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Article

Control of Power Electronics through a Photonic Bus: Feasibility and Prospects

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Abstract: The ubiquitous diffusion of Power Electronic Converters (PECs) in many fields of application including traction and energy conversion is suggesting the possibility of new and better integration of advanced power conversion and ICT services. This work investigates the possible advancements in the use of optical fibers for control of PECs, using Plastic Optical Fiber. The optical communication link connects the switching control to the converter control, following the line of separation between the expertises of the power electronic engineer and the control engineer. Control wise, the PEC becomes a black box compatible with any off-board controller, now immune from the Electromagnetic Interference (EMI) produced by the power switches. The redundant optical link is ready for the high switching (and sampling) frequencies possible with the use of SiC power semiconductor devices (100 kHz+). Distributed control of multiple PEC units and advanced telemetry for diagnostics and prognostics are targeted. A proof-of-concept demonstrator is presented and tested. Moreover, the possible evolution towards a power electronic cloud with remote management and orchestration is described.

Keywords: Plastic optical fiber, power electronics, remote control, SiC power devices

1. Introduction

Power electronic converters (PECs) are assuming a fundamental role in the modern society. Their growing diffusion is driven by the progress of transportation electrification (electric vehicles, more electric aircraft) and the new needs of energy grids (distributed generation from renewable sources calling for distributed power electronics, as well as EVs charging infrastructures and energy storage needed to handle the grid stability). The scaling demand for power conversion triggerered the developement of new devices such as SiC power mosfets that were considered too costly and unreliable until very recently.

This work deals with advancements in the use of optical fibers for control at switching level of PECs made with SiC power devices, aiming at the definition of a serial communication standard for the control of the PEC using Plastic Optical Fiber (POF).

In the literature, optical fibers are applied to PECs in different suboptimal ways, such as to command the gate drivers of the power devices, to sense their junction temperature, or to supply the gate drivers through power over wire in high voltage applications [1],[2],[3]. In all the reported cases, the optical link is used in "one signal per fiber" manner. In the late '90s the US Office of Naval Research promoted the standardization of PEBBs (Power Electronic Building Blocks) for shipboard power electronics [4], later adopted by ABB and other industrial players for medium and high power converters [5]. The PEBBs are "power processors" including power hardware and sensors, with minimal digital intelligence on board dedicated to hardware protection, execution of switching commands and serial communication with an external controller. The serial communication from the PEBB to the converter control unit is often realized with plastic optical fibers (POF): the dedicated communication

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protocol PESNet was developed, running on a 125 Mb/s serial communication line implemented on a Hard Clad Silica optical fiber [6]. The control architecture of PEBBs was formalized in [7], for 1MW+ power electronics. In turn, the main focus of the PEBB projects was on standardization of the power blocks, pursuing a system-level approach to the design of power electronic converters rather than on exploiting the advantages of optical communications. The efforts on the communication link were all in the direction of composing multiple blocks to make one single PEC, i.e. synchronization between modules, fault tolerance and plug-and-play features [8],[9]. Dealing with industry applications, the most significant result of the PEBB approach is the AC 800PEC controller from ABB, capable of controlling up to 36 synchronized PEBBs via the proprietary optical PowerLink protocol, with a cycle time of 25 μs. This was released one decade ago and was meant for rapid prototyping of PECs, and takes advantage of model-based design in Matlab/Simulink and Matlab embedded coder. A good review of communication protocols for PECs is in this recent publication [10]. Moreover, Aurora 8B/10B by Xilinx is used for hardware in the loop (HiL) testing of a PEC controller [11].

Despite the cited examples, the use of optical fibers in PECs control remains limited in everyday power electronics, missing to catch the new opportunities arising from higher demand and new power devices. This work proposes an original protocol for real-time control of PECs using POF. In accordance with [7], the optical communication link is placed between the switching control (on board of the PEC) and the converter control (off the PEC), on the line of separation between the expertises of the power electronic engineer and the control engineer. In this way, the digital hardware on board of the PEC is minimized and purposedly designed to be EMI-immune and reusable for any PEC structure, in standardized manner. Therefore, any real-time controller can be associated to the PEC via the optical communication, not subjected to the EMI produced by the power switches nor to any related design restriction.

One discontinuity with the past is that the priority here is to optimize the use of optical communication for one single PEC, targeting the exploitation of new SiC power modules. These power devices permit higher switching frequencies at the cost of more severe electromagnetic interference (EMI). The keys to make this idea successfull are that the communication protocol must be:

- as fast as possible, to minimize the overhead time required by data transmission and decodification;
- as simple as possible, foreseeing its implementation on a low-cost, dedicated integrated circuit.

Short overhead time permits to push the switching (and control sampling) frequency to the higher limits possible with SiC power MOSFETS (100kHz +). Room for more data permits more feedback data signals to be added for PEC diagnostics and prognostics computed off board.

A proof-of-concept demonstrator was presented, capable of controlling a 100W-brushless servomotor via a three-phase voltage source inverter [12]. The demonstrator utilizes a Xilinx Artix FPGA and integrated optical transceiver for ease of development. The goal of this paper is to finalize the approach towards a standardized, dedicated integrated circuit. As byproduct, this will be applicable also to modular PEBBs, i.e. to the composition of multiple converter modules as building blocks, for example in multi-level converter architectures with distributed control. Although not explicitely optimized for, the proposed protocol is already capable to manage 10+ devices in real-time using time-division multiplexing, with a distance of 40m between each node.

One foreseeable application is in the field of real-time hardware for development of PECs control. Key players in this field [13] would benefit from a standardized optical interface for commanding PECs, both for rapid prototyping and HiL.

Moreover, the proposed technology will enable power electronic clouds of power electronic systems that will possibly benefit of a software-defined remote management and orchestration. Telemetry data from the power electronic cloud will be exploited together with aggregated data from users for a holistic optimization.

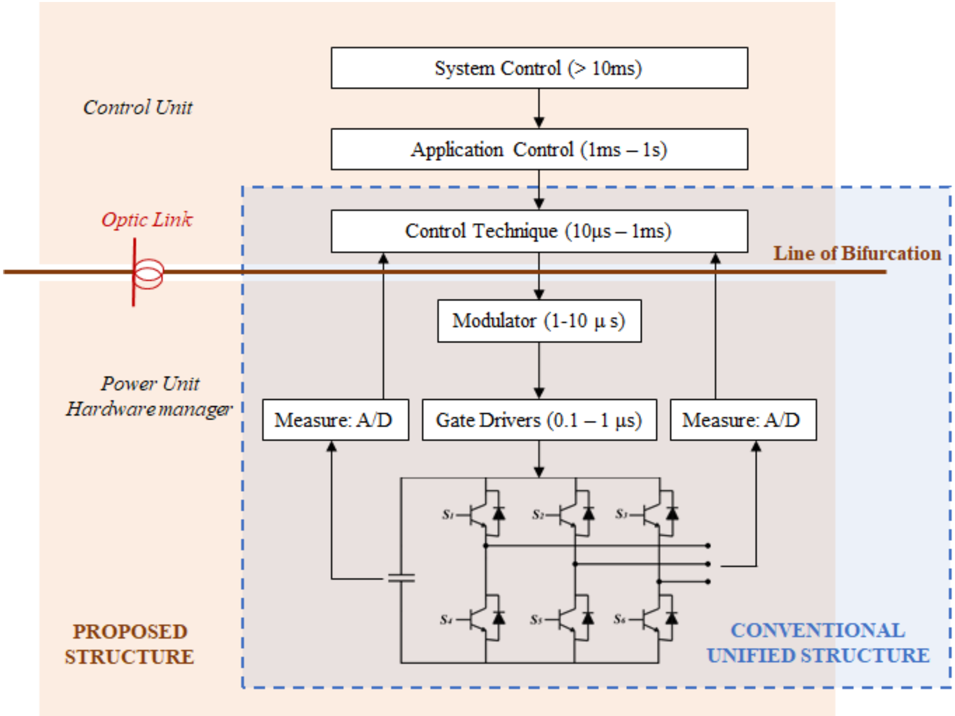

Figure 1. Common control layers for a PEC. Conventional and proposed solutions are highlighted.

2. Data Communication in Power Electronic Converters

Data communication in a PEC has been formalized in [7] as reported in Fig.1, following the organization by layers typical of data networks (e.g., ISO/OSI). The system control defines the objectives of the power electronic system and directs the functioning of application control layer towards that end. The converter layer subsystems that fall beneath the application control layer can be mimicked by a controlled current or a voltage source. The converter control layer implements the functions by determining the voltage references to be sent to the modulator (if any) of the switching control layer. The bottom-most hardware control layer manages the power devices.

A pertinent example is a wind farm where the power system operator (system control layer) dictates the required active and reactive power injection into the grid. The application control layer decides upon the working of each individual wind turbine (converter control layer) considering the optimum efficiency, reliability and maintenance.

It is emphasized that the latter two layers – switching and hardware control layer – are independent of the final application and are common for any PEC. This forms the basis of the replicable and modular PEBBs with minimum on-board intelligence to implementing switching control functions and a communication link to an external controller which, in turn, facilitates distributed control architecture and remote processing. A conventional PEC has a Microcontroller Unit (MCU) on-board for converter control, as depicted in Fig. 1. In the proposed structure, instead, the PEC ends with a switching controller, called hardware manager in [8], and delegates the converter control to an off-board control unit upstream via the optic link.

3. Photonic bus: Implementation and protocol

The photonic bus connects the Control unit and several PECs configured in a daisy chain through a bus made of a fiber pair. In the following, downstream refers to the command flow going from the control unit to the PECs while the upstream refers to the data stream from PECs to the control unit.

As commercially available fibers and transceivers are targeted, a pair of optic fibers are employed – one fiber for up-streaming and the other for down-streaming – to connect the Control unit to the first

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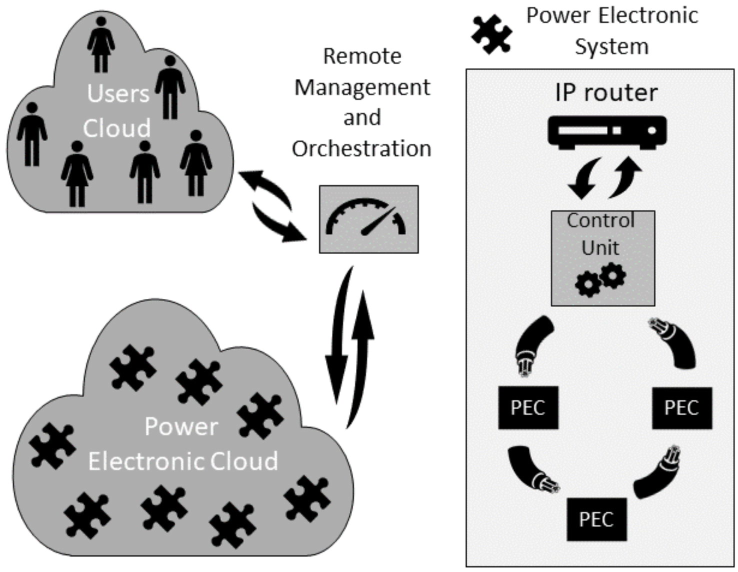

Figure 2. The daisy chain control scheme (right inset) as an element of the power electronic cloud

PEC, and each PEC to the following one. Such fiber pairs are widely commercially available from the main plastic optical fibers manufacturers and are directly compatible with transceiver optolocks. Couplers/splitters have been developed for plastic optical fibers as well, thus allowing the use of a single fiber carrying both upstream and downstream transmission, but they are not common as they introduce a distance penalty due to their high attenuation.

The daisy chain of many PECs is built using two transceivers on each PEC. Both downstream and upstream messages are received, decoded and then forwarded to the next node, down the chain for downstream messages or towards the control unit for upstream messages. Each PEC has its own address in the bus, which is used to correctly receive messages from the control unit or to tag the upstream data sent by the node. Given this decode-and-forward point to point structure, no collision is expected to happen in upstream transmission.

Besides the enumerated advantages of the optic link, it facilitates the integration with cloud and thus follows the Internet of Things paradigm. As displayed in Fig. 2, the Control Unit can be connected to an IP router to enable networking among several power electronic systems within a Power Electronic Cloud distributed in the Internet, according to the paradigm of the Internet of Things. The daisy chain control bus, besides enabling a remotized control by the Control Unit, may transport telemetry data that can be conveyed through the Internet in upstream, or may deliver in downstream the commands coming from the Internet to each PEC. So, the power electronic systems are virtually placed within a cloud relying on the Internet data transport to connect systems one to each other. Such a paradigm may enable the implementation of software-defined remote management and orchestration aimed at optimizing management of different systems and orchestrating their collective effectiveness. Depending on the specific application, the orchestrator could also benefit from the data from a cloud of users that may greatly help in optimizing the overall effectiveness of the power electronic cloud. An application field for which this approach could be largely beneficial is the generation of electricity from renewable sources. In this case, the power electronic systems are electricity generators – solar cells, wind turbines, etc – and the users are families and companies delivering data on power consumption.

3.1. Description of the protocol

Figure 3 describes the timing organization of the sampling and switching task. The switching frequency of the power devices dictates the sampling and switching period of the PEC. This is marked as T_{PWM} in Fig. 3 although not necessarily meaning that all PECs use Pulse-Width-Modulation. Typical

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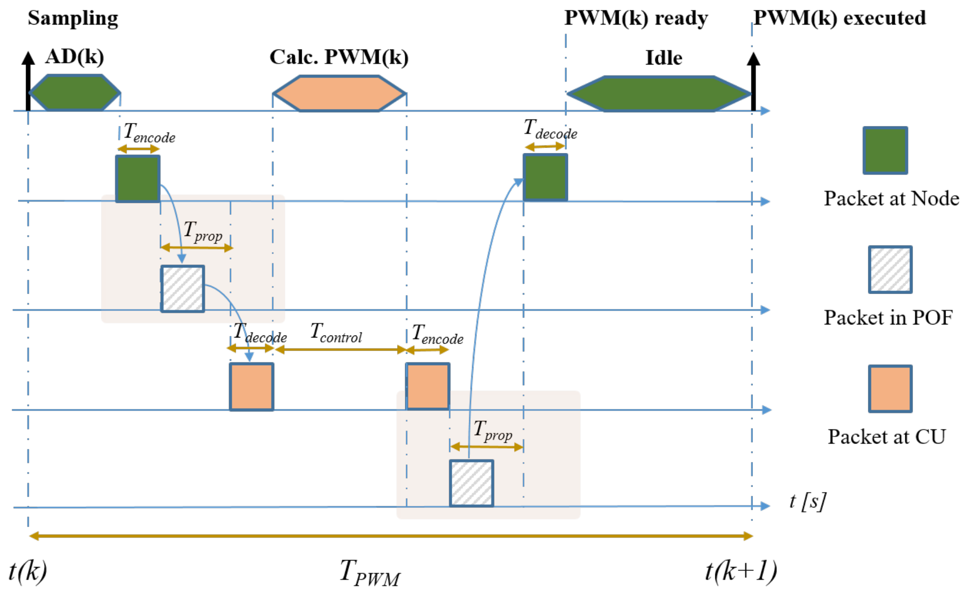

Figure 3. Timing diagram of the proposed optical link.

switching frequencies are in the order of 10 - 20 kHz, but the use of SiC power semiconductors is pushing these numbers higher, to 100 kHz and more in some cases.

At $t(k)$, the current flowing in the inverter legs is sampled by the ADC converters on the power unit (node) and is ready to be transmitted to the control unit; the time needed to transmit (T_{encode}) and receive the packet (T_{decode}) is the time needed to perform the parallel to serial and serial to parallel conversion of the 66bit words used by the 64/66b line protocol used, plus the protocol encoding and decoding overhead and the latency introduced by the clock and data recovery logic. T_{prop} is the propagation time of the light along the optical fiber; some time ($Calc.PWM(k)$) has to be reserved to the algorithm execution in the control unit microcontroller, while some idle time at the end of the cycle is needed to ensure that the new PWM values are correctly updated before the next cycle starts.

The overall Transmission time is defined as one-way total time to pass the data packet from one node to the other.

3.2. Transmission Overhead

Respect to a standard PEC control scheme, having the MCU on board, the optical communication introduces a time overhead equal to two transmission times. It is thus important that the transmission time is as negligible as possible, respect to the switching period. A transmission time in the order of $1\mu s$ is considered negligible. Figure 4 shows the ideal protocol performance, obtained considering only the bitrate of transmission and the propagation time of light in the plastic fiber, without taking in account implementation dependent latency overheads.

Our transmission protocol is based on 132bit packets, encoded as a couple of consecutive 66b words: the first word is tagged as /START (Block field type 0x78), while the second is tagged as /STOP (Block field type 0xFF), so each packet is able to carry up to 14 bytes of payload. The 66b sync header is always set to "10", i.e. control + data words.

Of these 14 bytes, the first byte contains the node address in the daisy chain (destination in the downstream from control unit to power node, or source node in the upstream from the nodes to the control unit), while the last byte is used to read/set discrete I/O pins present on the node itself. The remaining 12 bytes are organized as six 16 bit words; they contain ADC sampled data in the upstream channel and PWM duty-cycle values for the downstream. Further extensions of the size of the packet must consider the rules of the line protocol, so they can be done adding 64 bit data words (66 bits

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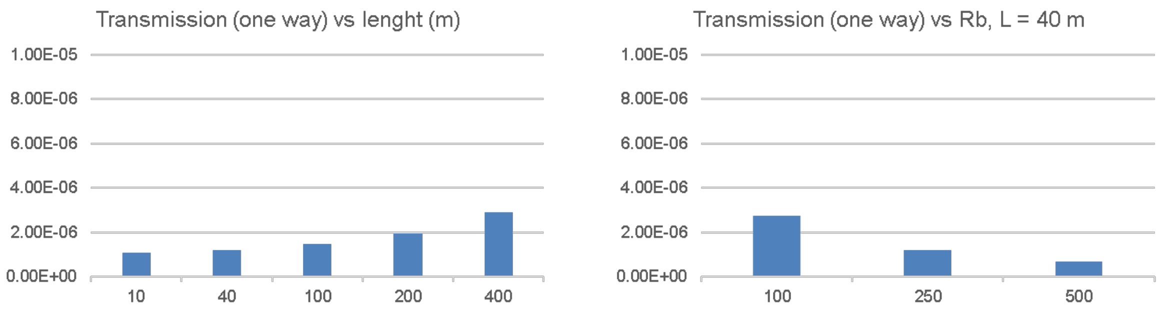

Figure 4. Sensitivity of transmission time to line length, bit rate and number of 16-bit words

when coded, marked with header 0 1) between Start and Stop frames. When data packets are not transmitted, the channel is filled with /IDLE words (Block Field 0x1e), as shown in Fig.5.

4. Proof-of-Concept Demonstrator

When building the proof of concept, in addition to the timing requirements explained in the previous section, the total cost and the relatively short fiber distance requirements are also considered. The system cost and ease of use constraints promoted in choosing an integrated, tool-less transceiver solution commercially available: the optolock design allows for establishing a connection by just cutting the fiber ribbon with a pair of scissors and locking it into the correct position. As short distances are targeted, POF optical bandwidth does not deteriorate received data; hence, it is not necessary to reconstruct the transmitted waveform using A/D conversion and filtering implemented in Digital Signal Processing [14].

The fiber itself is a simple PMMA Poly Methyl Meta Acrilate plastic fiber, standardized as A4a.2; it has a large core diameter (980 μm) covered with a thin (10μm) layer of cladding, so it can be deployed without using specialized tools, but it has two main disadvantages, a large attenuation (180dB/Km using red light at 650nm, such as the one used by the transceivers we have chosen) and a low bandwidth length product (about 40MHz per 100m), which limit the possible maximum length and the maximum data rate.

The strict real-time requirements impeded to relying on a Forward Error Correction code as the Reed Solomon 237,255 used in [14], limiting the link length to the 40m at 250Mb/s declared by the transceiver manufacturer. In order to successfully operate the optical channel, both DC balancing and an adequate data transition density are needed: these requirements are fulfilled by adopting a line

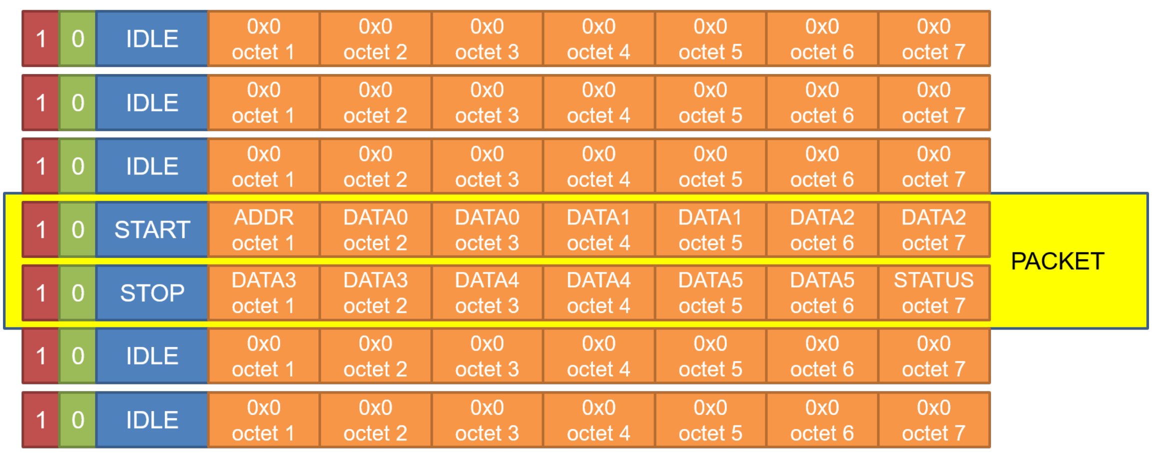

Figure 5. Example of packet flow.

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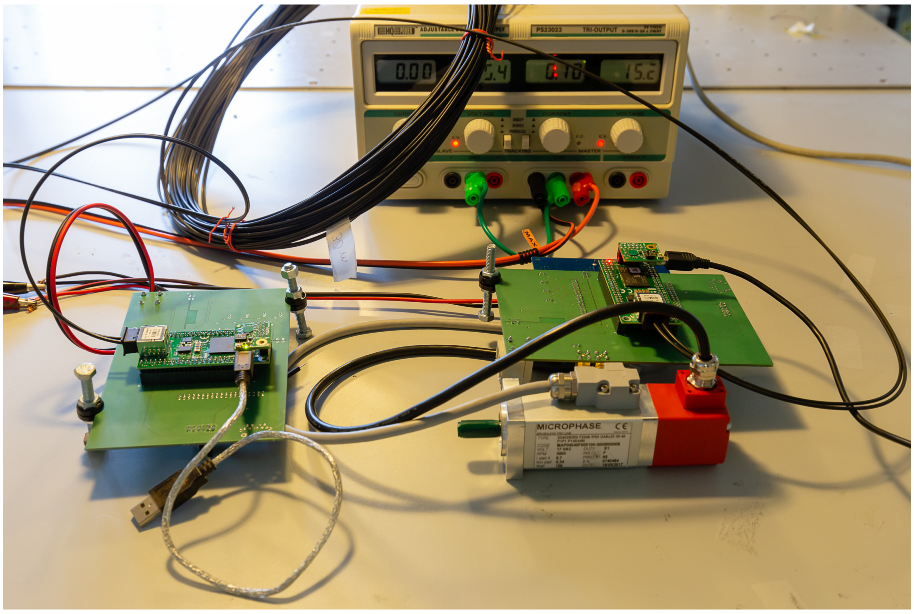

Figure 6. Demonstrator setup.

code such as the 64/66b. This line coding is widely adopted – e.g., in 10G Ethernet – because it requires a 2 bit overhead over 64 bit words with a limited 3% overhead, and enables a more efficient data transmission. Moreover, the transition density and the DC balancing are randomized by scrambling the data and control words with a known polynomial before optical transmission.

On the power unit, i.e the remote node, a Finite State Machine takes care of handling PWM update and ADC sampling. On the Control Unit, as soon as a packet is received, an interrupt is raised and the microcontroller core can access those values on five registers, memory mapped on a known location on the system AXI bus. Once the algorithm computation is completed, the updated PWM duty cycle values are written on the registers of the transmit section and the downstream packet is ready to be sent to the target node.

The first trials have been performed sharing a single clock all over the network to synchronize transmitters and receivers. As a further development step, a clock and data recovery section has been added to each of the nodes to take care of the small frequency differences among nominally equal clock sources. Among all the possible clock and data recovery approaches, a fully digital solution able to recover all the incoming bits is selected. Incoming asynchronous data stream is oversampled at 4X its nominal rate and the recovered bits are inserted in a FIFO, deep enough to account for small clock variations and jitter. As it is typical for this solution, the receiver FIFO that moves data from the asynchronous clock domain to the internal system clock can encounter an underflow (the clock on the receiver is slightly faster than the transmitter) or an overflow condition. The control logic solves this situation by adding/removing an IDLE word after the descrambling section of the 64/66b decoder. This operation is safe because the optical bus is mainly filled with IDLE words with only occasional data packets: as we are dealing with a real time control system, the performance bottleneck is not the available bandwidth, but the total latency.

The remote node was built around a commercial mini-module with a Xilinx Artix FPGA, an integrated optical transceiver and two 2.54 mm spaced expansion slots; and the two units are connected by a 40 m POF pair and successfully managed to control a three-phase voltage source inverter, used for vector control of a brushless servomotor. The servomotor is rated 100 W, 3000 rpm, and the PEC is a X-Nucleo-IHM08M1, a 60 V dc input, 15 A ac output expansion board for STM32 Nucleo boards by ST-microelectronics. The PEC and servomotor are purposely off-the-shelf equipment and of small size, as the emphasis here is on demonstrating the real-time control capability via POF. A custom

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Table 1. Power unit occupation

Resource	Utilization	Available	Utilization percent
LUT	8024	63400	12.6
LUTRAM	341	19000	1.8
FF	11084	126800	8.7
BRAM	8	135	5.9
IO	34	210	16.2
MMCM	1	6	16.6

Table 2. Control unit occupation

Resource	Utilization	Available	Utilization percent
LUT	13036	63400	20
LUTRAM	1047	19000	5.5
FF	14700	126800	11.5
BRAM	35.5	135	26.3
DSP	6	240	2.5
IO	24	210	11.4
MMCM	1	6	16.6

adapter board has been developed to connect the FPGA module to a ST expansion board and to a second optical transceiver to daisy-chain more units. In table 1 we report the occupation of the Artix 100 device hosted on our minimodule: as the occupation is low, simpler (i.e. with smaller FPGA) mini-modules will be considered to lower the total remote module cost.

For the control unit, the first trial were performed with the same mini-module as the remote node, but this time instantiating a full Microblaze microcontroller with built-in floating-point unit running at 100MHz. The control code has been written using standard C language, so it will be simply recompiled when targeting other cores; it has a small footprint (a few KB of RAM) and it can be executed from the embedded BRAM blocks present on the ARTIX device. The FPGA occupation reported by Vivado is presented in table 2.

The second set of trials will run on a commercial board with a higher performance Xilinx Zynq XC7Z010 FPGA: such a component is suitable to our prototyping purposes, having on board both FPGA resources (needed for the real time optical communication) and a real 600+MHz ARM A9 core with its embedded peripherals; the optical transceiver will be added on a custom board using an expansion connector.

Further work will see to the implementation of advanced control algorithms on this higher performance platform, enabling smarted power conversion, and the telemetry section needed to upload working data on a cloud data pool, making remote monitoring and fault analysis feasible.

5. Conclusions

The use of a plastic optical fiber bus in order to implement a remotized control of several power electronic converters has been proposed. This solution follows the recommendation [7] for a multi-layer structure in controlling PECs. In particular, the converter control and the preceding layers are assigned to a control unit while the switching and the hardware control layer forms the power unit, communicating through a fiber optic channel. For the optical bus, a daisy-chain structure has been proposed, enabling the connection of up to 10 PECs; each optical link can have a maximum length of 40 meters. Each PEC can use a packet carrying 112 bits of payload for bidirectional communications, thus enabling control remotizing, telemetry and remote orchestration. These capabilities, together with the enforcement of the power electronic system with an IP router, may enable clouds of of power electronic systems according to the Internet of Things paradigm. Such a prospective can permit a remote software-defined management and orchestration of many power electronic systems, taking also advantage of data from the possible communities of users.

A proof-of-concept demonstrator has been implemented and presented, showing the feasibility of such an optical control structure: the tests showed the implementability of such a communication bus, proving the possibility of remotely controlling a motor with our communication bus. Further work is carried on in optimizing the hardware and software layers, with the goal of bringing up a first internet of power enabled distributed control device.

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