A Novel Real-Time Wear Detection System for the Secondary Circuit of Resistance Welding Guns

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Abstract: Currently, many resources are invested in high-production automotive factories to correct quality defects caused in the bodywork due to secondary circuit wear. In the same way, energy losses are generated due to the increase in resistance caused by secondary wear, thus reducing efficiency and increasing the final cost of the product. This happens because, at present, there is no method that allows the predictive detection of problems in the secondary and the arms of the welding gun. Consequently, a solution must be developed to carry out predictive maintenance applicable to the automotive industry to detect this defect. This research provides an answer by proposing a method to detect variations in the state of the secondary of the welding gun using existing data in the welding process, specifically, the evolution of the angle of degassing of the IGBTs of the welding control. To validate the relationship between the control shift angle and the increase in wear, an electronic simulation software was used to simulate the behaviour of the real welding control.

1 INTRODUCTION

The resistance welding process is one of the most widely used in the automotive industry for joining the metal parts of the bodywork, representing around 90% of all welded joints in a bodywork (Koskimäki et al., 2007; Yu et al., 2014; Hwang et al., 2013). As the name of the process indicates, it is the resistance to the current flow of the metals to be welded that causes the localized increase in heat and the formation of the nugget welding. For this process, it is also necessary to exert pressure on the parts to be welded for a specific welding time. Ultimately, therefore, welding is generated by a combination of heat, pressure, and time.

Despite being able to summarize the resistance welding process as the combination of heat, pressure and time, this process is highly complex, since it involves different fields of study such as electromagnetism, electronics, thermodynamics, materials and mechanics. (Li et al., 2007)

Throughout different investigations, it has been described how the different welding parameters can influence the quality of the welded joint, such as pressure (Zhou et al., 2014; Sun et al., 2007; Ibáñez et at., 2021), the current (Aslanlar et al., 2007; Hwang et al., 2011), the welding time (Aslanlar et al., 2008) or the misalignment of the welding electrodes (Ibañez et al., 2020). From all these studies it can be concluded that either due to external factors or due to welding parameters, there are many factors that directly or indirectly affect the final quality of the welded joint.

To achieve adequate welding quality, it will therefore be necessary to guarantee that the parameters influencing welding quality remain stable over time. One of the defects that can cause variations in the application of the correct parameters in welding, especially in the application of current, is the mechanical state of the electrical circuit of the welding gun, specifically, of the secondary circuit of the gun. , that is, the arms of the welding gun.

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Over time, the way of applying the current to the welding points has been changing to achieve the highest quality with the best possible efficiency and power consumption. If the behavior of a single-phase alternating welding machine is observed, it can be determined that there are inherent losses in the alternating voltage supply (Zhou et al. 2001). For this reason and to guarantee the optimum quality of the welding, three-phase welding machines are used. The three-phase voltage is rectified to convert it from single-phase to direct current. This rectified current results in lower power losses and higher quality welding (Munesada et al.2010).

In this type of converter-based welding machines, the three-phase voltage of the industrial mains line, typically 440V and 50/60Hz, is converted to single-phase direct voltage and stored in a capacitor bank to smooth the voltage.

The capacitor bank is connected to the inverter circuit formed by an IGBTS bridge that modulates the wave at a higher frequency than the line. Usually, to achieve higher welding quality and greater control over the welding current, the wave is modulated at a frequency of 1000Hz, this type of machine being known as mid frequency direct current (MFDC).

The alternating wave produced at the output of the inverter feeds the single-phase transformer of the welding gun. (Saleem et al. 2011). This will allow to have a continuous current in the secondary of the transformer. This working mode prevents the welding current from having zero crossings that would cool the part, allowing faster heating of the welding gun. In addition, by working with direct current, inductive power losses or problems with the magnetic material of the machine are avoided (Wei, 2004; Nagasathya et al 2013,).

In MFDC machines, the secondary voltage is determined by the primary voltage, which, as mentioned, is modified by the inverter controlled by the IGBTS. If a constant IGTS control shift angle is maintained, the secondary voltage should remain constant. Starting from this point, it can be stated that the welding current, according to Ohm's law, will be determined by the resistance of the secondary, that is, the resistance of the welding arms and the resistance of the metal to be welded. As the total resistance of the secondary circuit increases, the current flowing between the electrodes decreases (Arslan et al 2020). This makes it essential to guarantee the maintenance of the resistance of the welding arms in such a way that the way in which the current is applied to the metal to be welded is not affected.

2 MFDC MACHINE AND SECONDARY LOAD

The welding current is a fundamental component to chieve optimal welding quality. In the electronic diagram of Figure 1, the stages of the power circuit can be observed differently from the three-phase line of the electrical network to the continuous single-phase line of the welding electrodes.

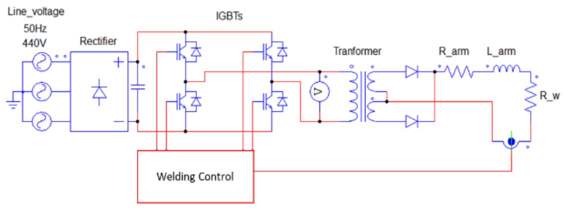

Figure 1: Welding machine electrical schematic.

Modern welding machines have a current control system, in such a way that it is guaranteed that the current established by parameters is being applied to the metal to be welded. The welding machine analyzes the secondary current every millisecond and modifies the control shift angle of the IGBTs firing to modify the primary voltage, as it can be seen in the results obtained from the simulation in figure 2 for the different angle s of shot (α=30°, α=80° and α=105°). As the control angle between the control signals of the IGBTs increases, the effective primary voltage decreases, thus decreasing the secondary voltage and current (Zhou & Cai,2014).

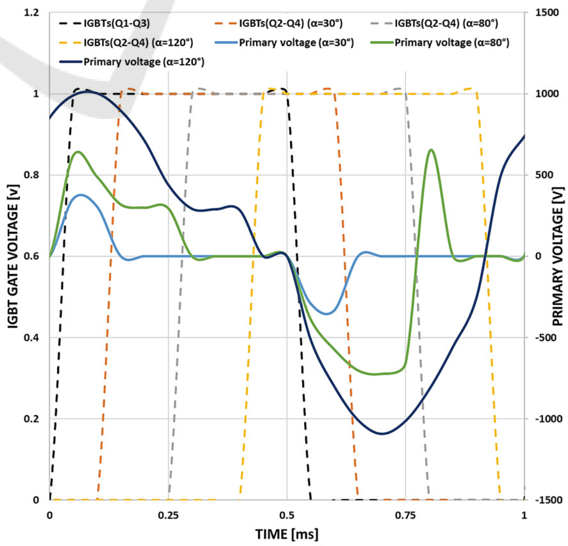

Figure 2: Response of the primary voltage as a function of the control shift angle of the IGBTS.

From Figures 1 and 3, the behavior of the IGBT rectifier can be divided into six segments in one period. These six segments can be summarized as:

- State 1: In this state, the IBTS Q1 and Q4 are conductive, therefore it is in active mode with positive output voltage and output current i.e., the DC side power is converted to the load.
- State 2: At this point Q1 and D3 go on, freewheeling mode with zero and positive output voltageoutput current.
- State 3: Diodes D2 and D3 then conduct in feedback mode with negative and positive output voltage and output current. Power from the load is sent back to the DC side.
- State 4: returns to active mode with Q2 and Q3 conducting with negative output voltage and output current. The DC side power is converted to the load. State 5: Return to freewheeling mode with Q2 and D4 conducting with zero and negative output voltage and output current.
- State 6. Finally, Q1 and D4 conduct in feedback mode with positive voltage and negative output current. Power from the load is sent back to the DC side.

According to this description, the output voltage will depend on the period that it is in each of the states, that is, on the control shift (. Therefore, by adjusting the control shift, the output voltage can be adjusted.

The Fourier series of the output voltage can be obtained as follows:

$$V_{prim} = \sum_{n=1,3,5\ldots} \frac{4V_d}{n\pi} \sin\left(\frac{n\alpha}{2}\right) \cos(n\omega t) \qquad (1)$$

Where V_d represents the output voltage at the rectifier and α is the control shift.

In this way, the secondary voltage can also be related to the control shift angle of the IGBTs, as the welding control increases the control shift angle between the signals, the secondary voltage is reduced. In a similar way and due to the power conservation law, the secondary current will also be influenced by the primary power, therefore, as the control shift angle between the control signals increases, the welding current decreases, considering constant resistance, can be obtained from the simulation figure 3, in which the relationship between the control shift angle and the final welding current is observed.

Following Ohm's law, the welding current is determined not only by the secondary voltage but will also be influenced by the resistance of the secondary circuit. This resistance of the circuit can be divided into two blocks: The first load can be defined as those elements that do not directly participate in welding, that is, joints between the copper elements of the gun, cooled braids, welding arms, etc. If the welding gun is in an optimal state of maintenance, this resistance should remain constant. In the second load block are those elements that have an active role in welding, that is, this resistance is made up of the electrode holders, the electrodes, the connection between the electrode and the metal, the resistance of the metal and the resistance of the union between the metals to be welded. This resistance will depend on the type of material, the type of electrodes and the wear of the electrodes.

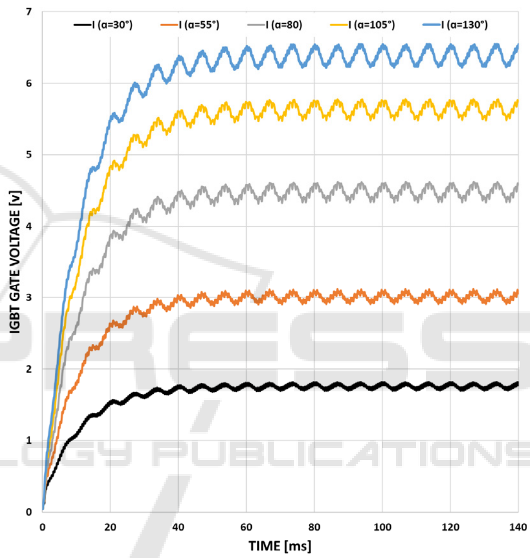

Figure 3. Response of the secondary current as a function of the control shift angle of the IGBTs.

Due to this variability of the welding points and to guarantee the energy supplied to the joint and therefore the quality of the joints, the welding machines regulate the control shift angle of the IGBTs in such a way that the current supplied does not depend on resistance, but this will depend solely on the control of the welding machine.

3 SECONDARY CIRCUIT WEAR

Eventually, mainly due to the erosion caused by the fatigue of the work cycles of the welding guns, the secondary circuit begins to show wear. Specifically, these wears appear in the first block of the load defined in the previous section.

The wear that can appear in the secondary is very diverse, since, based on the definition of this load block, it is made up of different components and joints, as shown in figure 4. The main worn elements that can occur in a secondary are:

- Corrosion on welding arms caused by water leaks at welding gun joints or caused by changing electrodes.
- Transformer pins worn or fired due to poor cooling or lime scale.
- Cracked arms caused by metal fatigue over time.
- Clogged refrigerated braids.
- Cracked or missing weld strips.

All these wears contribute notably to the increase in the resistance of the first load-bearing block. This first block does not initially have a direct influence on the weld if the welding machine control can reach the optimum welding current. However, as these wears become more noticeable, typical welding problems begin to appear, such as sparks, inconsistent weld joints, or even missing welds.

On the other hand, an increase in secondary resistance means an increase in the power consumed during welding. If this increase in resistance is caused by wear, the power supplied to the welding point will be the same, however, the power consumed during the process will increase, causing greater energy consumption.

Figure 4: Real cases of wear in the secondary circuit.

Figure 5 shows the control shift angle necessary to reach each of the currents. Each of the curves represents a parasitic resistance value of the secondary corresponding to the simulated resistance value of the first block, keeping the second block with a constant load. In this way, it can be verified that as the resistance of the secondary caused by wear increases, the angle necessary to achieve the desired current also increases, that is, the voltage of the primary increases and therefore the energy consumed during welding.

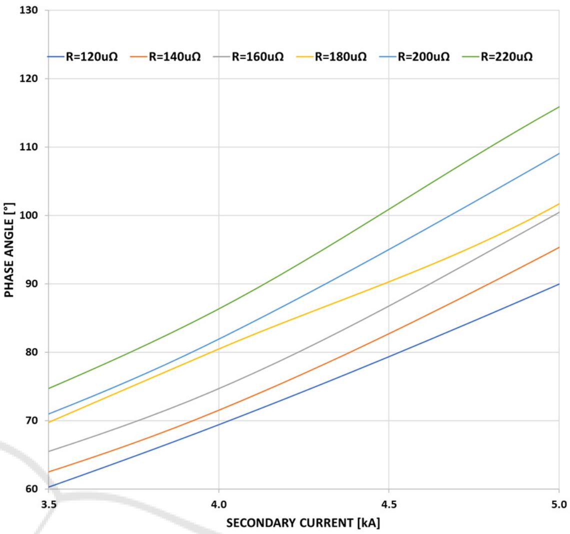

Figure 5: Evolution of the control shift angle depending on the resistance of the secondary.

4 SECONDARY WEAR DETECTION

Due to the implications of this defect in both welding quality and energy consumption, its early detection is essential.

Specifically, a method is presented for the predictive detection of secondary circuit wear by monitoring the control shift angle of the IGBTs. The method bases its operation on the collection of welding data in real time from the welding guns during their normal work cycle.

The welding cycle of a welding gun in a real welding line can be described as: the new electrodes are placed on the electrode holder and welding points begin to be made on the metal to be welded, in the specific case of the manufacture of the car body, the characteristics of the metals to be welded vary depending on the piece, so each specific welding joint needs its own parameterization to achieve the required welding quality. After making a series of welding points, usually between 150-200 joints, the electrodes are milled to return them to their initial geometry and remove any dirt that might remain attached.

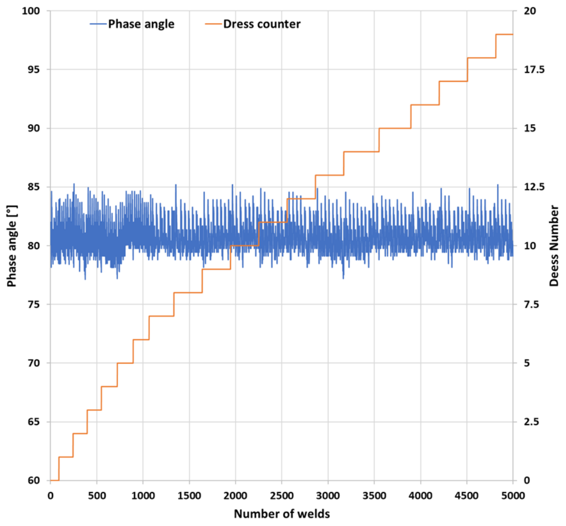

Figure 6: Control shift angle along the electrode life.

Within this work cycle, there is a variation of the welding current and the control shift angle of the IGBTs. This variation is given both by the differences in the metal to be welded and by the degradation of the electrode. It can be considered that this variation remains constant when passing from one duty cycle to another, so if the entire cycle is reduced to a single value, it could be stated that the average current and the control shift angle should remain constant.

Figure 5 shows the control shift degrees for a welding gun together with the evolution of the number of joints made. It can be seen how despite the variation between each of the points represented, the trend remains stable.

After observing that the usual behaviour of the work cycle between milling is stable, the hypothesis can be raised since when the secondary circuit begins to show wear, a distortion will be observed in the wear data due to the correction of the welding machine to guarantee the desired current.

Figure 6 shows the actual data of a welding gun that shows a beginning of degradation. In this case, it is observed how it goes from a stable behaviour to a behaviour with a downward trend. This means that for the same welding current, the welding machine needs a higher electrical consumption and therefore the parasitic resistance of the secondary circuit has increased.

From the comparison of figures 6 and 7, it can be determined that by carrying out continuous monitoring of the control shift angle of the IGBTs, it is possible to detect changes in the parasitic resistance of the secondary circuit. In other words, the hypothesis of the analysis of the evolution of the control shift angle for the determination of the increase in wear in the secondary circuit of the welding machine is confirmed.

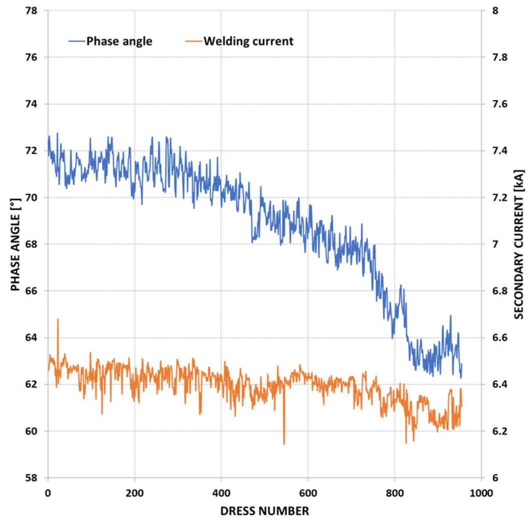

Figure 7: Evolution of the control shift angle with the wear of the secondary circuit.

5 REAL-TIME MONITORING SYSTEM

This method is designed to be applied in real welding lines, specifically, for this study, ARO type C and X welding guns controlled by means of the BOS6000 welding timer have been analysed.

First, a protocol is established for the acquisition of welding data in real time. This first step notably reduces the amount of data that is handled, since, as shown in the previous sections, each of the control shifts of each welding point is not analysed, but rather it is analysed based on the average control shift of all weld joints made throughout a milling cycle.

Therefore, this first step collects the data from the welding database, performs the average by cycles and indexes the data in the database on which the alarms are generated.

$$W = Q_3 + 1.5IQR \quad (2)$$

For the generation of alarms, a simple method of detecting changes in behaviour is established. As shown in equation 1, the warning limit is established by calculating the sum of the third quartile plus 1.5 times the interquartile of the data series. Similarly, the alarm level is established as the sum of the third quartile plus 3 times the interquartile as describe in equation 3.

$$A = Q_3 + 3IQR \quad (3)$$

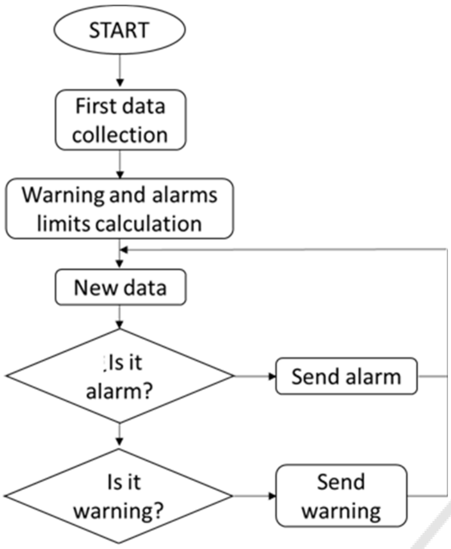

Figure 8: Alarm system.

Therefore, initially, an initial amount of data is needed to calculate the quartiles and thus establishing the warning and alarm limits, that is, an amount of data is needed to make an initial calibration.

In this way, when new data arrives from a specific welding gun, the data is labelled according to whether it is within the established warning and alarm thresholds. When a welding gun begins to show wear, the data will go from being in the good working group to the warning or alarm group, thus being able to carry out the necessary actions to reduce and minimize the quality problems associated with this defect.

In short, this entire system can be described according to the flow chart in Figure 8.

This programming has been carried out for validation on 450 welding guns installed on a real welding line. Usually, a welding gun installed on a high production line can do around 10,000 welding points per day, which would mean working with around 450,000 data per day. With the simplification of the average between milling cycles, this amount of data can be reduced to about 2500 daily data, which significantly reduces the number of resources needed for their management and analysis.

Figures 9 and 10 show two real graphs of behaviour for two different welding guns in a period of two months.

Figure 9, corresponding to what has been called gun A, shows the behaviour for a welding gun in good condition. The offset angle data oscillates within a range of two degrees but rarely reaches the warning threshold, so it is not necessary to carry out any maintenance on the welding gun.

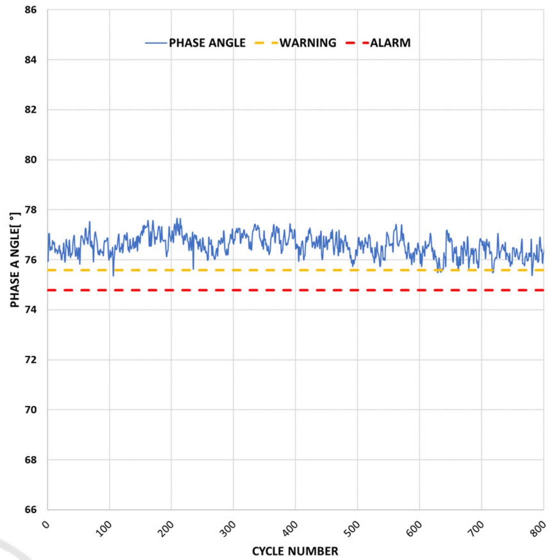

Figure 9: Evolution of the control shift angle gun A.

However, looking at Figure 10, the data shown presents three behaviour zones. In the first zone, or initial zone, the data is above the warning threshold but shows a variable behaviour. In the second zone, the data exceeds the warning threshold, and the value remains stable over a certain time, finally, and as no maintenance action is performed, the offset angle data increases significantly, which means that the resistance of the secondary is increasing exponentially.

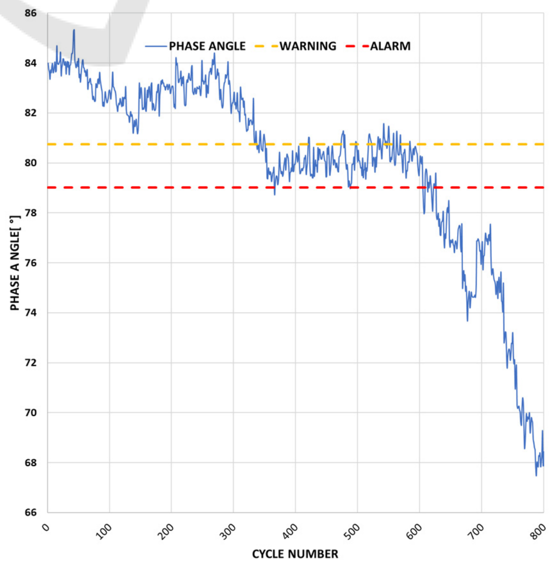

Figure 10: Evolution of the control shift angle gun B.

Similarly, comparing both figures it can be seen how the energy consumption, as described in the previous sections, remains constant over time for gun A, however, to perform the same welding cycle gun B needs each time a greater contribution of energy, which is lost in the parasitic resistance of the secondary.

In short, from the comparison of figures 9 and 10 it can be determined that the method chosen for setting the warning and alarm thresholds seems to be the right one to carry out predictive maintenance.

6 CONCLUSION

Throughout this paper, an effective method for detecting wear in the secondary circuit of resistance welding guns has been shown. This defect causes a decrease in welding quality and also an increase in energy consumption in resistance welding processes. Electronic simulation has shown how the relationship between current and control shift angle is easily demonstrable. From this relationship it has been assumed that if an analysis of the history of the data is carried out, an increase in the wear of the secondary welding circuit can be determined.

This method has been applied in a real factory, adapting the study for data reduction, and simplifying the analysis and sending of alarms to those responsible for maintenance.

From the real data acquired in the production lines, it has been possible to validate that this method is viable and reliable for the detection of wear problems in the welding lines through the analysis of the shift angle control.

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