STUDY OF WIRELESS EMBEDDED SYSTEM FOR ARC WELDING SIGNALS MONITORING

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Abstract. *Welding processes are the most important ones in use for metal joining in industry and according to ISO 3834, welding is a special process, since it cannot be completely inspectioned against imperfections only after its completion, i.e., the constant monitoring is required. Thus, the manufacturer must adopt suitable methods in order to guarantee the necessary quality to welded products and also to guarantee documentation for audition, corrective actions and personal revision. These methods include welder skills, preparation and qualification of welding procedure and monitoring of process variables. Therefore, it is aimed to study the monitoring system application viability and to perform analyses of variables of arc-welding processes. The final proprietary technology must presents scalability, portability, autonomy, low cost and flexibility during operation. Also, the study embraces the initial analyses of welding signals, the definition of physical architecture, data communication and assessment of its main advantages and limitation against commercial products. The main contribution lays on the horizon of the hard use nowadays of TCP/IP protocol, dissemination of computer networks in industrial environment and the development of portable products for data communication (such as notebooks, smartphones and palm computers). These technologies integrated to welding process monitoring plus the readiness of wireless communication unveil a very powerful tool on the context of ISO 3834. It is concluded that the developed system bonded to welding could expand the workability of remote supervision equipment through computing network.*

***Keywords**: Welding, Monitoring, TCP/IP, Wireless, ISO 3834.*

1. INTRODUCTION

Among the manufacturing processes, especially in metal permanent union, arc welding has been one of the most important processes used in industry. Welding being a special manufacturing process - quality assurance and inspection of the weld against defects cannot be realized only after its completion (ISO 3834, 2005) - with its widespread use, development and improvement of equipment and methods are needed for process constant monitoring.

The refereed standard deals with the quality requirements for metals fusion welding, providing guidance on practices to achieve quality in the joints and how to document the entire process, ranging from the welder's qualification, the qualification of welding procedure until the process parameters monitoring such as current, voltage, and others. The application of this type of standard is not mandatory for manufacturers, but to achieve welding processes and final products with higher quality, standards like this are reliable references to good practices in achieving the desired quality. In addition, your documentation can be used in audits, corrective actions and review staff.

There are several devices from different manufacturers that do monitoring of several variables in welding process, each with its specific focus on witch parameters that are monitored, with their advantages and limitations. Programmable equipments are also available on the market, such as acquisition devices DAQ (Data Acquisition) from National Instruments, adaptable to welding monitoring with the addition of signal conditioners and transducers. Ongoing trends follow the creation of equipment for practical and simple use, with the elimination of adaptive circuits and greater installation flexibility - the monitoring equipment must be adapted to the manufacturing environment and not otherwise. Demand for flexibility, especially tend to modify the way the welding parameters monitoring is accomplished by replacing the traditional system of cables by a wireless communication system.

The initial idea of building an embedded device - complete and independent system, but prepared to perform an unique determined task (CUNHA, 2007, OLIVEIRA, 2006) - with wireless communication, as well as its flexibility of installation, originated in the dissemination computer networks in manufacturing environments and technological development of communication products, portable data (notebooks, smartphones and handhelds), hence making possible the integration of welding processes monitoring with the wireless communication helpfulness a reality achievable and promising technology. By creating this kind of technology related to welding, it's possible to expand its applicability to control systems and remote monitoring; facilitating many of welding procedures, for example, in environments hostile to humans, as well the possibility of trained experts perform supervision without being present at the operation site.

In this context, welding parameters monitoring, fits the purpose of this work: a study for design and construction of a system for wireless monitoring and analysis of arc welding variables, having proprietary technology, scalability, portability, autonomy, flexibility and low cost / simplicity of operation. To carry out the process parameters monitoring it's necessary, first, to know them. Because, through the knowledge of their characteristics, is possible to do signals acquisition for further analysis and documentation. Thus, this study includes an initial analysis of welding signals, and with characteristics determined, define the physical architecture, such as sensors, communication devices and storage, among others, communication mean and data visualization.

2. METHODOLOGY

To develop the monitoring system, the work has been divided into three stages: the study of signals needed in welding processes monitoring, the definition and construction of the physical system (hardware) to be used, and at last, the definition and implementation of the communication topology between the acquisition system (physical system) with the final user interface and data presentation (software).

2.1. Study of the Involved Signals

The study and documentation of welding signals are so important to qualify the process that the standard ISO 17662:2005 defines witch variables should be monitored in different welding processes, specifying since the global signals (all processes) to the most specific (for each process). With this, the monitored information should be documented according ISO 3834:2005 standard.

A brief description of the signals division based on ISO 17662:2005 is listed below and as the focus of this work is specifically arc welding signals Tab. 1 shows the needs required by the standard.

- **To all the processes:** Base Material and Filler Metal; Joint; Welding Power Source; and others.
- **To most of the processes:** Consumables; Purge Gas; Shield Gas.
- **Specific to arc welding: Waving; Electric Variables; Mechanized Welding.**

Table 1 – Arc welding specific variables that should be monitored. (ISO 17662, 2005)

	Instruments and Techniques
Electric Variables *	
Current	Ammeter – Rectified Mean Value of current.
Voltage	Voltmeter – Rectified Mean Value of voltage.
Mechanized Welding	
Travel Speed	Measured by ruler and chronometers.
Wire Feed Speed	Measured by ruler and chronometers.

*Can be continuously monitored. The sampling time must be acceptable to guarantee a stable reading. Must consider the difference between mean and RMS if tong-tests are used.

This study does not consider, initially, the waving (transverse oscillation of the torch relative to the joint direction) and travel speed monitoring, since these parameters are directly involved with the welder skills (manual welding), and/or with the drive systems characteristics of the welding torch (welding with fixed peace) or of the peace (welding with moving peace). Therefore, the objective of the monitoring system is being able to instrument and monitor the electrical signals (current and voltage) and the wire feed speed (when applicable) of arc welding processes.

To evaluate electrical parameters of arc welding, an experimental setup was performed, where bead on plate welds was deposited and the electrical signals were acquired. A voltage divider circuit added to a galvanic isolator was used for voltage instrumentation and a Hall Effect transducer for current, were used for signal conditioning. An USB acquisition system from National Instruments with a sampling rate of 125 kS/s was used, to observe the frequencies present in the welding signals and, with this information, it's possible to determine the minimum sampling rate. Table 2, shows the regulated parameters to the tests. The equipment and supplies in common to all tests are shown in Tab. 3.

Table 2 – Used parameters in the welding processes.

Test	Voltage [V]	WFS [m/mim]	Metal Transference	Wire [mm]
1	32,0	7,0	Spray	1,0
2	32,0	8,0	Spray	1,0
3	19,0	6,0	Short-Circuit	1,0
4	22,0	5,3	Short-Circuit	1,0

Note: WFS = wire feed speed.

Table 3 – Welding parameters common to all tests.

Shield Gas	Ar+8%CO_2 (13 l/mim)
Type of Welding	Automatic
Process	GMAW
Filler Metal (wire)	ER70S-6
Base Metal	Carbon Steel
Welding Power Source	*IMC digitec600*

2.2. Physical System Definition

Given the parameters to be monitored (voltage, current and wire feed speed) as defined before, needed devices and circuits should be selected and designed to build a complete physical system, which is able to pick up signals from their sources, adequate them to the acquisition device limitations, convert them to digital signals that are sufficiently precise, and finally, prepare and send them to the system user interface, as shown in Fig. 1.

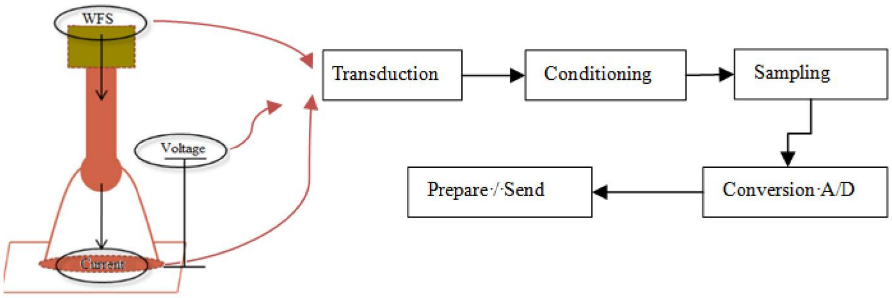

Figure 1 – Flowchart of steps to obtain the signals of welding.

The transformation of physical phenomena of the monitored signals into electrical signals occurs with the use of transducers. Most digital converters use voltage as input signal, so arc voltage does not require a transducer. For the current and wire feed speed, was chosen, respectively, a Hall transductor and an optical quadrature encoder. The choice of the Hall is due the flexibility of installation (its mobile clamp make it easily moved from one conductor to another, ie, open loop clamp), reading linearity and its simplicity of use (just supply it and put it on the cable, so a voltage signal proportional to current in its output be generated). The encoder is capable of measuring angular velocity of a shaft attached to it with frequency proportional to rotational speed, isolating electrically the acquisition system and providing the direction of rotation through sequences of digital pulses. The interpretation of its output signal is simple, efficient and robust, advantages for use in industrial environments.

The next step for the signals acquisition is their conditioning, adapting them to the input of an analog-digital (A/D) converter. In terms of electric magnitude, the range of transducer voltage output, for current, or arc voltage itself, should be adapted to the converter range (voltage divider). Moreover, a circuit of galvanic isolation - circuit electrically isolated acquisition from the power (welding) –, analog filters to remove frequencies outside the scope of the study, adequacy of impedance, and circuit protection for the MCU (microcontroller) are needed.

The use of MCUs for the sampling, conversion, preparation and storage of digital signals was defined initially, since this type of controller eliminates the need for computers (portability), so it's an independent system (embedded). Its programmable nature ensures scalability, and much of MCUs available commercially already have peripherals for conversion (ADC) and storage (memory), and in specific products, peripherals, which work directly with quadrature encoder.

Despite the wide variety of commercially available products, the speed of data processing, storage capacity and programmability and, above all, the resolution available in the A/D converter are necessary take into account. The voltage, current and wire feed speed adjustment on welding power sources have a resolution of 0.1 V, 1 A and 0.1 m / min, respectively. So, the A/D converter must have sufficient resolution to take readings with this resolution.

Finally, the wireless communication device should be selected. There are several types of transmitters without cables commercially available and they are by infrared or radio frequency, each with its advantages and limitations. The use of infrared, in a short assessment, does not fit the requirements of this system, since it requires a direct line of data transmission (transmitter and receiver aligned). In an industrial environment obstacles and the constant movement of people and the machinery make this kind of communication inadequate. This is the main but not the only limitation of this method of wireless communication.

In radio frequency communications, there are international regulations that defined bands available for use in industrial, scientific and medical journals, without licensing: ISM bands - Industrial, Medical-Scientific and (ITU, 2008). Among them, 2400-2500 MHz (2.4 GHz), was popularized in the implementation of wireless networks such as

Wi-Fi (IEEE 802.11b / g), Bluetooth (IEEE 802.15.1) and ZigBee (IEEE 802.15. 4). The high frequency makes those devices practically immune to noise generated by welding equipment and their communication modules are commercially available from several manufacturers, for integration with micro controlled systems, like cell phones, notebooks, etc. Table 4 summarizes the main features of these wireless technologies.

Table 4 – Comparison table for wireless technologies (GALEEV, 2004).

Standard	Bandwidth	Consumption of energy	Protocol Stack	Strong Point	Applications
Wi-Fi	Uo to 54 Mbps	400 mA TX *standby* 20mA	~100 kB	High data rate	Internet, computers nets, data transfer.
Bluetooth	1 Mbps	40 mA TX *standby*0,2mA	> 100 kB	Interoperability, replace the cable	USB wireless, headphones, mouse
ZigBee	250 kbps	30mA TX *standby* 0,3 mA	4 - 32 kB	Low cost, Long life with battery	Remote control, products with batteries, sensors

In first place, the ZigBee communication is not advisable for this system because the low data rate (250 kbps) when compared to others and, for the user data reception, it is necessary to have a ZigBee module also connected to the UI (user interface) system. In portable data processing equipment (notebooks, smartphones and handhelds) this type of communication is not commercially inserted and would require the design of a receiver module compatible with this equipment.

The communication by Bluetooth performs transmission peer-to-peer. In other words, two devices must be paired and connected to each other to perform the communication (BLUETOOTH SIG, 2010). In a manufacturing environment, the pairing would complicate the access to the monitoring system. Further, the Bluetooth data rate is about 1 Mbps, lower when compared to Wi-Fi's. In this way, the Wi-Fi standard was chosen for communication between the acquisition system and user interface, cause present a higher data rate and greater flexibility of use (monitoring inserted into a common network of computers).

2.3. Communication Protocol and User Interface Definition

The last step is the result of all decisions taken throughout the study to develop a wireless monitoring system. Chosen the Wi-Fi technology, and looking for flexible and simplified user interface, there are few options for communication protocols, such as TCP (Transmission Control Protocol), UDP (User Datagram Protocol), FTP (File transfer Protocol) and others. Ensuring the integrity of transmitted data is extremely important for this system and the storage should be performed continuously (without interruption), so TCP is the most appropriate protocol.

As the user interface, with TCP Wi-Fi communication, it's possible to create a program at the application layer of TCP / IP stack and use it to transfer files via FTP, email or, finally, one page HTTP (Hypertext Transfer Protocol). About all these interfaces, the HTTP Web Page quite likely has more scalability and being the most dynamic, flexible and independent device (it's possible to use either a cell phone as a computer). The programming tools are free, considering that development tools are almost expensive, it's an advantage. Programmable products generally require proprietary software, which are often more expensive than the physical device.

3. RESULTS AND DISCUSSION

3.1. Study of the Signals

Using the methodology presented in Section 2.1, it's possible to conduct the study and observe the signals frequency components up to 62.5 kHz (half the data sampling, at 125 kS/s), according to the Sampling Theorem. This maximum frequency is sufficient, since the welding signals has the highest frequency component limited, which is the switching of the power supply itself, around 20 to 30 kHz for most commercial equipment.

It is known that in analog to digital signals acquisition and sampling systems, the higher is the sampling rate, the higher is the level of information about the sampled signal and, also, the greater is the amount of data being transmitted or stored for the same period of time. In terms of transmission or storage, it's reasonable to always seek the least amount of data (sampling rate) as possible without degrading the information. Importantly, in different situations, different characteristics may be considered important or not.

For purposes of discussion, two approaches were defined to monitoring welding signals: science and technology approaches. The scientific approach is focused on study of welding processes, used usually in laboratories and welding research centers, looking for details about the signals, ie, observing the variations each setting parameters and their influence on the weld bead. The other approach, the technological, is focused on process documentation and monitoring in a production environment, then, not being necessary so many details, but containing enough information for troubleshooting and verification of possible defects. Characteristics like average and RMS values are important, but the pattern of switching can be ignored, thus reducing sampling rate and, therefore, the amount of data to be transmitted or stored, simplifying the monitoring device and storage.

To determine the sampling rate for welding signals acquisition, current and voltage signals was acquired for the runs described in Tab. 2 were performed, with duration of 2 seconds and mathematical calculations were performed on them. As an example, the waveforms for a short circuit welding (Test 3) are illustrated and, subsequently, all the final results will be presented. Voltage and current frequency components were evaluated by Fast Fourier Transform (FFT). Figure 2 illustrates the signals in Test 3 and their corresponding FFT, where it's possible to observe the dominant frequency in each case.

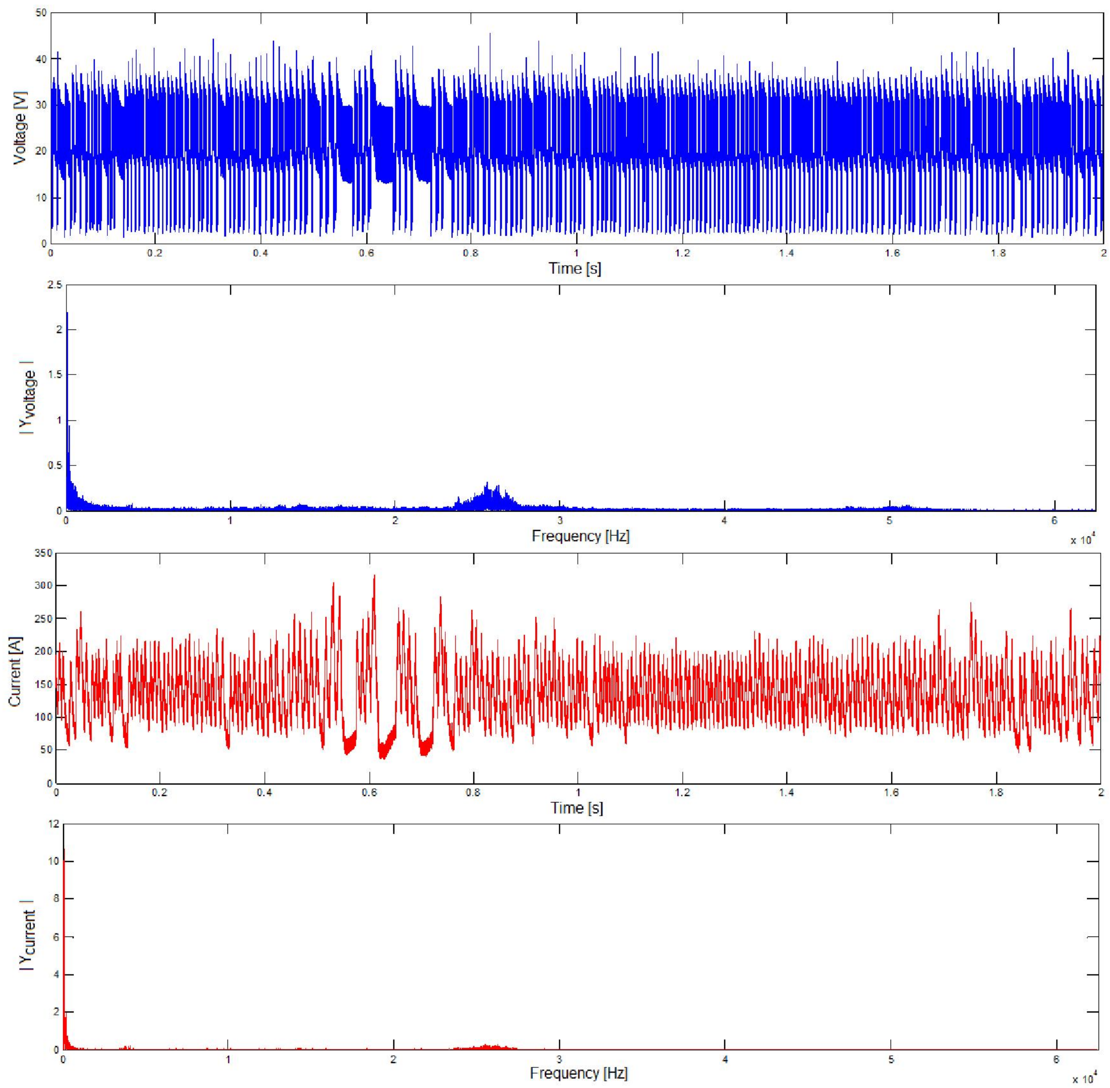

Figure 2 – Electrical signals of voltage and current for the third Test, and their FFTs.

Both signals spectra shows significant intensity concentrations at low frequencies (near DC level - 0 Hz), around 25 kHz. As previously mentioned, the frequency around 25 kHz is attributed to the welding power supply switching behavior. The low frequency components are, by prior knowledge of different welding processes physics and behavior, features actually related to the process itself, for example, detachment of drops or short circuits. The DC level is the average value.

In Fig. 3 and Fig. 4 it's possible to observe details of signals in Test 3 and its FFT. In each figure, the upper left corner is the oscillogram of the waveform for the short circuit, in the lower left corner is a closer observation of welding power supply switching and, finally, to the right, is the FFT signal highlighting their low frequency components. It is known that to control the average voltage (welding type constant voltage source), the machine switches the current, and when it occurs (~ 25 kHz), there is a range of values current and voltage, then not characterizing noise in acquisition, is just the behavior of the power supply controller.

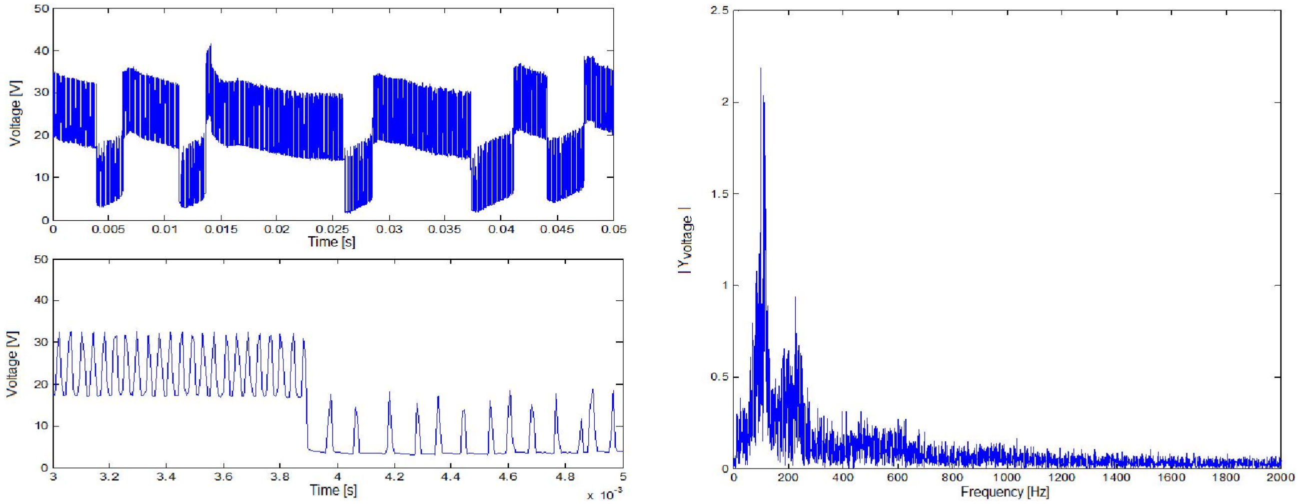

Figure 3– Details of signal voltage and its FFT for Test 3.

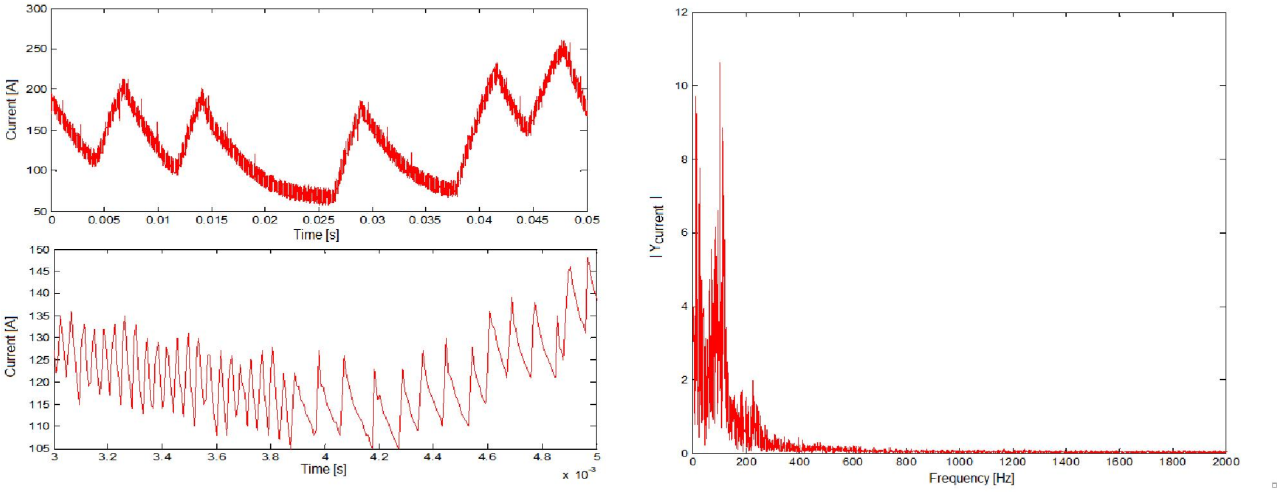

Figure 4- Details of the current signal and its FFT for Test 3.

The FFT spectra for voltage and current, it's possible to observe that information (welding signals) is up to 300 Hz. This frequency, therefore, for a technological approach is the maximum frequency for observe the desired information contained in these signals. Table 5 lists the frequencies of maximum interest for the technological approach, encountered in all the tests.

As previously mentioned, the amount of data is directly proportional to the sampling, because in the same interval of time there are more values (samples) to be stored or transmitted. More data is generated by the acquisition system, the greater is the consumption of the communication channel with the user interface, which has known, has traffic speed limited (bytes/s). For a scientific approach, the switching characterization accurately (square wave) asks sampling rates at least 125 kS/s, and for the technological approach the welding signals characterization, for itself, can be performed with 1250 S/s. Figure 5 compares the signals acquired by the two approaches for Test 3, where the acquired signal was attenuated with a Butterworth second-order low-pass filter at 625 Hz (no attenuation at low frequencies only) to obtain the sign in technological approach. It should be noted that, although they are presented and discussed the results for Test 3 (due to limited space), similar behavior was observed for the other tests.

Table 5 – Maximum frequency of interest observed in the signals.

Test	Frequency [Hz]
1	250
2	300
3	300
4	200

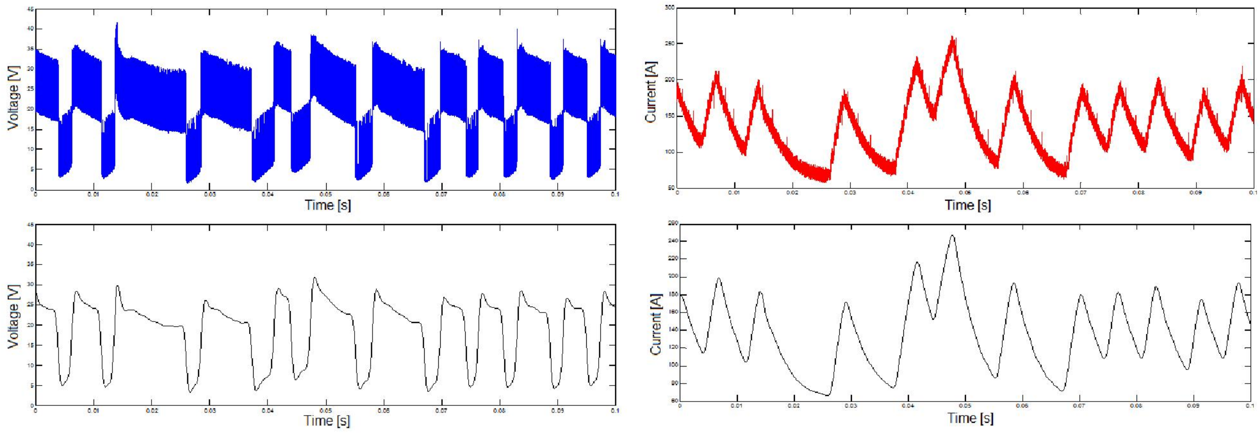

Figure 5- Comparative between oscillograms of signals from scientific approaches (above) and technological (lower). Left: Voltage, Right: Current.

Statistically, the Pearson correlation coefficient (r) measures correlation intensity between two vectors. Normalized correlation values between 0.5 and 0.8 indicate a moderate correlation and values above 0.8 and below 1 are considered highly correlated (SANTOS, 2007).

The voltage and current acquisition at 1250 S/s after passed by second order Butterworth low-pass filter at 625 Hz is similar enough or not to these same signals sampled at 125 kS/s after passing through the same filter in signals. Figure 6 illustrates the waveforms, both attenuated, sampled at 1250 S/s and 1250 kS/s in Test 3. It should be emphasized that a lower sampling rate was simulated by a higher rate of acquisition, after the filter, looking for points at specific time intervals (period 800 ms) and ignoring the intermediate points to them. Through this, it’s possible to discern if the signals sampled with selected rate, and filter cut-off frequency are correlated.

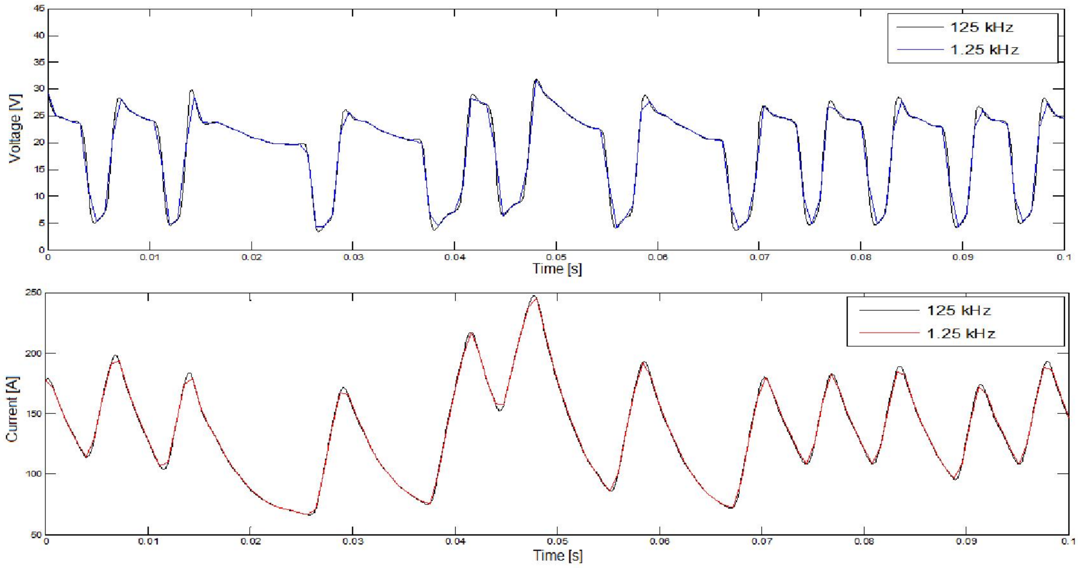

Figure 6 - Comparative oscillogram of voltage (upper) and current (bottom) at 125 kS/s and 1250 S/s sampling rates.

The two sampling rates waveforms similarity and the signals correlation coefficient, average and RMS values (listed in Table 6), can be compared mathematically. As mentioned, the desired values resolution measured are 1 A for current, and to voltage of 0.1 V.

Table 6 – Mathematical comparison of the signals of welding with two sampling rates.

Run	Voltage [V]				*r*	Current [A]				*r*
	Mean		RMS			Mean		RMS		
	125 kS/s	1250 S/s	125 kS/s	1250 S/s		125 kS/s	1250 S/s	125 kS/s	1250 S/s	
1	32,1	32,1	32,1	32,1	0,83	221	221	221	221	0,99
2	32,1	32,1	32,1	32,1	0,80	238	238	238	238	0,99
3	18,8	18,8	20,4	20,4	0,90	134	134	141	141	0,96

4	21,9	21,9	23,1	23,1	0,91	150	150	157	157	0,98

The 1250 S/s sampling rate is strongly correlated with the higher sampling rate in all tests; hence, the lower rate is sufficient for the welding electrical signals characterization. It is also important to note that was no change in both signals average and RMS values in all tests, taking into account the resolution desired for each parameter. Finally, adjusting the sampling rate of the Pulsed MIG (MIG-P), it was simulated a square wave of variable frequency and the same calculations have been made about it. For frequencies up to 300 Hz, a 1250 S/s sampling rate shows br satisfactory, showing no distortion in average and RMS and a correlation coefficient of 0.82. The typical frequency range for the MIG-P is from 50 to 200 Hz (SCOTTI and PONOMAREV, 2008). The sampling rate, therefore, is appropriate for this process, if the proposal of monitoring is for technological approach.

3.2. Proposed Acquisition System

According to the stages defined in 2.2, devices and circuits for conditioning should be selected. The Hall Effect transducer LEM HT500-SBD was defined, with a measuring range of ± 500 A, effective linearity of 0.5%, frequency response at 50 kHz and output voltage ranging from ± 5 V (Lem Components, 2002). The transducer for wire feed speed is an encoder, Bourns EM14, of 64 pulses per revolution per phase (it has two stages) with a lag of 90 degrees between the phases to indicate the direction and speed of rotation up to 120 RPM (BOURNS, 2008). Figure 7 illustrates the transducers chosen. The electrical signals conditioning from the transducers is for the voltage signal made with an electrical circuit composed of a voltage divider to adjust to the range of the A/D converter, a galvanic isolator, ISO122P (BURR-BROWN, 1993), to protect the microcontroller (MCU), an Butterworth low-pass second order analog filter (Malvino, 2006) with cutoff frequency at 625 Hz and a buffer for impedance matching. For the current signal there is no need for galvanic isolation and the speed signal power is not required the use of any conditioning circuit.

Figure 7- Transducers: LEM HT500-SBD (left) e Bourns EM14 (right).

To the choose of the MCU is required prior knowledge of the requirements relating to it, as A/D converter resolution and sampling rate, the program memory and data amount in accordance with the wireless communication module (TCP/IP stack size, Tab. 4) and processing speed. According to the resolution requirement defined in Section 2.2, it is defined the A/D converter resolution of 12-bit (Tab. 7).

Table 7 – Comparison of resolution in the measurements for different resolutions of A/D converters.

	Range	Requirement	A/D 10 bits	A/D 12 bits	A/D 14 bits
Voltage	±100 [V]	0,1 [V]	±0,196 [V]	±0,048 [V]	±0,012 [V]
Current	±500 [A]	1 [A]	±0,978 [A]	±0,244 [A]	±0,061 [A]

The Microchip ZeroG ZG2100M was chosen as the Wi-Fi communication module. This choice is due to the documentation availability on the communication protocol, examples of TCP/IP stack use (the library cell is supplied by the manufacturer), and national technical support and, finally, integrated manufacture development boards availability. Table 8 directs the selection of MCUs for its use in data transmission efficiency with the device ZeroG ZG2100M.

Table 8 – Performance of TCP/IP stack for different MCUs (MICROCHIP, 2010).

Micro controller	MIPS	Wi-Fi Module	Data Rate (kbytes/sec)			
			TCP with (X) byte TX FIFO			UDP
			200	2000	8000	
PIC18F97J60	10.4	ZeroG ZG2100M	5	21	25	14
PIC24FJ128GA010	16	ZeroG ZG2100M	9	44	54	46
dsPIC33FJ256GP710	40	ZeroG ZG2100M	11	67	93	52

PIC32MX360F512L	80	ZeroG ZG2100M	12	66	94	53
PIC32MX795F512L	80	ZeroG ZG2100M	12	69	96	56

** MIPS – Million instructions per second; TX FIFO – Transfer queue.*

Considering the A/D converter resolution, processing speed and program memory and data amounts in each MCU, the dsPIC33FJ256GP710 was defined as the device to be used. Its transmission efficiency is equivalent to greater processing power MCUs with lower cost, and its 16 bit architecture with wide documentation (MICROCHIP, 2007) makes it more accessible to programming.

3.3. Proposed User Interface

With communication protocol and HTTP user interface defined in section 2.3, the following assumptions are needed for the user interface:

- Mean, Rectified Mean and RMS values calculation and display for the current and voltage signals, (documentation and monitoring);
- Continuous display of dynamics graphs with time set (window), (monitoring);
- Possibility of storage of data received, (documentation);
- System versions information, both in monitoring and user interface;
- Manual for using the system;
- Administrative Settings (like updated versions of the firmware).

Is important to observe that all interactions with users will be dependent only on the use of an updated web browser, available free of charge to any device with network access in which the monitoring system is inserted.

4. CONCLUSION

A study of a wireless monitoring system for arc welding process was proposed in this work. The signals to be monitored, voltage, current and wire feed speed, have been defined and characterized in their frequency characteristics. Sampling at 1250 S/s and an analog filtering at 625 Hz were determined enough to observe these signals with high reliability and no average and RMS information loss. To the physical system, a Hall effect transducer for current and an encoder for wire feed speed was chosen, as the dsPIC33FJ256GP710 processor board and the Wi-Fi module for data transmission. A Web Server has been shown the most appropriate, dynamic and flexible user interface. All the proposals were successfully completed, it is possible to conclude that the resulting system can be developed with own technology, scalability, portability, autonomy, low cost and flexibility/simplicity operation.

5. ACKNOWLEDGEMENTS

The authors thank to LAPROSOLDA / UFU by the availability of personnel and infrastructure, CAPES for funding the scholarship, CNPq (Process 473953/2009-9 and Process 307554/2008-2), FAPEMIG (Process TEC - APQ- 01389-08), and PROPP-UFU.

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