# Design of a Virtual-Instrumentation System for a Machining Process

E. Portillo, I. Cabanes, *Member, IEEE*, M. Marcos, *Member, IEEE*, D. Orive, and J. A. Sánchez

***Abstract*—This paper presents a virtual-instrumentation system (VIS) that aims at measuring the evolution of key magnitudes in a nonconventional machining process called wire electrical discharge machining (WEDM). The VIS consists of two well-different parts: the acquisition system that measures process signals (voltage and current) and the virtual measurement of relevant magnitudes (such as energy, peak-current distribution, and ignition delay time). The data-acquisition system provides flexibility and ease of storing tests under different machining conditions without extra hardware construction or adaptation. It is based on a commercial data-acquisition board that works at very high frequencies (up to 10 MSamples/s). The virtual measurement is carried out by modeling and processing the acquired signals. The VIS has been employed to monitor and detect low-quality cutting regimes in WEDM.**

***Index Terms*—Data acquisition, electrical discharge machining, virtual-instrumentation system (VIS), virtual sensor (VS).**

## I. Introduction

WIRE electrical discharge machining (WEDM) is based on material removal through a series of controlled electrical discharges applied between two electrically conductive electrodes (workpiece and wire electrode). The discharge rate is about a few microseconds. A dielectric fluid is injected into the gap, which is the space between the electrodes. In order to provoke a discharge, the machine power supply applies a voltage (specified by the operator by means of the open-voltage parameter) between the electrodes. Then, the discharge is produced after the dielectric ionization. The period of time when the ionization happens is known as the ignition delay time. Between two consecutive discharges, the dielectric cools the gap and removes the erosion debris during an adjustable period of time known as the off-time.

Each discharge is characterized by both the gap voltage and the discharge current. Fig. 1 shows a schema of a WEDM process with a theoretical discharge pulse represented by its voltage and current (the final shape of the signals depends on the specific machine). Both signals can directly be measured from the WEDM machine. The basic variables of a discharge are marked on the signals: peak current $(I_{\mathrm{p}})$, gap voltage $(U_{\mathrm{g}})$, ignition delay time $(t_{\mathrm{d}})$, and discharge duration $(t_{\mathrm{e}})$.

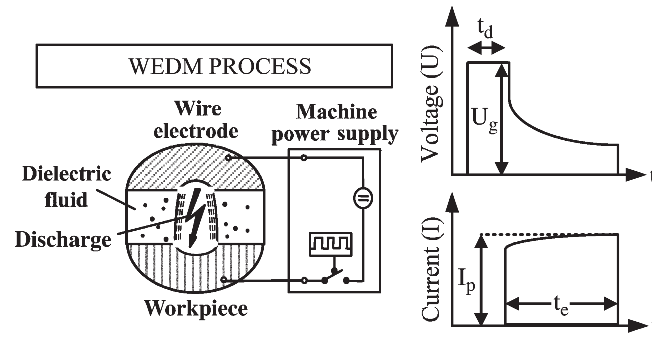


Fig. 1. Schema of WEDM process.

The most common choice to measure, analyze, monitor, and control this machining process has been developing proprietary hardware (HW) systems that infer relevant magnitudes of the machining process, for instance, monitoring circuits that estimate the position on the wire where the discharge happens [1]–[5]. Other authors have developed detecting circuits aimed at counting discharges in a sampling interval [6]. Another common strategy consists of applying some criteria to classify the discharges and then developing circuits that count each type of discharges in a sampling interval [7]–[9].

However, the time invested in the design and development of the proprietary HW systems is significant. Moreover, these HW systems present a lack of flexibility since they have been normally designed for a specific type of power supply of the studied machine, specific machining parameters, and workpiece material. Thus, if any of these factors is modified and it has not previously been considered during the design of the HW system, it should be reconstructed in order to adapt to the new machining conditions.

Another limitation found in their works is that dedicated circuits are designed for measuring a restricted number of key magnitudes. Thus, it is not feasible to consider all the magnitudes that characterize the process, since only some preselected ones are measured. This may limit the types of future analysis to be carried out.

A virtual-instrumentation system (VIS) would allow to design simultaneous virtual sensors (VSs) of different magnitudes in a versatile way. In this respect, this paper presents a flexible, configurable, and extensible VIS aimed at measuring any kind of magnitudes from a basic physical signal acquisition. The

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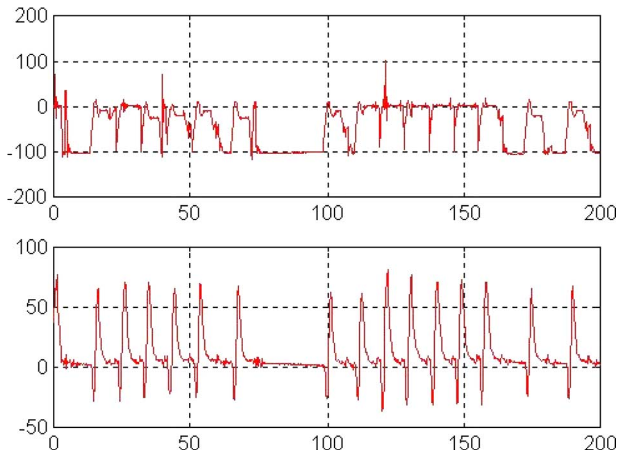

Fig. 2. Snapshot of 200 $\mu$s with 15 discharges. Fifty-mm-height tool-steel (AISI D2) workpiece.

VIS employs a commercial data-acquisition board that can continuously capture current and voltage signals at very high sample rates that range from 20 kSamples/s to 10 MSamples/s per channel. By processing these signals, four VSs have been designed and developed using a virtual-instrumentation software. Therefore, the use of the virtual-instrumentation software not only facilitates the acquisition-system configuration and programming but also provides the researcher with the same programming tool to develop VSs.

The applicability of the developed VIS has been proved in a real industrial application that monitors and detects low-quality cutting regimes in WEDM.

## II. Acquisition-System HW

An acquisition system that is employed to acquire the current and voltage signals has been implemented. The acquisition HW has been defined considering the characteristics of the current and voltage signals. One of the intrinsic features of the discharges produced in WEDM is their strong stochastic nature. This is the reason why two equal pieces machined with the same machine parameters never produce the same sequence of discharges. In fact, the voltage and current of consecutive discharges can vary notoriously even under stable cutting conditions. To illustrate this, Fig. 2 shows a snapshot of 200 $\mu$s with 15 discharges that are consecutively produced using the user parameters obtained from a machine lookup table.

The WEDM machine specification establishes that the discharge duration of common discharges ranges approximately from 2 to 5 $\mu$s and that the ignition delay time is higher than 2 $\mu$s in the 99% of the discharges. The upper limit of the voltage signal is determined by the open-voltage machine parameter (130 V in this case). The upper limit of the peak current is 230 A and depends on the power parameter. Thus, the acquisition-system requirements have been as follows: continuous-time acquisition, a sampling and storage rate of 5 MSamples/s per channel that provides at least ten samples per current and voltage pulse, and two analog input channels with independent resolution. All these requirements are met by the commercial acquisition board NI-6115 with a PCI bus. Some of the characteristics of this board are as follows [10]:

1) four analog input channels;
2) no multiplexer switching between the channels;
3) dedicated A/D converter per channel;
4) 12-b resolution;
5) 10-MSamples/s per channel maximum acquisition sampling rate (including the four channels acquiring and storing to disk concurrently);
6) AC or dc coupling;
7) eight input ranges from ±200 mV to ±42 V. Each channel can independently be configured for a different voltage input range. This independently allows to really have a 12-b resolution per channel of the input range;
8) antialiasing filters per channel;
9) differential measurement;
10) absolute accuracy at full scale of 10.22 mV in ±10-V working range.

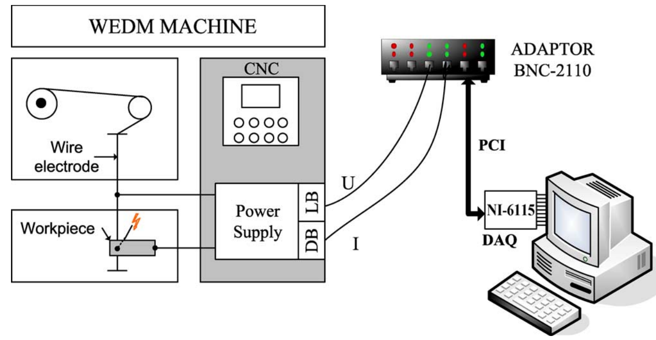


Fig. 3. Main component of the acquisition system.

Fig. 3 shows the main component of the acquisition system. Voltage and current are directly acquired from the logic board (LB) and the discharge board (DB) located in the WEDM machine, respectively. In order not to exceed the maximum working voltage of the board (42 V), the voltage signal is measured from a voltage divider located in the LB of the WEDM machine. Thus, the voltage input range is modified as follows:

$$\frac{U_i}{F} = \frac{130}{26.43} = 4.92 \text{ V} \tag{1}$$

where $U_i$ is the open voltage, and $F$ is the attenuation factor applied by the voltage divider. Therefore, the voltage input channel has been set to ±10 V to achieve a good agreement between resolution and bandwidth. The voltage signal is transmitted using a low-voltage shielded cable.

The current signal is taken from the DB of the WEDM machine through the A622 Tektronix current probe. It provides 10 or 100 mV/A. Since the maximum input current of the probe is 100 A, it is measured from four of the ten existing current cables. Thus, the current input range is modified as follows:

$$I_{\max} \cdot \text{PO} \cdot \text{CP} = 230 \text{ A} \cdot 0.1 \frac{V}{A} \cdot \frac{4}{10} = 9.2 \text{ V}. \tag{2}$$

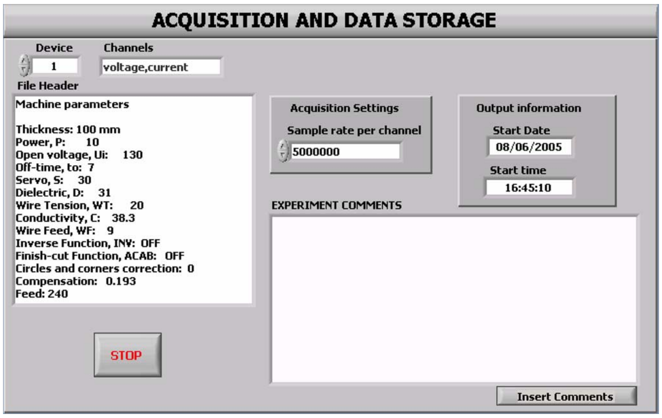


Fig. 4. Acquisition VI.

Where $I_{\max}$ is the upper limit of the current signal, PO is the probe output, and CP is the proportion of the number of cables. The current channel input has also been set to $\pm 10$ V.

Both signals are transferred to the BNC-2110 noise-rejecting Bayonet Neill-Concelman (BNC) I/O connector block which is attached to NI-6115 data-acquisition board through SH68-68-EP noise-rejecting shielded cable. Each BNC connector placed in the BNC adapter is provided with a two-position switch: floating source (FS) and ground-referenced source (GS). As its label points out, the FS is selected when measuring floating-signal sources. In this case, the amplifier negative terminal connects to the ground through a 5-k$\Omega$ resistor in parallel with a 0.1-$\mu$F capacitor. This resistor provides a return path for the $\pm$200-pA bias current. Otherwise, the FS is not likely to remain within the common-mode signal range of the programmable gain instrumentation amplifier (PGIA). Consequently, the PGIA saturates, causing erroneous readings. As GS is concerned, it is selected when measuring GSs for avoiding ground loops [10], [11].

The acquisition-system PC is a 3.6-GHz Pentium IV provided with 300-GB storing-space hard disk and 2 GB of RAM memory. Since the file system is new technology file system (NTFS), the file-size limit to continuously be stored mainly depends on the hard-disk capacity. In the specific case of wire breakage in WEDM, the duration of a test continuously acquired can last from 4 to 60 min, which corresponds to around 5 and 75 GB, respectively.

## III. Acquisition-System Software

Labview high-speed libraries have been used for the development of applications aimed at exploiting the acquisition-system HW.

One of these applications is the acquisition VI. In a first phase, it has been necessary to acquire and record experimental tests in order to analyze the two basic signal behaviors (current and voltage). Based on the results of this analysis, the VSs have been designed using the acquisition VI. This VI performs signal acquisition at the required sample rate (up to 10 MSamples/s per channel). Fig. 4 shows the acquisition VI user interface.

Since the acquisition is continuous, a circular buffer is used. Hence, while the buffer is filled with data from the NI-6115 board, another subVI retrieves blocks of data from the buffer. When the end of the buffer is achieved, the acquisition VI returns to the beginning and continues filling the same buffer. When the data are overwritten before being retrieved, the VI sends back an error. In order to avoid this error, two parameters have been adjusted: the buffer size and the number of scans to be stored on a disk at a time [12]. One sample is equal to 2 B. Given a total sampling rate of 10 Msamples/s (5 MSamples per signal), the hard-disk maximum transfer rate should be higher than 20 MB/s. Therefore, a high-performance hard disk that achieves more than 30 MB/s has been selected. The maximum buffer size that is allowed by Labview high-speed libraries is approximately 15 MSamples. Considering the required sampling rate and the maximum buffer size, it would be filled in 1.5 s. Thus, the maximum time delay between the two operations (filling and retrieving from the buffer) is 0.5 s. A value of 5 MSamples for the number of scans to be stored on a disk at a time is enough to avoid samples to be overwritten.

Before executing the VI, the user has to fill in four fields. The first field is the number of device assigned to NI-6115 acquisition board. Second, the user has to introduce the names of the virtual channels. A virtual channel is a shortcut to a preconfigured analog input channel of the NI-6115. Every time a VI calls a virtual channel, the respective analog input adopts the preconfigured characteristics such as the gain and the grounding mode. The third field is the file header. The last field is the sample rate per channel, which is 5 MSamples/s in this case.

This VI stores on a disk a data file, known as data filename.BIN, that contains the file header, the test date, the test start time, and the current and voltage data. The BIN file format optimizes an online data storing as well as the storing capacity.

Once the acquisition is stopped, the VI reminds the user to insert comments and incidents occurred during the test. The VI saves a second file named data filename_comment.BIN with the test comments in the same directory as the data file.

Storing the data files on DVDs has been decided in order to deal with the significant size of the generated files and the important number of tests to be carried out. Taking into account DVDs' capacity, it has been necessary to develop a VI in order to split those files with a bigger size than 4.7 GB. Although there are several free applications for splitting files, a specific VI has been developed to obtain a well-categorized experimental database. Thus, each partition is preceded by the original file header and other parameters which were defined by the acquisition VI.

In summary, the acquisition system has been used for measuring and recording the process signals (current and voltage) in a set of experimental tests in different cutting regimes. As explained in the next section, the results of the analysis of the exhaustive experimental database have allowed to define the VSs.

## IV. Virtual Sensors (VSs)

At the sight of the stochastic nature of the discharges, a preliminary analysis of the experimental database confirmed that one unique discharge is not relevant to recognize low-level quality regimes in WEDM. In contrast, a specific trend in the behavior of a set of consecutive discharges indicates the

TABLE I
COV OF THE REFERENCE VALUES

| | $E_{ref}$ | $I_{ref}$ | $tdh_{ref}$ | $tdl_{ref}$ |
|---|---|---|---|---|
| CoV (%) | 2,08 | 4,64 | 2,51 | 0 |

quality of the cutting regime. In this preliminary analysis, stable and degraded cutting regimes have been considered in order to determine the relevant magnitudes that allow identification of the quality of the cutting regime and, consequently, anticipation of a wire breakage. For instance, it has been observed that a rise in discharge energy produces a higher thermal load on the wire, which increases the risk of a wire breakage, and low ignition delay times indicate the appearance of short circuits between the electrodes. The latter can also produce a wire breakage [13]. In this respect, the idea of a VS is to infer the behavior of a set of discharges from the basic variables of each discharge pulse. The main advantage of VSs is that they can be constructed in a versatile way. Thus, if other magnitudes are required in the future, VSs can easily be constructed in the same manner. Four VSs have been defined that aimed at identifying the quality of the cutting regime: VSs for energy (VS-E), peak current (VS-I), high ignition delay time (VS-TDH), and low ignition delay time (VS-TDL).

The mathematical model of the VSs is based on a relative calculation with respect to reference values. It is defined as the moving relative frequencies that exceed or are lower than the reference values of the peak current, discharge energy, high values of the ignition delay time, and low values of the ignition delay time. The reference values have been established through the analysis of high-quality cutting tests from the WEDM machine. They are defined as the class when the relative cumulative frequency achieves 99% in stable cutting in a statistical sample size of 0.5 s, which is equivalent to approximately 40 000–50 000 discharge pulses. This statistical sample size yields a small coefficient of variation (CoV) of the reference values (see Table I). Thus, the statistical sample size is representative to define the appropriate reference values. The CoV has been calculated for 40 samples of 0.5 s each.

The virtual measurements are calculated along time, respectively, in a sliding window $N$. For instance, a time window of size $N$ that is equal to 5 ms concentrates an information about a range of 400–550 discharges. The sliding window $N$ is divided into $M$ basic windows of size $N/5$, which is aimed at making the results independent from the starting time of the analysis and at reducing the delay time for detecting a low-quality cutting regime. When the newest basic window $M$ fills up, it is appended to the sliding window, the oldest basic window is removed, and statistics over the sliding window are recomputed.

The generic mathematical expressions and the associated algorithms that are used to obtain the virtual measurements carried out by the VS are the following.

1) For each section $j$ of size $M$, compute the number of discharges that exceeds or is lower than the reference value of each VS $(n(\mathrm{VS\_ref})_{\mathrm{j}}$ and the total number of discharges $(n_{Tj})$.
2) For the first block of samples contained in a time interval of size $N$, compute the number of discharges that exceeds or is lower than the reference value of each VS $(S_{\mathrm{VS\_ref}})$ and the total number of discharges $(S_T)$

$$S_{\mathrm{VS\_ref}} = \sum_{j=0}^{N} n(\mathrm{VS\_ref})_j \tag{3}$$

$$S_T = \sum_{j=0}^{N} n_{Tj} \tag{4}$$

where $j = 0 \cdot M, 1 \cdot M, 2 \cdot M, 3 \cdot M, \ldots, N$.
3) For the following sections $j$ of size $M$, compute the evolution of the VS measurements

$$E(\mathrm{VS})_{j+1} = \frac{S_{\mathrm{VS\_ref}_{j+1}}}{S_{T_{j+1}}} = \frac{S_{\mathrm{VS\_ref}_j} + n(\mathrm{VS\_ref})_{j+1} - n(\mathrm{VS\_ref})_{j-N}}{S_{T_j} + n_{T_{j+1}} - n_{T_{j-N}}} \tag{5}$$

where $j = N + 1 \cdot M, N + 2 \cdot M, N + 3 \cdot M, \ldots$.

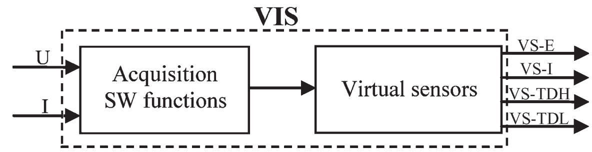

Fig. 5. VIS basic internal structure.

The VIS has been implemented in Labview. The basic internal structure is shown in Fig. 5. As expected, the VIS employs the software libraries used in the acquisition VI.

For the development of the VIS, a user-friendly interface has been developed. It is divided into two sections: input and output values.

From the input-value section, the user introduces input data related to the desired analysis time and to the current machining parameters.

The output section monitors the virtual measurements. Fig. 6 shows the VIS interface. The graphic on the right side depicts the evolutions of the measurements of the four VSs.

## V. APPLICATION EXAMPLE

In order to prove the applicability of the VIS, it has been employed and extended to develop a diagnostic system. The diagnostic system is an extension of the VIS for a specific application. This reflects the flexible and extensible characteristics of the defined system.

It detects in advance the low-quality cutting regimes and, in the worst case, anticipates a wire breakage in WEDM. Wire breakage is one of the most detrimental effects since the machining process is stopped until a new wire is threaded.

The developed diagnostic system anticipates a wire breakage considering the parameters stated by the user, the virtual measurements calculated from the WEDM machine data (current and voltage signals), and the experimental knowledge (see Fig. 7). The experimental knowledge has been inferred from the analysis of the stable and unstable experimental

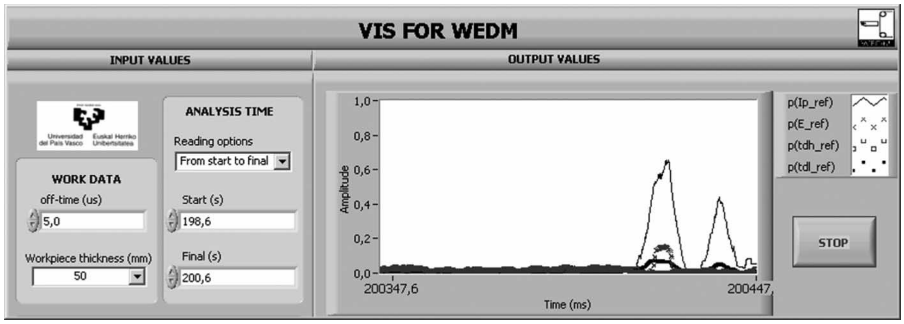


Fig. 6. VIS interface.

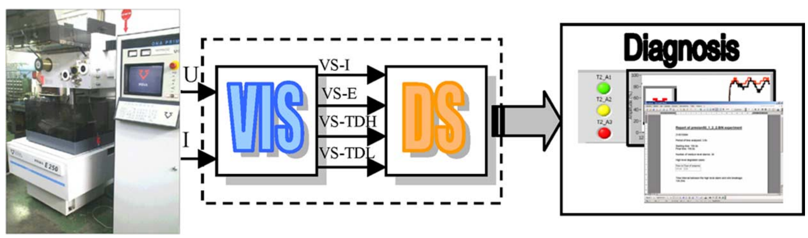


Fig. 7. Diagnostic system structure.

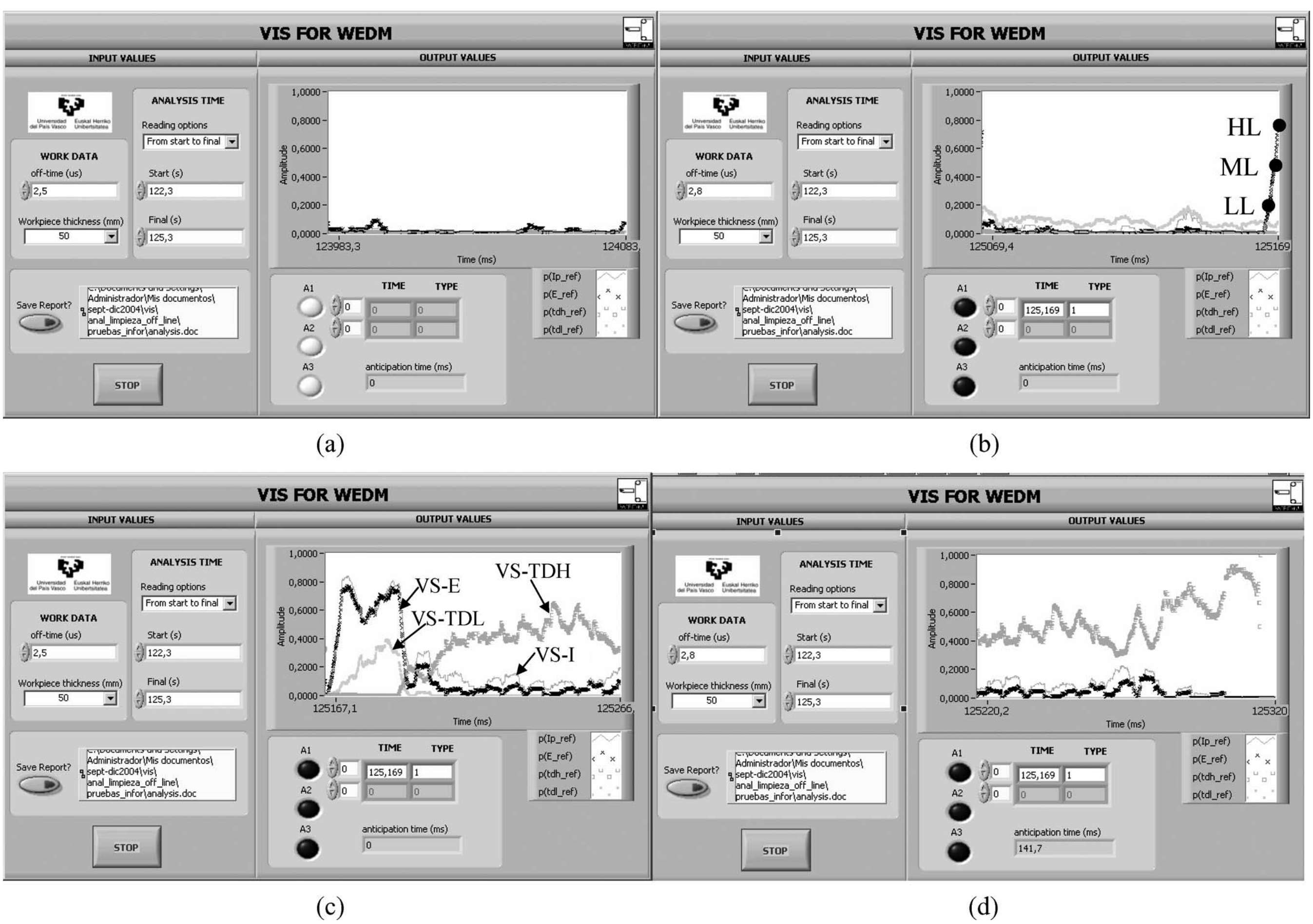


Fig. 8. Diagnostic-system application example. (a) Virtual measurements with an acceptable level of stability. (b) Virtual measurements with low-quality regime. The HL alarm is triggered due to an increase of the energy virtual measurement. (c) Virtual measurements after the triggering of alarms. (d) Virtual measurements just before the wire breakage.

tests. In particular, different types of wire-breaking phenomenon have been classified. Thus, depending on the behavior of the described VSs, low-level (LL), medium-level (ML), and/or high-level (HL) alarms are triggered. The alarms inform about the increasing risk for occurring instabilities and wire breakage. The alarms turn different colors when triggered.

The information about the degraded cutting regime being detected and the trigger time instant are also displayed. The user can also obtain an automatic summary report of the analysis. The report contains an information about the specific working parameters, the date of the test, the total time interval analyzed, and the start and final times of the analysis. It also reports the type of alarms being detected, the time instant, and the associated degraded phenomenon. Finally, it shows the time interval since the HL alarm is triggered until a wire breakage happens.

Fig. 8 shows some snapshots of the diagnostic-system execution. The example refers to one of the performed experimental tests on the WEDM machine. In particular, the experiment consists of provoking the wire breakage by increasing the discharge frequency. Fig. 8(a) shows the virtual measurements some seconds before the wire breakage. At that time, the level of stability is quite acceptable since any virtual measurement achieves a high value. Consequently, none of the alarms is triggered.

Fig. 8(b) shows a sudden increase in the energy virtual measurement. This provokes the progressive triggering of the LL, ML, and HL alarms. In that moment, the fields Time and Type register, respectively, the time instant in which the HL alarm has been triggered (125 169 s) and the type of wire-breaking phenomenon that has provoked the triggering of the alarm (type 1, which corresponds to a sudden increase in the energy virtual measurement).

The VIS also allows visualization of the behavior of the virtual measurements after the triggering of alarms [see Fig. 8(c) and (d)]. Fig. 8(c) shows the important increases in the energy measurement as well as in other virtual measurements such as low values of ignition delay time. Finally, Fig. 8(d) shows the virtual measurements just before the wire breakage. The diagnostic system has foreseen the wire breakage 141.6 ms before it happens.

## VI. Conclusion

The use of virtual measurements provides important advantages for the analysis and development of machining solutions in the WEDM process. The advantages are related to the development of more extensible and flexible analysis systems compared to those based on the HW *ad hoc* design. According to this, a virtual-instrumentation software has been designed and developed in this paper. It consists of two parts. The first part is based on a data-acquisition board that can continuously capture current and voltage signals at very high sample rates that range from 20 kSamples/s to 10 MSamples/s per channel. The second part contains four VSs that measure the key-magnitude evolution of peak current, discharge energy, high values of ignition delay time, and low values of ignition delay time, respectively.

In this paper, the applicability of the VIS has been proved in the design and development of a diagnostic system that allows detection of the low-quality cutting regimes in WEDM in advance. A total of 50 experimental tests performed on a WEDM machine has been validated. The results have been successful, showing an average system efficiency of 96% in workpieces of 50-mm height. The efficiency ratio considers both the influence of false-negative and false-positive cases, and it does not take into account the experimental tests carried out with an erroneous adjustment of mechanical components.

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