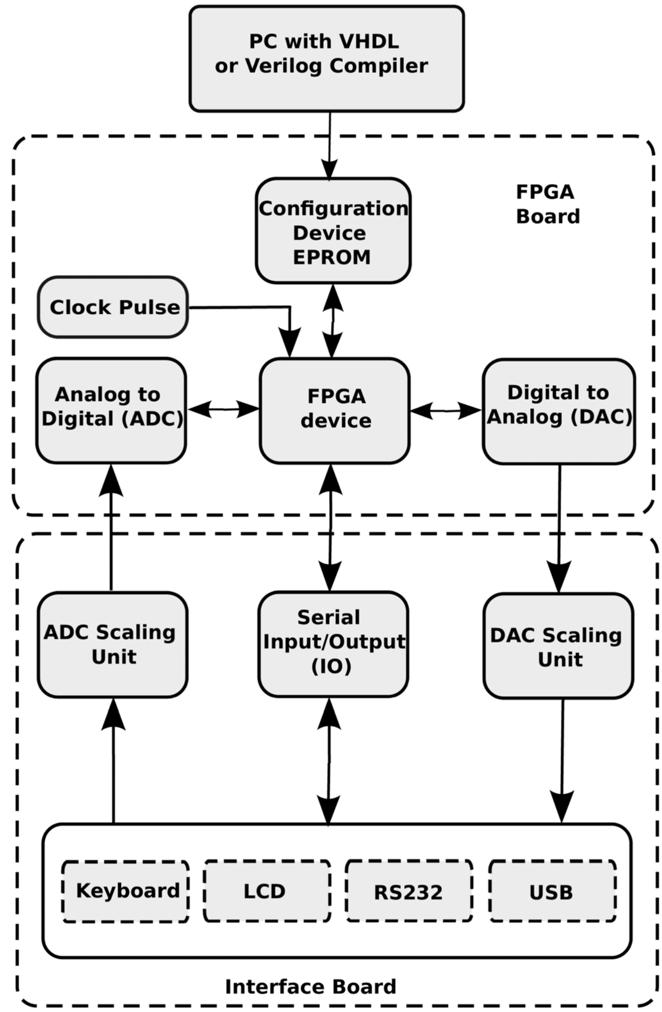

Fig. 5. Block diagram of FPGA-based digital platform.

We can determine whether to use an FPGA as a coprocessor or as a complete SoC (System on Chip) solution. Sometimes it is useful to combine DSP with FPGA so that DSP provides to complicated calculations while FPGA takes care of the rest, as shown in Fig. 6. It is possible to combine standard host processors with FPGAs on the same board, with the external host processor performing system processing. By moving some of the processing tasks inside the FPGA processor overhead can prevented. Alternatively, integrating all processor functions on a single FPGA-based SoC platform is possible to simplify design complexity and reduce system costs.

The FPGA's ever-increasing density makes it possible to easily integrate one or two RISC processors to be a complete system-on-a-programmable single-chip solution. Designers of motion control systems now developing single-chip solutions for controlling complex systems to achieve both high levels of integration and low cost. With combining advantages of different modules, it is possible to integrate a microcontroller such as ARM Cortex-M3 [72] or MicroBlade [73] with the additional advantage of enabling hardware acceleration for functions implemented in FPGA fabric. Combining these capabilities with configurable analog, results in high efficient single-chip motion controller.

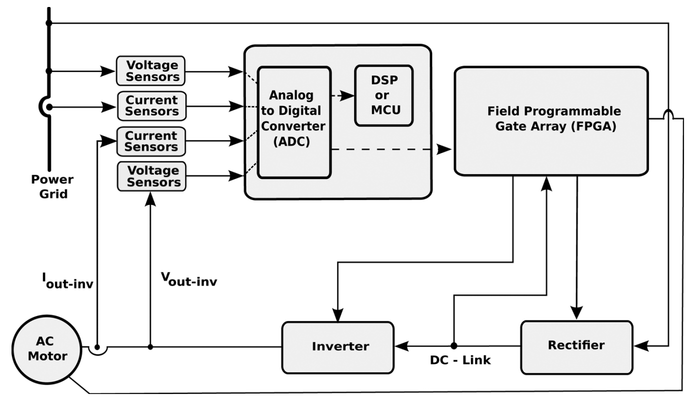

Fig. 6. FPGA-based motor drive.

The classical design flow tool for FPGA is Verilog and VHDL (Very High Speed Integrated Circuit Hardware Description Language) but programing in this way in designing controller for complex systems, needs a great deal of time and as a consequence, long time-to-market and high cost of the production [74]. When a rapid prototyping procedure is desired, HDL automatic code generation is directly possible with automatic HDL code generators like Simulink HDL Coder™ [75] or National Instrument's LabVIEW add-in module [76]. This method fits control engineers as well as rapid prototyping needs. When good control performance is required, coding must be done in HDL that leads to substantial efforts during the design of the hardware architecture [62].

VI. Programmable Logic Controllers (PLCs)

A Programmable Logic Controller (PLC) is a standalone microprocessor-based control modular system which is using both analog and digital signals as inputs and making decisions by executing prewritten programs actuated by analog and/or digital outputs, the later available in a wide range of options (5, 24, 120–230 V, etc.). These devices are suitable for multiple I/O arrangements with a high modularity, resistance to electrical disturbances and wide temperature ranges when little electrical design is required [77]. For many years, they have been used in many industries and in the power system infrastructure for automation processes. They can communicate through Ethernet, RS-232, RS-485 or RS-422, etc., and modules are available for almost all industrial busses (e.g., PROFIBUS, PROFINET, etc. [78]). For writing a control logic into PLC various softwares are available like SIMATIC STEP 7 [79] by Siemens or RSLogix 5000 provided by Rockwell Automation [80]. Different manufacturers produce PLCs with exclusive memory organization, I/O addressing, and instruction sets. So, even if the general concept is identical in all PLCs but written programs are not changeable between them. This is a significant limitation and one of their drawbacks [81].

They were typically employed in industries where the cost of maintenance and development is relatively high due to the total cost of the automation, especially when future changes to the system would be expected, or easy maintenance is fundamental. In fact, due to their generality, they can be easily adopted in many different situations and replaced at low cost, when needed, even in a remote location or in a harsh environment. Regarding our main purpose in this paper, because of PLC-based system's response time, high cost, and complexity they are not very sufficient to use in power converters control.

VII. Real-Time (RT) bus System Architectures

General-purpose industry-standard buses have been around for more than three decades. At first, Rack-and-Stack instruments were the preferred architecture for designing test systems. The industry standard communications path between instruments and computers typically equipped with GPIB. Later on, the modular architectures like VXI and PXI got popular for companies and engineers. Following is the short review on some of the important Industry RT bus system/protocol standards.

A. GPIB

For more than 40 years, digital systems have been available in market place, beginning with the first digital functional systems introduced in the late 1960s. In the 1980s with the introduction of GPIB (General Purpose Interface Bus) based architecture by Hewlett-Packard, integration and control of a flexible digital subsystem as part of a custom system made possible. GPIB was standardized as the IEEE-488 industry standard for communication between instruments and computers and many instrument controllers came with built-in GPIB interfaces [82]. The test software, written in Basic, Pascal, or Fortran and the instruments returned ASCII data back to the computer. Consequently, the test system architecture was rack-and-stack instruments which was the dominant architecture for a long time. In the early days of the Personal computers, RS-232 and a parallel interface were the only built-in standard I/O for the computer. As a result, engineers needed to insert a GPIB interface card into an empty PC slot to use it as an instrument controller. Nowadays, with LAN to GPIB and USB to GPIB converters, control of traditional GPIB instruments could be done directly without inserting any interface card [83]. Due to their limited performance, this standard was never of interest in power converter design.

B. VME, VXI

The VMEbus (Versa Module Eurocard) was first introduced by Motorola in 1981 and it became a preferred bus in a short time [84]. Because of its good performance and high bandwidth, its competitors such as FutureBus and Multibus have disappeared shortly. The VME bus module is now integrated into a single chip on board with other IP cores to simplify hardware design complexity and improve the robustness and the stability of systems. One drawback to VME is that it is an asynchronous bus and the total bandwidth in a VME system is shared between the devices. Furthermore, the synchronization capabilities that many applications require cannot be achieved directly over VMEbus [85]–[87].

VXI (VME bus eXtension for Instrumentation) introduced in 1988 that added timing, triggering, and synchronization features needed to the VME architecture that changed the discrete rack-and-stack instrumentation to a more modular card-based system. VXI offers much faster transfer rates and also smaller size and the standards necessary to combine the VMEbus with GPIB that could meet the needs of future applications [88].

By the late 1990s, VXI-based digital systems became the most dominant architecture for digital subsystems. The first significant change in the standards was the definition of 64-bit bus systems in 1995 that resulted in doubling of the bandwidth. VXI-based test systems could be controlled via an extemal PC over GPIB or MXI (a special link for VXI). Due to their high computing capability and ruggedness and the availability of high-speed ADC/DAC VME boards, this standard was often employed in the 1980s and 1990s for research and development of high-performance digital inverters.

C. PXI

With the increasing availability of high density and high-performance analog electronics such as CPLDs and FPGAs, National Instruments introduced another modular standard named PXI (PC1 extensions for Instruments), based on the Compact PCI bus in 1997. PXI uses the two most diffused buses, PCI and PCI Express, which is the fastest-growing standard since GPIB that meets the demands of modular instrumentation [89].

PXI Express technology is the latest addition to the PXI platform, which increases bandwidth and enhances timing and synchronization [90]. It is a synchronous bus and each of its devices has a dedicated bandwidth. It is also possible to have peer-to-peer communications bypassing the root chipset, which increases the efficiency by reducing the system bus utilization. As an example in [91], compact PCI/PXI chassis with high voltage boards which utilizes DC-DC HV converter shown using LabView with remote monitoring and control of modules over the Ethernet. The high voltage cards can be easily adopted to a particular voltage and current requirement.

D. LXI Bandwidth

LXI (LAN extensions for Instruments) are instrument modules which have the advantage of being small in size, modular (like VXI and PXI), and self-contained (like an instrument) so they do not need an expensive cardcage enabling them to use off-the-shelf PCs and low-cost LAN cables. LXI modules can be mixed and matched in the test system as needed and could be configured with software to make various types of measurements. LXI modules use a combination of external triggers and IEEE-2588 timing and synchronization. Measurements begin with external trigger based on a random external event. IEEE-1588 timing will provide tight synchronization between modules over the LAN [92].

E. PMBUS

In recent years, there were a lot of endeavors to comprise power electronics devices in communication platforms to have more flexible and efficient power control and monitoring. Most of today's systems are using digital solutions from various suppliers and consequently require different GUIs from each of them to configure the system. Standardization may help digital designers in developing software packages that will communicate effectively, no matter what controller from which supplier they are using. With the flexible standard communication between devices based on both analog and digital technologies, there will be a reduced design complexity and shorter time to market.

The first attempts in the standardization of power management functions was the dynamic voltage scaling for microprocessors via Voltage Identification Codes (VID). Another step in this regard has done by the Z-One power and communication bus architecture. The PMBus™ (The Power Management Bus), which is an open standard power-management protocol introduced in 2005 [93]. This protocol is implemented over the industry-standard SMBus (System Management Bus) serial interface and enables configuring, control, and RT monitoring of power system devices such as isolated DC/DC converters. The integration of the processing system with programmable logic offers high-performance and low-power consumption comparable to ASIC, suitable for microprocessor powering Voltage Regulator Modules and offline AC/DC power supplies [94]. PMBus has a comprehensive set of commands that facilitates communication between different devices and the central processor or host.

F. Hybrid Architectures

In addition to cost, size, power consumption, and monitoring capability, new designs should also be able to integrate with other manufacturers off the shelf products in an environment containing a large variety of electronic equipments. Many large automated test systems require more digital channels than one module can provide. In this case, several modules need to be linked together to form a multiple hardware platforms. All modules within a single platform will use the same timing sets allowing all channels to run synchronously. For large test systems, it is very difficult to cover all instrumentation needs in a single platform, making integration of multiple platforms an absolute necessity.

With combining components from multiple hardware platforms, such as VME, VXI, PXI, GPIB, USB, and Ethernet into one single system, hybrid systems arose [95], [96]. By using these systems, it is possible to integrate various components into their existing systems with a layered architecture as needed without a complete redesign. Hybrid system architecture helps to take advantage of both VME equipment and newer technologies such as PXI that greatly enhances upgrade and maintenance processes. However, not all interfaces provide equivalent performance, so in addition to I/O port availability, integrators should consider performance implications.

VIII. Current and Future Trends

As the embedded market grows, significant changes happen both in design and manufacturing. The trend is toward multiprocessors and systems on chip with heterogeneous hardware cores. Future multicore probably will work independently without a need to any central controller, and will have some level of adaptivity to changes both in system and environment during the RT operations. This will simplify the cooperation between different processing units and avoid problems with failures in some parts of the system. Currently, some of the manufacturers are combining embedded technologies together to form a single solution in one integrated chip to have reconfigurable features for allowing the change in hardware functions without interrupting its run. As an example, SmartFusion from Actel combines a ProASIC 3 FPGA fabric, advanced mixed-signal capabilities, and a ARM Cortex-M3 processor into a single device [73]. User-customizable ARM-based SoC FPGAs by Altera are available in the market [97]. Another example is the Zynq-7000 family of Extensible Processing Platform (EPP) products, which combines an ARM dual-core Cortex-A9 processing system with Xilinx 28 nm unified programmable logic architecture [98]. While each device in the Zynq-7000 family has the same processing system, programmable logic and I/O resources could vary between devices to serve a wide range of applications as needed.

The integration of the processing system with programmable logic significantly increases the functionality and utilization of hardware resources and decreases power consumption comparable to ASIC. It also offers the flexibility and efficiency of an FPGA and the ease of programmability of a microprocessor. This integration enables high bandwidth and low latency for RT industrial networking interfaces and motor control systems.

Other attempt in the architecture change is to use separate processor cores in a single chip with different functions. In this manner, each subprocessor is capable of running independently (having different DMA, memory, and clocking) that allows to separate Control from Host functionality. With this integration, it is possible to have RT control and advanced connectivity in a single device.

One example for this kind of multicore and multi-subsystem is the Concerto F28M35x microcontrollers which combine Texas Instrument's C28x core and control peripherals with an ARM Cortex-M3 core and connectivity peripherals [99]. Applications such as solar inverters, intelligent motor control, smart grids, and electric vehicles could benefit from separating communication and control issues in a single-chip solution. Complex converters with cascaded modules (e.g., DC/DC converter + inverter) can be easily realized, too. As an example, in a typical automation or power drive application, the Control subsystem can handle the variable-speed motor control across multiple motors, while the Host subsystem forms the communications bridge and monitors the motion profiles and overall system management.

IX. Conclusion

Digital control systems revolutionized the industrial world virtually eliminating those drawbacks typical of analog systems and allowing the diffusion of sophisticated control techniques, not applicable without them. In the field of power converters, they were fundamental for the evolution from DC drives with analog control and relatively high efficiency and performance, to high-performance AC drives with modern and energy efficient techniques, like vector and sensorless control. Recently, they are driving the grow of renewable energy systems. Nowadays, almost all power converters except those with very low power, include one or more microcontrollers, DSP or Application Specific Integrated Circuit (CPLD, FPGA) or a combination of them; in low-power systems based on custom chips a digital controller is usually embedded in the form of hybrid ASIC. At the same time, they are gaining new applications and in a future they will be employed wherever power or energy must be controlled.

This paper attempted to give an overview of this field describing its main problems, analyzing present systems and drawing some potential developments.

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