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Power Line Communication System for Grid Distributed Renewable Energy

Nguyen TV [1,2], Petit P[1], Aillerie M[1], Charles JP [1] and Le QT [2]

[1]*Lorraine University, LMOPS-EA 4423, 57070 Metz, France*

[2]*Quang Ninh University of industry, Quang Ninh, Vietnam*

Abstract

The multi-sources nature of renewable energy production can be taken into account thanks to involving the solutions of distributed architecture based on individual DC-DC converters, connected to a direct current (DC) bus. Associated to this architecture, to assume simply the communication between the modules, one solution is the use of the DC bus power bus to support the communication between optimizers and a central controller using a power-line communication approach (PLC). The current work consists, at first, in the analysis of the pertinent information necessary to exchange between DC-DC converters and a central controller and, at second, by the development of a new hardware solution for the PLC from the conception of the communication system to the realization of a prototype. The various possible devices connected on the bus or networks are considered as programmable logic controllers, various sensors, microcontrollers and grid inverters. At minima, the information to exchange between the various devices may include the maximum power point of photovoltaic modules (MPP) and the temperature of the individual sources. At first, the ASCII Modbus protocol was chosen in the present work to assume the PLC communication on the DC bus. The interfacing circuitry between the DC bus and PLC controller is achieved by TRSV04 transceiver and power coupling circuit.

Keywords: Power-line communication (PLC); Direct current bus; Smart dc-dc converter; Optimizer; Renewable energy; MODBUS protocol

Introduction

The suitability of the proposed network for DC system is assessed by its compliance with the requirements set for specific applications in renewable energy generation and conversion system. We present a simple hardware implementation of a distributed architecture based on smart DC-DC optimizers integrating both, the power conversion and interface communication stages. This work is done in the aim of a realization taking into account the efficiency of the global system and its economical approach with a low-cost communication solution PLC_{DC}.

This choice of PLC system eliminates the need of using extra wires or complex wireless interfaces to assume the inter-communication between individual converters.

Power line communications systems operate by impressing a modulated carrier signal on the DC bus. The data is transmitted safely and reliably. Finally, development of such PLC system in distributed architecture based on DC bus configuration amounts to solve the problematic of the plug-in and interface of a small level information signal emitter-receiver with a high voltage power line module.

The described system is based on network architecture for the DC bus system that meets all the requirements presented above and only PLC_{DC} developments will be presented in this contribution; the main energy converter functions, with their MPPT (Maximum Power Point Tracking) algorithms and the self-power stage were presented in previous contributions [1-5]. This means also that the PLC_{DC} systems can be considered in each converter, as an additional stage to the main energy conversion stage, without modification of its basic structure. It is to be noted that a self-power supply stage can also be added in the optimizer. In this paper PLC interface is controlled by a dedicated Peripheral Interface Controller (PIC). Nevertheless, an optimizer integrating both the functions of tracker and PLC_{DC} master-slave control by a PIC microcontroller can easily be used.

In the aim of the integration of a communicant system in a renewable energy generator system, the current work presents the design and the realization, up to a complete laboratory prototype allowing the test and evaluation of all the technical choices and involved concepts, a system able to communicate on DC power lines. In the present work, the corresponding hardware and software elements of the data transmission interfaces for both, the individual converter, i.e. the slave interface, and the controller, i.e. the master interface were developed. The final realization of several prototypes, slaves and master units, and the communication between them, are tested and some improvements are suggested to achieve industrial qualification.

Design of a Master-Slaves PLC System on DC Bus

The work is on the Amplitude Shift Keying (ASK) structure of modulation, which is commonly considered in industrial communication network. ASK works by assigning unique pattern binary digits to different amplitudes by representing digital data as variations in the amplitude of a carrier power signal remaining constant. The advantages of ASK are its simplicity due to the associated low bandwidth requirements, so it is easy to implement transmitter and receiver with a small number of components and the detection is also facilitated. In this structure of modulation, the information carrier is a rectangular-wave signal in the 50 kHz frequency range. In ASK, the On-O Keying (OOK) method is one possible modulating method used for the data transmission [6,7]. This modulated signal is superimposed on the 400V DC voltage. In the present realization, to implement the OOK method, we have used a PIC16f876 microcontroller, realizing a half duplex power-line transceiver. It is to be noted that such kind of microcontroller or equivalent integrating circuit is generally used to drive the individual DC-DC converters as power sources in distributed

***Corresponding author:** Vinh Nguyen, Lorraine University, LMOPS-EA 4423, 57070 Metz, France, Tel: +33 3 54 50 54 00; E-mail: vinhnt@qui.edu.vn

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DC bus architecture.

Taking into account the previously presented study and the chosen approach for renewable energy generator, we have developed a PLC system with two different types of circuits for the transmitter-receiver: one, functioning in a slave mode dedicated to the individual optimizers, a second one considered as the master, being the interface with the central management controller. These circuits are presented in Figure 1 with upper and lower parts for the slave and master circuits, respectively. In the chosen solution, the receiver parts of the slave and master circuits are identical and only the transmitter circuits are different. For experimental validation of the technological choices that we have done in the present study, the DC bus voltage is specifically adjusted to 400 V, as determined by the transformation ratio fixed in each individual DC-DC converter. The PIC microcontroller, a PIC16F876 in our application, rep-resented in Figure 1a, is also used for the MPP tracking in the energy conversion part of the step-up DC-DC converter which is installed corresponding to a PLC slave. The PIC microcontroller creates a signal frequency carrier for the controller switch MOSFET M as well as for M1 of the PLC master-slaves circuits. The comparator converts data levels to the reference ones to obtain the two digital levels 0V and 5V.

The main electronic component of the receivers of the PLC master and slave circuits is a transistor mounted in a common emitter mode, which role is to adapt PLC signal from the DC bus to the microcontroller input, pin RC7/RX of the PIC microcontroller. In this circuit, the received signal enters first to the demodulator, which recovers the original data. An interfacing branch is used to isolate the receivers from the 400 V dc environments. It is composed by R1, C2 and combine with the filter circuit L1, C3.

In the proposed PLC transmitter part of the slave circuit, the effect of distortion is minimized, by a careful selection of a constant and stable carrier frequency (fc). Therefore, an oscillator is built using the PIC microcontroller generating modulating signal at a frequency of 50 kHz. The amplification of the signal was designed using a Q2N2226 transistor, dedicated for low-voltage and high-speed applications, especially in inductive circuits. The interfacing circuit consists of a forward-converter transformer where both primary and secondary windings conducting simultaneously with opposing magneto-motive forces along the mutual flux path. The difference of the magneto-motive forces is responsible for maintaining the magnetizing flux in the core. When primary winding current is interrupted by switching o the switch, the dotted ends of the windings develop negative potential to oppose the interruption of current blocking the diode, and thus, interrupting the conduction. To reduce the current delivered by the DC bus in the secondary coil, thus avoiding possible saturation, we added, in Figure 1b, a self, Ls, and a capacitor, C1, in the interfacing circuit of PLC system master-slaves. Each PLC slave circuit connected on the DC power-line corresponds to a node. The current passing through the PLC transmitter part of the slave circuit is equal the output current of DC-DC converter. The purpose of the Ls coil, Figure 1b, is to limit the saturation current in the circuit magnetic of Lp1-Lp2 transformer. Thus this work design is the same as a forward-converter transformer on the DC bus. The current coming from all source-nodes of the DC bus crosses the PLC transmitter part of the master circuit.

Communication and Transmission Protocol Implemented in PLC Modules

The work on implementation of the MODBUS protocol in master like slaves microcontrollers. An exhaustive amount of information about the protocol is given on the website [8,9]. Referring to those documents the ASCII mode protocol for PLC slave and master was developed and tested successfully. Experiments consisted in reading two slaves connected to HVDC bus. Reading frames sent by master were composed of thirteen ASCII characters, including longitudinal redundancy checksum byte (LRC), necessary to exchange dependability. As shown in Figure 2, the response frame from slave was composed of fifteen ASCII characters, with the need to compute LRC byte depending on the value of transmitted data before response frame sending. The ASCII characters are described below:

Reading frame:

- Start delimiter
- Slave adress1
- Reading request
- Momery words address to read
- Carriage return and line feed

Response frame:

- Start delimiter
- Slave adress1
- Reading request
- Number of bytes
- 6 blank bytes
- Carriage return and line feed

In the response frame the blank characters are replaced by the four ASCII characters of the two read data bytes added with the computed LRC.

Obviously, received LRC byte was always compared to compute one's, both for master and the two slaves. So LRC byte allows to checked frame integrity: thanks to all this mean possible serious disturbances on DC bus can be instantaneously detected as it was done in our power line communication design on the DC [10-12]. Available baud rates are limited by the carrier wave frequency (maximum baud rate equal to about 10% of the carrier frequency) to take account of the receiver filter delay group, and DC power line impedance. Concerning the microcontroller, the only limitations are the highest baud rate of the universal synchronous asynchronous receiver transmitter (USART) (115200 bit/s with 20 MHz CPU clock).

In spite of different role, PLC master and PCL slaves consist of common blocks: the same microcontroller, the TRSV04 (described further), the power line interfacing circuit and the power supply. The PLC master microcontroller generates the packets of data to TRSV04 transceiver whose role is to superimpose these packets on the HVDC bus using ASK at the programmed carrier frequency. Considering the slave receiver, the TRSV04 detects the carrier and then decodes the modulation and deliver logic levels to microcontroller. The same process occurs when a slave unit replies to the master. As explained above all the packets are transmitted according to the ASCII Modbus protocol.

In the master module shown in the Figure 3a, see a LCD 16×2 (Liquid Crystal Display - 2 lines with 16 characters per line) for data display. It can operate both in 4-bit or 8-bit mode. All useful data concerning PV (Photo Voltaic) system can be displayed: PV module temperature,

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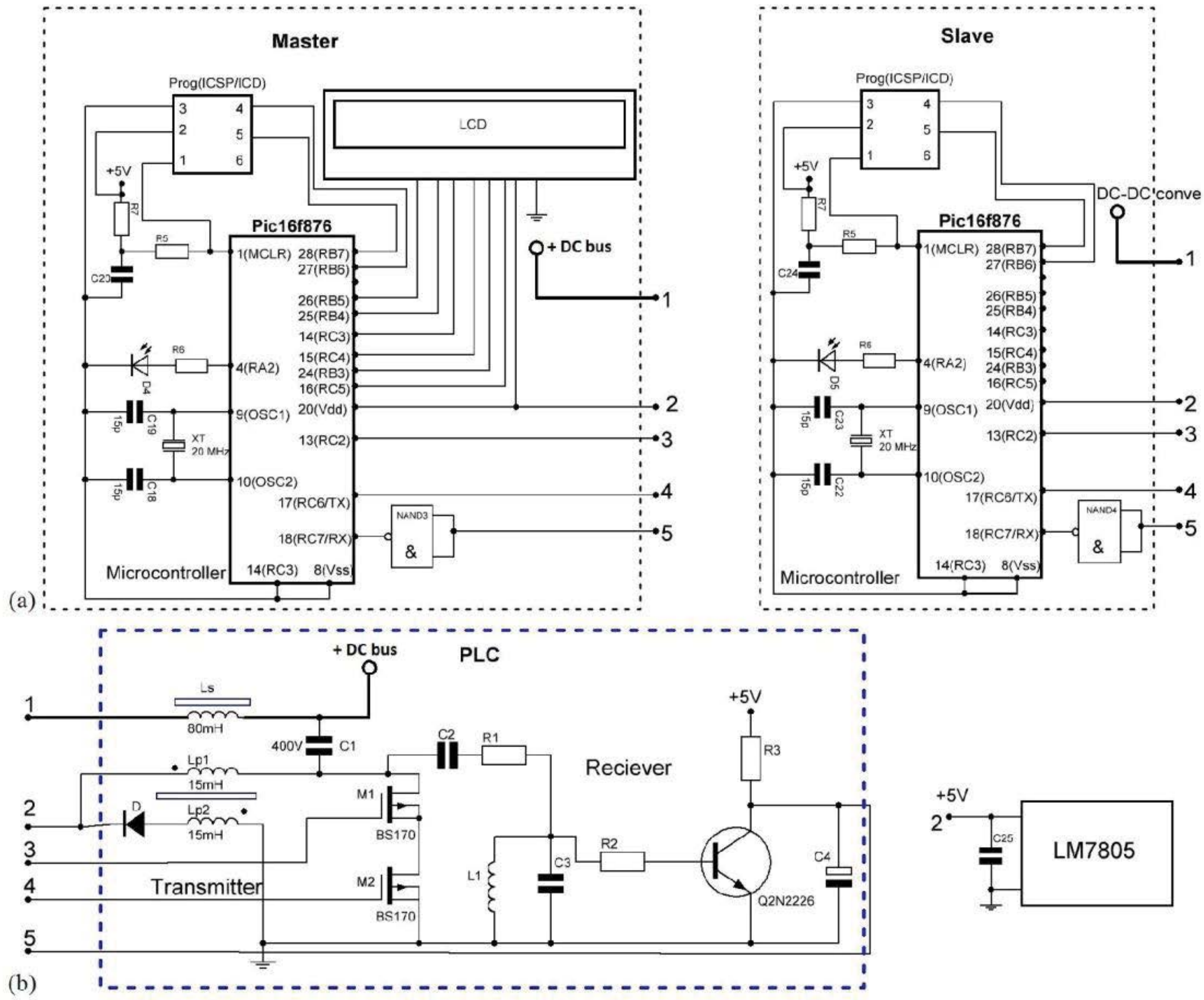

Figure 1: a) The PLC system master-slave; b) Implementation of the microcontroller for transmitter and receiver parts of PLC master and slave.

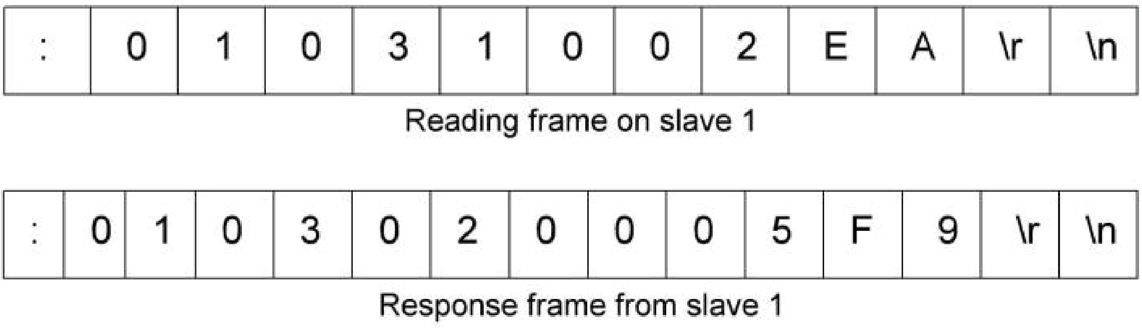

Figure 2: MODBUS frames in ASCII type.

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PV module maximum power point (MPP), which can be detailed by electrical measures like PV module voltage, PV module current and DC bus voltage directly realized by optimizers (as shown in Figure 3b). Tests have consisted in exchanges between the master and two slave units by reading of the slave sensors, the number can extend for the module slaves correspond with the number of the DC-DC converters connect parallel on DC bus [13-17]. A simple potentiometer has been used as an analog sensor and, after ADC conversion, the measurement transferred in a 16 bits format via the DC bus. For the moment the quantification of all the PV system measurement is limited to 10 bits (microcontroller resolution in the case of laboratory optimizers). But measurement devices with higher resolution can be considered like, as evoked above, PV module temperature but also irradiance useful for PV system diagnosis.

In the case of optimizers which are considered as slaves, their principal function is obviously energy conversion with the highest efficiency based on a Maximum Power Point Tracker (MPPT) but we can add other functions like PV module monitoring, with the ability to detect and diagnose local shadowing due to buildings around, trees, leaves or simply dirt on PV modules, and to measure a deformation of the I/V curve. Follow a few modifications it would be easy to imagine a way to implement an intrusion detection system, especially in the case of PV modules set on the ground. When an intrusion occurs, input power of the optimizer changes like in the case of a fugitive shadowing and can be computed from to the input optimizer voltage and the current sensors. The power change detection is diagnosed by optimizer as intrusion information. This status located to one particular PV module is sent to the PLC master. Nevertheless, to avoid false alarm detection, it would be necessary to verify intrusion status on other optimizers before displaying security message on the master LCD. A complete monitoring system should allow parameters transmission to optimizers, like specific operating points (for instance safety voltage for firemen) or independent control of distributed sources.

Implementation

The two modules transmitter and receiver coupled together by the medium used for data transmission, i.e., the DC bus are shown in the Figures 4,5 and 6. Both the master and slaves boards are directly connected to the DC bus. The microcontroller (PIC16F876A) of PLC interface transmitter module is programmed to transmit ASCII characters composed of seven data bits and one even parity bit which are fed into the TRSV04. The TRSV04 transmits the data at the programmed frequency of 50 kHz by binary ASK technique on the DC power line.

The receiver TRSV04 of PLC master detects the carrier amplitude and converts it to a logical value as shown further in Figure 4 towards the microcontroller. These data are treated before displaying on the LCD. The medium chosen for these first tests is an ASI bus cable (Actuator Sensor Interface) which could even be convenient to transmit power, from to sufficient section (higher than 2 mm^2). Exchanges between master and slave can be considered as quite dependable in the first experimented case of data transmission without power on the DC. No errors were detected by LRC function of Modbus, in the case of small distance between master and the two slaves. More over we observed no transmission errors with PLC modules in the case of significant distance between master and slaves as described in following lines.

The experimental tests were performed with master and slave modules connected via a DC bus of around 150 meters long as shown in Figure 6, with 100 meters between master and the first slave module and 50 meters between the two slaves. In Figure 7 and Figure 8 shows oscilloscope traces of the transmitted signals owing on the bus.

In Figure 7 see, first signal (yellow), a reading frame transmitted via the TX pin of the master microcontroller. The fourth wave is the signal visible on the RX pin of master microcontroller (green signal): we can obviously see response frame from slaves, but also master reading frame itself. The second signal (blue) corresponds to the RX pin of a slave module microcontroller: we easily identify master frame but also proper slave transmission which is visible alone on third wave corresponding to slave TX pin (violet signal). Reading frame duration (first signal) is a little higher than theoretical calculus: thirteen characters conformed to USART protocol (one bit start, seven data bits, one parity bit and one stop bit) would have 104 ms with 2400 baud rate. In fact few additional delays have been programmed to insure transmission reliability, so we can estimate real duration around 120 ms for reading frame. In the case of slave response, fifteen characters have a theoretical duration of 120 ms. Real duration is measured around 140 ms. So, a complete exchange has a minimal duration of around 260 ms, implying a DC bus refreshing frequency order of lower 4 Hz. Even RTU mode is implemented with the hope to double refreshing frequency, the relative slowness of this bus induces to plan a maximum of functions directly embedded in distributed optimizers (local energy counting for example). In the case of urgent safety state dedicated to firemen or for maintenance, ability to control all the optimizers in the same time (classical zero addressing) should allow a response in only 120 ms (ASCII Modbus protocol).

Not visible on Figure 8, the PLC information signals present a rectangular shape with amplitude of V normally superimposed on the DC bus. We note a small delay for this signal to establish to a stable level, implying a systematic group delay. The shape at the bottom is the logical level obtained at the output after demodulation (blue signal) of the ASK modulation (green signal) of the DC bus signal. It is easy to understand that the speed limitation is mainly due to the global delays observed here Figure 9 shows at the upper shape the voltage observed on the DC bus when a transmission is send to the slaves (green signal). The second curve corresponds to the signal modulation obtained accorded on the carrier frequency i.e. 50 kHz with the impedance over the power line 1,5 Ohm and influence of the impedances output of the DC-DC converters connect parallel on the DC bus.

Future scope

A specific study must be achieved to evaluate the influence of high scale of impedance variations of the DC bus. Some improvements must be experimented concerning the master unit and especially for the dimensioning of the passive filtering elements which have to drive high level of currents supplied by all the connected generators. The scope appears as limitless since communication requires no additional wiring. At first our study was dedicated to on grid architectures implying multi renewable energy sources (PV modules, wind generators . . .) and charges like inverters, with the aim to increase the global efficiency in procedure transmission of energy in spite of possible disturbances like important shadowing. DC bus is also appropriate to smart monitoring including other devices like industrial control components (programmable logic controllers, graphic terminals . . .) or simply a computer connected to DC bus via PLC master and naturally to Internet for all the conveniences induced and can install security in the PLC system to supervision the dispersed sources.

Conclusion

This contribution presents new developments of communication

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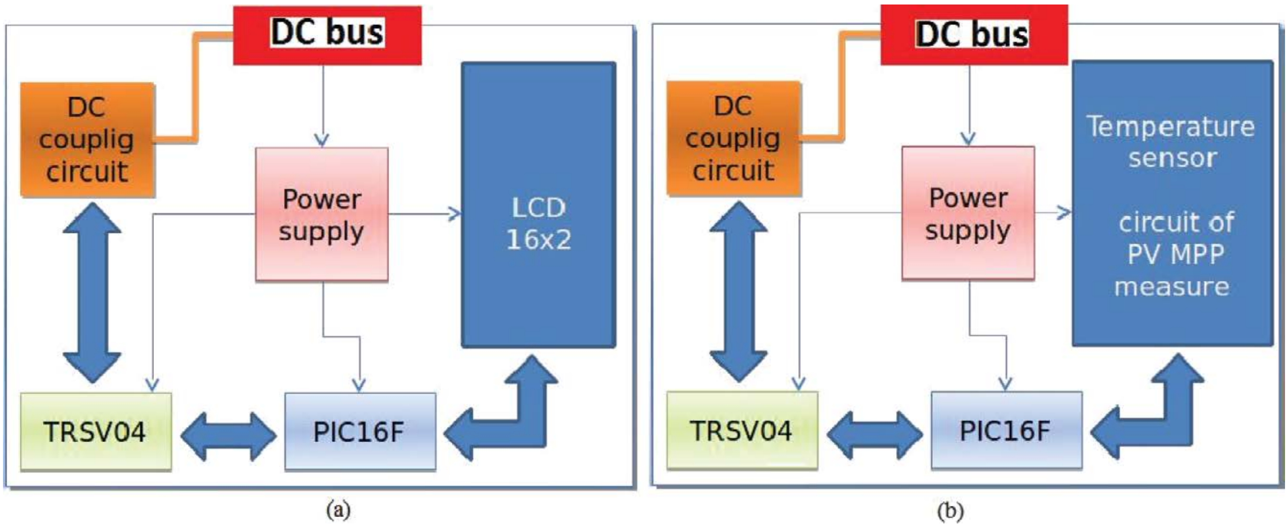

Figure 3: a) PLC master module block diagram; b) PLC slave module block diagram.

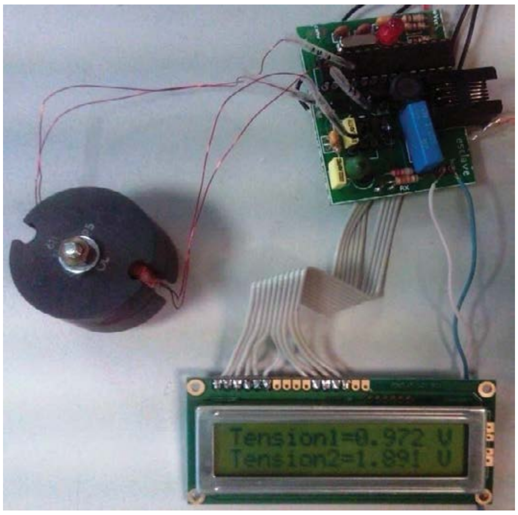

Figure 4: The transceiver board of the master TRSV04.

Figure 6: The Transmitter and Receiver Coupled to the DC bus.

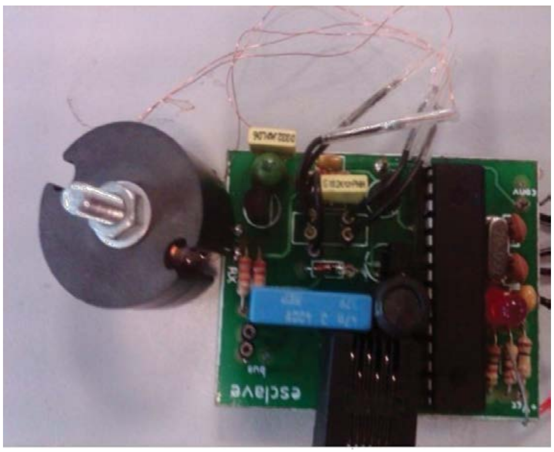

Figure 5: The transceiver board of a slave TRSV04.

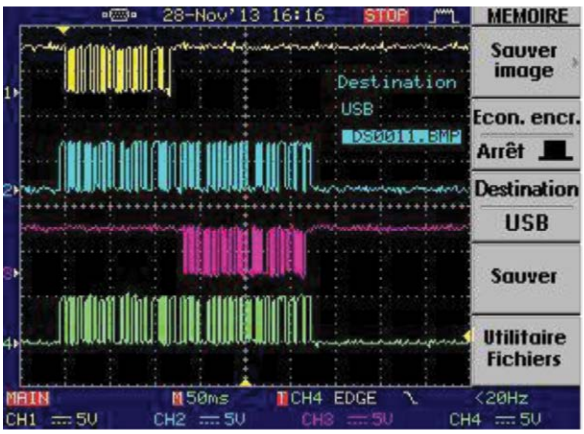

Figure 7: Master and slave frames on oscilloscope: microcontroller USART signals and transceiver PLC data.

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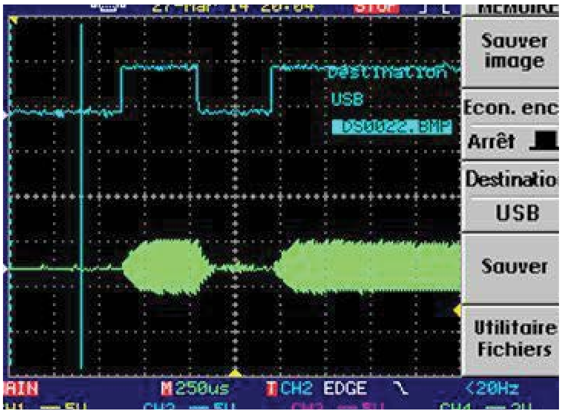

Figure 8: Signal of receiver module of the PLC master-slave.

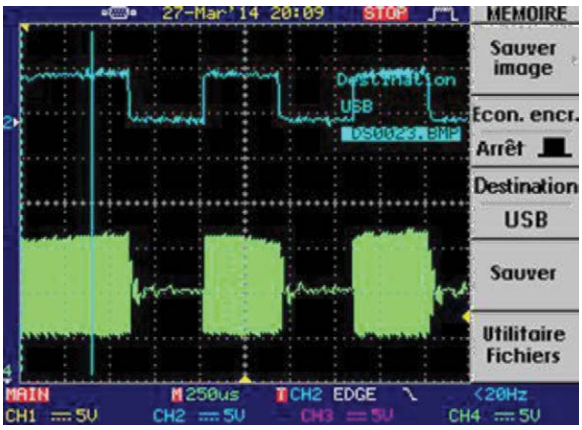

Figure 9: Signal of receiver module of the PLC master-slave.

system dedicated for distributed renewable energy production generators. The basic concepts initially fixed for this original development of communication system are based on a low cost, low frequency carrier, avoiding propagation phenomenon and allowing long distances.

Thus, this work explores, up to the realization of a complete prototype system, the communication between individual devices (DC-DC converters and a master controller) constituting a renewable energy generator and using power lines (a DC bus) as information support based on a PLC technology at a very low frequency carrier. The communication protocol is based on the widely accepted Modbus protocol. The presented system communicates successfully and is able to receive and transmit data without any errors. This system constitutes the base for an implementation in a massively parallel architecture in the case of stand-alone PV systems, and even self-consumption solutions integrating smart storage. As no extra wires dedicated to communication are required in the proposed solution dedicated for power electricity transport, the reduce of the cost should be noticeable, by reducing the wire section because of high voltage of the DC bus and by the present implemented simple communication system.

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