Power quality analysis of Gas Metal Arc Welding process operating under different drop transfer modes

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Abstract. This work deals with power quality analyses related to the effect of different drop transfer modes in Gas Metal Arc Welding (GMAW) processes. The different drop transfer modes of GMAW process could be classified into: short-circuiting, globular, spray and pulsed. The correct choice of GMAW parameters is essential for optimal performance of the welding process. On the other hand, optimal parameters (from the point of view of the welding process) can lead to different power quality problems on the *AC* side of the local electric utility, according to the desirable transfer mode. In this sense, some power quality analysis based on metering results related to voltage fluctuations, harmonics and interharmonics will be presented to investigate the relationship between power quality problems and GMAW process operating under different drop transfer modes.

Key words. Interharmonics, harmonics, voltage fluctuations, GMAW, drop transfer modes.

1. Introduction

Gas Metal Arc Welding (GMAW) is one of the most common welding processes in industrial facilities around the world. Four types of GMAW drop transfer modes are identified and characterized by the size and frequency of the droplets, namely, short-circuiting, globular, spray and pulsed-spray. Depending on the mode, a specific electrical load take places, presenting intermittent behavior and causing some power quality disturbs at the local power systems, such as voltage fluctuations and flicker, and harmonics and interharmonics. However, the current literature does not clarify how much this disturbances can affect power quality. One reason for that could be the difficulties of determining this influence. Thus, the aim of this work is obtain the power quality analysis of GMAW process in different drop transfer modes.

2. GMAW drop transfer modes

The GMAW drop transfer mode is associated with many factors, including current level, wire diameter, arc length, voltage level, specific power supply characteristics and shielding gas. The importance and main characteristics of each transfer mode is presented in several sources [1], and they can be summarized in Fig.1. The three first transfer modes are classified as natural modes, while the fourth mode is considered as controlled mode, according to Scotti *et all* [2]:

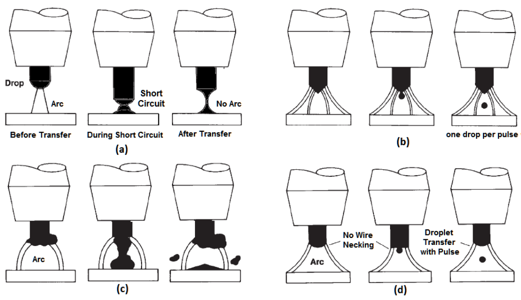


Fig. 1. GMAW drop transfer modes. (a) Short-circuiting, (b) Pulsed, (c) Globular and (d) Spray.

A. Globular drop transfer mode

GMAW with globular drop transfer mode is often considered the most undesirable of the four major GMAW variations. As the weld is made, a larger diameter ball of molten metal from the electrode tends to build up at the end of the electrode, often in an irregular shapes. When the drop finally detaches, mainly due to the gravity force, it falls to the workpiece, leaving an uneven surface and often causing spattering. As a result of the large molten droplet, the process is generally limited to flat and horizontal welding positions [2][3]. Electrically speaking, during this mode the current oscillates to high and low according to the process of the drop growth (progressively arc length shortening).

B. Short-circuiting drop transfer mode

In short-circuiting (or short-arc) GMAW, molten droplets form at the tip of the electrode, but, instead of dropping to the weld pool when their critical size is reached, they bridge the gap between the electrode and the weld pool, as a consequence of a not long enough arc length. This causes a short-circuit, which tends to extinguish the arc, which is quickly reignited after the surface tension of the weld pool pulls the molten metal bead off the electrode tip. This process is repeated about 100 times per second, making the arc appear constant to human eyes. This type of metal transfer provides better weld quality and less spatter than the globular variation, and allows for welding in all positions[2][3], but voltage and current oscillates to highs and lows (one inverted to the other) at the same frequency of the metal transfer.

C. Spray drop transfer mode

Spray transfer was the first metal transfer method used in GMAW. In this GMAW process, very small droplets are detached at a high-frequency, as a result of high average current (high electromagnetic forces). The droplet flight through a stable electric arc (almost steady current and voltage traces) from the electrode to the workpiece. High-quality weld finish and high production is obtained [2][3].

D. Pulsed drop transfer mode

In the P-GMAW, it is possible to obtain a sequence of small droplets detaching in a very regular free-flight form (spray-like). This is reached by pulsing the current at a calculated frequency and duration [4], above a transition current. The advantage of this transfer mode is the regularity of the transfer, despite the low heat input (average current level below the normal transition current). Figure 2 shows the current waveform (periodical variation of current and voltage) and equation (1) presents the average current for P-GMAW.

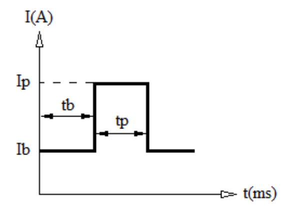


Fig. 2. Current waveform for P-GMAW (pulsed drop transfer mode).

$$I_m = \frac{I_b.t_b + I_p.t_p}{t_b + t_p} \quad (1)$$

Where,

I_p = Pulse current;
I_b = background current;
t_p = pulse time;
t_b = background time;
$t = (t_p + t_p)$ pulse cycle time.

3. Mathematical model of GMAW

Figure 3 shows a simplified electrical circuit representation of a welding power source, including some variables that determine its operational performance. In GMAW welding process modeling, the major parameters are contact tip-to-work piece distance (CTWD), arc length (l_{arc}), stick-out (l_s), droplet displacement (x), source resistance (R_s), source inductance (L_s), electrode resistance (R_e), contact resistance between electrode and *CT* (R_{arc}), arc voltage (V_{arc}), open circuit voltage (V_{oc}), arc voltage constant (V_o), wire feed speed (S), melting rate (W) and also the arc length factor (E_a) [5-7].

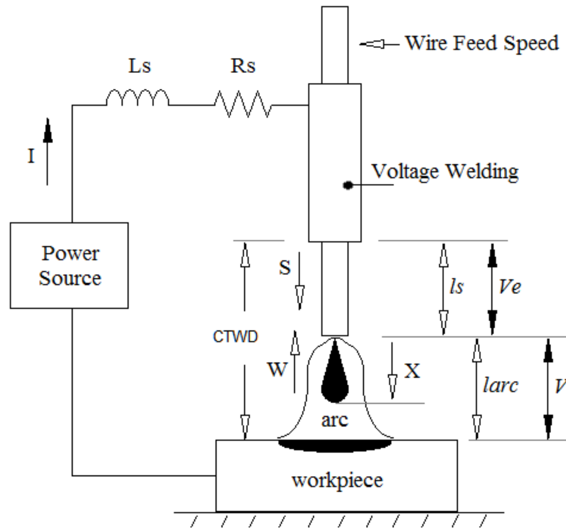


Fig. 3. Schematic diagram of the GMAW process [5].

According to figure 3, the equation (2) can be obtained.

$$CT = l_s + l_{arc} \quad (2)$$

The electrode length variation rate depends on wire feed speed (S) and on melting rate (W), as indicated in equation (3).

$$\frac{dl_s}{dt} = S - W \quad (3)$$

The relationship between the melting rate (W) and the welding current, indicated in equation (4), is usually described by two forms of electrode heating: arc heating and Joule heating.

$$W = k.k_1.I + k_2.l_s.I^2 \quad (4)$$

Where,

$k = 0$ (if $l_s = CT$) or $k = 1$ (if $l_s < CT$). k_1 and k_2 are constants depending on the type and size of the electrode and shielding gas [7].

Thus, the welding process could be represented by equations (3) and (5).

$$\frac{dI}{dt} = -\frac{1}{L_s}[(R_s + R_e).I + V_{arc} - V_{oc}] \quad (5)$$

The arc voltage is determined by Ayrton equation [7, 8], as follows.

$$V_{arc} = E_a.l_{arc} + k.V_o + R_{arc}.I \quad (6)$$

4. Voltage fluctuations and interharmonics

Voltage fluctuations problems can arise from the operation of electrical loads which produces expressive reactive power variations and from loads which produces interharmonics current injections into local power systems, resulting interharmonics voltage distortions [9]. In fact, voltage fluctuations and interharmonics cannot exist individually.

An interharmonic voltage has a frequency that is a non-integer multiple of the fundamental frequency of 50 or 60 *Hz*. Analytically, the frequency of voltage fluctuation (f_f) is equal to the modulus of the difference between the interharmonic frequency (f_{ih}), superimposed on the fundamental signal, and the immediately adjacent harmonic frequency (f_h), according to equation (7) [10].

$$f_f = \left| f_{ih} - f_h \right| \tag{7}$$

The measurement of voltage fluctuations is developed by the use of a flickermeter device, established by IEC 61000-4-15 standard [11]. Figure 4 shows a simplified block diagram for IEC 61000-4-15 standard establishing the functional and design specifications of a flickermeter.

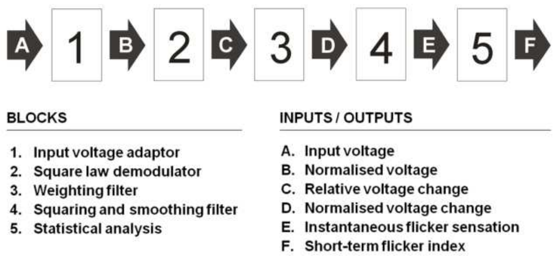


Fig. 4. Simplified block diagram of the IEC flickermeter.

The Short-term flicker index (*Pst*) is the measure of severity based on a 10 *min* observation period and is derived from the instantaneous flicker sensation records (output E).

5. Experimental Procedure

Figure 5 shows the acquisition system for power quality and welding process data.

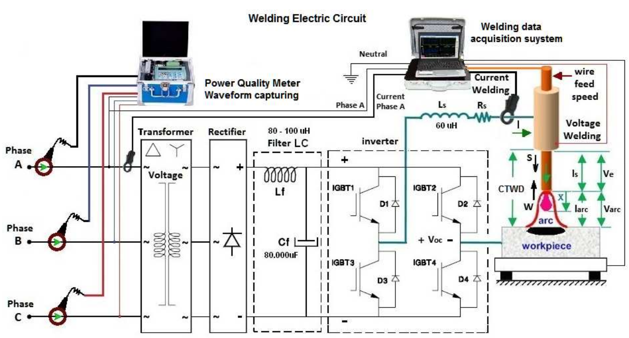


Fig. 5. Schematic diagram of acquisition system.

The three-phase voltage and current on the primary side of welding machine transformer were registered considering a rate about 64 samples per cycle. Also the arc voltage, welding current and electrode speed were registered. Welding tests were carried out with the four types of metal transfer modes: short-circuit, pulsed, globular and spray. An electronic welding power source (secondary chopped), rating value of about 12 *kW* and maximum output current equals 500 *A*, was used. The wire (electrode) diameter was 1.2 *mm* and the gas flow was kept around 15 *l/min*. The parameters were properly set to allow satisfactory conditions for welding with the fourth transfer mode.

A. Short-Circuiting

In this part of the investigation, the welding machine was set at three voltage levels (19, 21 and 23*V*). It was employed 2 contact tip-to-work piece distances (CTWD) (12 or 16 *mm*) and three mixtures of protective gases (CO_2, Ar + 25% CO_2 or Ar + 8% CO_2). By means of setting the wire feed speeds between 4 and 6 *m/min*, the resultant mean current ranged from 150 to 200 *A*.

B. Pulsed

The present test have considered the pulse time, the pulse current and the background current equals to 4 *ms*, 300 *A* and 50 *A*, respectively. The background time was modified to achieve the desired frequency. For each test, the feed rate was adjusted in advance to allow proper welding condition. Table I gives the parameters used in the P-GMAW test. Other parameters used in all tests were *CTWD* equals to 12 *mm* and as shielding gas the blend Ar + 8% CO_2.

Table I. – Parameters used in the tests with P-GMAW

Ip (*A*)	Ib (*A*)	tp (*ms*)	tb (*ms*)	f (*Hz*)	Im (*A*)	CTWD (*mm*)	Shielding Gas	Wire feed Speed (*m/min*)
300	50	4	25.0	34.5	84.5	16	Ar + 8% CO_2	2.7
300	50	4	18.0	45.5	95.5	16	Ar + 8% CO_2	3.0
300	50	4	15.3	51.8	101.8	16	Ar + 8% CO_2	3.0
300	50	4	14.0	55.6	105.6	16	Ar + 8% CO_2	3.3
300	50	4	12.7	60.0	109.9	16	Ar + 8% CO_2	3.6
300	50	4	11.5	64.5	114.5	16	Ar + 8% CO_2	3.8
300	50	4	10.6	68.7	118.7	16	Ar + 8% CO_2	4.0
300	50	4	9.3	75.2	125.2	16	Ar + 8% CO_2	4.3
300	50	4	7.6	86.2	136.2	16	Ar + 8% CO_2	3.5

C. Globular

The tests related to globular transfer mode have considered one voltage level (equals to 28 *V*), with a contact tip-to-work piece distance of 16 *mm*) and CO_2 as shielding gas. The wire feed speed was set at 6 *m/min*, leading to an average current round 180 *A*.

D. Spray

The spray transfer mode tests have considered one voltage level (equals to 30*V*), with a contact tip-to-work piece distance of 16 *mm*) and Ar + 25% CO_2 as shielding gas. The wire feed speed at 10 *m/min* lead to an average current around 300 *A*.

6. Results

To determine the *Pst*, the files were synchronously overlapped for 720 seconds, crossing out the first 120 seconds in order to get rid of transients due to flickermeter digital filters. Thus, the investigations have considered a 10 minutes uninterrupted welding process evaluation for *Pst* index. The harmonic spectrum of voltage and current was made with a 1 *Hz* resolution (60 cycles sample windows), in order to better identification of interharmonics frequencies.

A. Short-Circuiting

In total, twelve tests were developed to the short-circuiting drop transfer mode. Figure 6(a) shows the instantaneous voltage and current (phase A only) in the primary side of the welding machine transformer and also the arc welding voltage and the *v x i* characteristics for each test. The voltage and current harmonic distortion in the primary current is due to the presence of three-phase diode rectifier and the non-linear load (arc welding). It is observed that the open arc duration time (t_{arc}) and short circuit duration time (t_{sc}), in each cycle, are rarely identical (thus, the frequency of short circuit is not constant). The frequency of short-circuit is given by $f_{sc} = 1/\ t_{arc}+t_{sc}$. At the time of open arc (t_{arc}), while the rate of fusion (W) decreases due to the current reduction, the length of the electrode (l_s) increases up to it reaches the weld pool again, reopening the arc.

If the frequency of short circuit is constant, the change in current magnitude will be smaller like the voltage variations, decreasing the instantaneous flicker sensation and *Pst*. The arc welding *v x i* characteristic shows that the transfer of the drop to the weld pool is performed unstable. As there is a higher demand for current at time of short circuit, the capacitor cannot discharge or maintain the required power and. In this case, greater power will flow from the source. This fact depends on the energy stored in the capacitor and the load request (arc welding). The primary side current presents a low frequency component according to the frequency of short circuit. This frequency is not constant (characteristic of the pulsed mode). These characteristics of welding machines generate harmonic and interharmonics currents. Table IV shows the magnitude of test voltages and currents in the short-circuiting mode in two different situations: with (arc welding) and without load (just plugged in). Figure 6(b) shows the instantaneous flicker sensation, which one presents the maximum and minimum values equals to 14.98 *pu* and 2.11 *pu*, respectively.
Table II shows the *Pst* for different parameters test conditions related to short-circuiting drop transfer mode. All the registered *Pst* values were higher than 5.0 *pu* (except the test-10). The instability of the frequency of short-circuit generates a wide frequency spectrum with harmonic and interharmonics in current and voltage input, as shown in Figure 6(c).

B. Pulsed

Figure 7(a) shows the instantaneous voltage and current in the primary side of the welding machine transformer and in the arc welding side for the P-GMAW tests, considering the frequency of 51.8 *Hz*. The background time (t_b) and pulse time (t_p), as much as the background current (I_b) and peak current (I_p), were imposed by the welder as the input parameter of the welding machine.

Table II. – Parameters used in the tests with short-circuit

Test	Voltage (*V*)	CTWD (*mm*)	Shielding Gas	Wire feed Speed (*m/min*)	Pst (*pu*)
#1	21	12	CO2	4,5	5.3321
#2	21	12	Ar + 25%CO2	4,4	5.2930
#3	21	12	Ar + 8%CO2	4,3	5.0315
#4	19	12	CO2	4,3	5.4241
#5	23	12	CO2	6,5	5.2122
#6	19	16	CO2	5,5	5.5841
#7	23	16	Ar + 8%CO2	6,5	5.0957
#8	21	16	Ar + 25%CO2	5,5	5.1329
#9	21	16	CO2	6,8	5.1537
#10	21	12	Ar + 8%CO2	6,9	4.9906
#11	21	12	Ar + 25%CO2	6,7	5.0686
#12	21	12	CO2	6,5	5.6454

Table III. – *Pst* results for the P-GMAW tests

Freq (*Hz*)	CTWD (*mm*)	Shielding Gas	Wire feed Speed (*m/min*)	Pst (*pu*)
34.5	16	Ar + 8%CO_2	2,7	4.9143
45.5	16	Ar + 8%CO_2	3,0	4.9054
51.8	16	Ar + 8%CO_2	3,0	4.8158
55.6	16	Ar + 8%CO_2	3,3	4.9153
64.5	16	Ar + 8%CO_2	3,6	4.8346
68.7	16	Ar + 8%CO_2	3,8	4.9055
75.2	16	Ar + 8%CO_2	4,0	4.9055
86.2	16	Ar + 8%CO_2	4,3	4.8615
60.0	16	Ar + 8%CO_2	3,5	4.7825

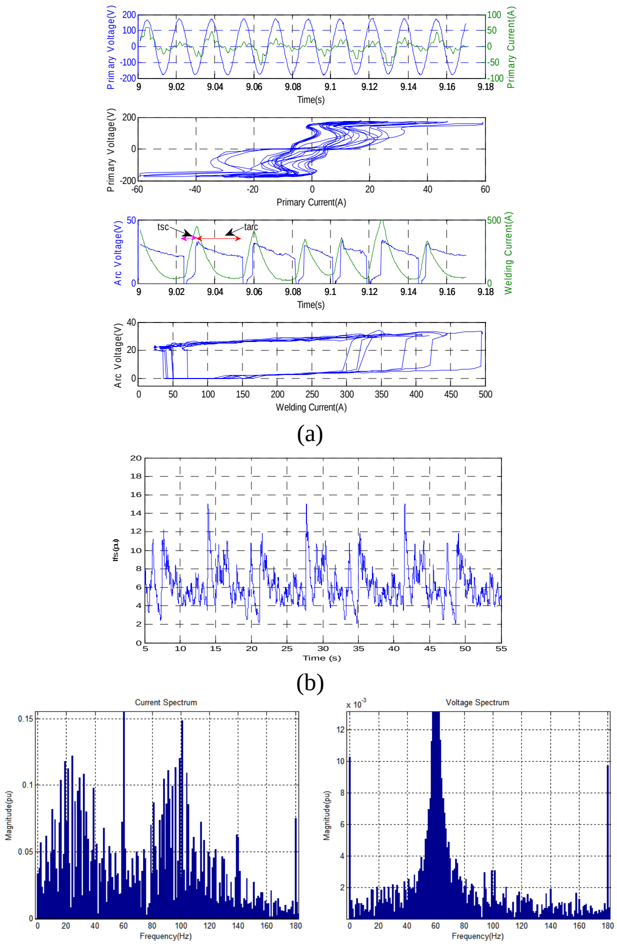
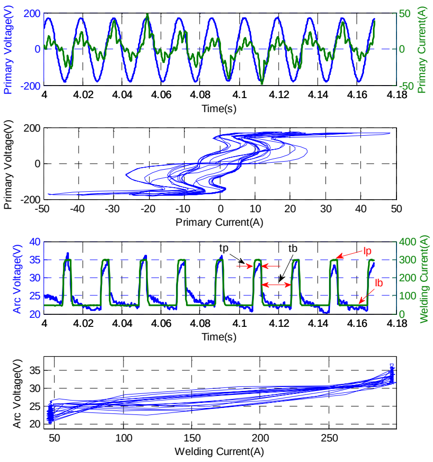


Fig. 6. Oscillograms of the test 9 - short-circuiting transfer mode:(a) Voltage, current and characteristics *v x i* on primary side and low voltage welding side, (b) I_{sf} (*pu*); (c) Current spectrum on the transformer primary side; (d) Voltage spectrum on the transformer primary side.

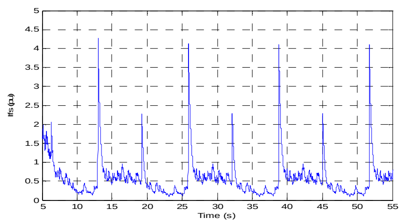
The pulse frequency ($f_p = 1/\ t_b+t_p$) is the number of peak current, which occur in one second. A pulse cycle time ($t= t_b+t_p$) is defined as the period from the start of the pulse to the end of the background time just before the next pulse. An important observation is that the pulse frequency is directly related to an interharmonic frequency on the voltage signals. This phenomenon is shown in figure 7(c), where the interharmonic at frequency of 51.8 *Hz* can be clearly observed.

Depending of the busbar impedance, the same interharmonic frequency (equal to the pulsed frequency) will be present in the voltage spectrum. For the test about 51.8 *Hz* pulsed frequency, the highest current magnitudes are presented in interharmonics frequencies around 9 *Hz* and 112 *Hz*, with values of 0.25 *pu* and 0.26 *pu*, respectively. The reflection on the voltage interharmonics with frequencies around 9 *Hz* and 112 *Hz* were 3.5‰ and 3.0‰, respectively. Figure 7(b) shows the instantaneous flicker sensation (I_{sf}), indicating a maximum value equal to 4.27 *pu*.

Table III shows the values of pulse frequency (CTWD) shielding gas, wire feed speed used in each test and the related values of *Pst*.



(a)



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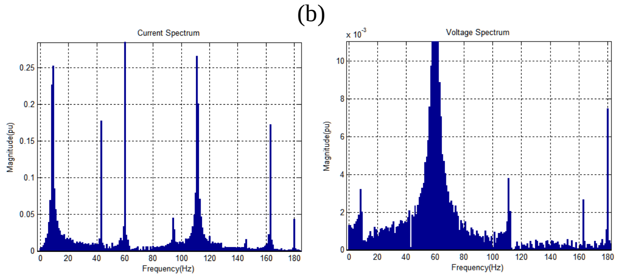


(c)

Fig. 7. Oscillograms of a test with P-GMAW (pulse frequency of 51,8 *Hz*): (a) Voltage, current and characteristics *v x i* on primary side and low voltage welding side;(b) I_{sf} (*pu*);(c) Current spectrum on the transformer primary side;(d) Voltage spectrum on the transformer primary side.

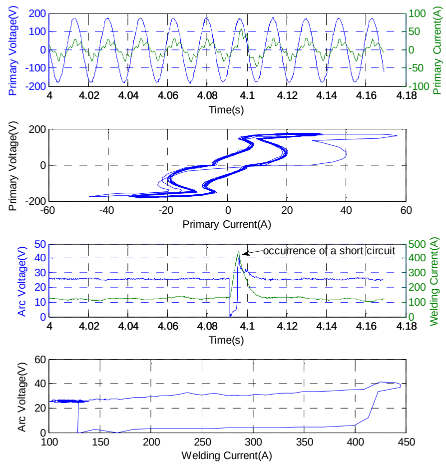
The voltage spectrum presents a wide range of frequencies around 60 *Hz* (due to the spread spectrum), but relatively larger amplitudes of interharmonics with frequencies between 9 and 112 *Hz* can be clearly identified.

Tables IV and V shows the results of the magnitudes and frequencies of harmonics and interharmonics current on the primary side voltage as well as the values of currents and voltages with and without load. In these cases, only the 3rd, 5th e 7th harmonics are informed. The magnitude of the voltage on the primary side with load and no load, for the 3rd, 5th e 7th harmonics are reduced as the load is imposed. This feature is valid for the current in the primary side only to the 3rd harmonic. For the 5th e 7th harmonics, happens the opposite.

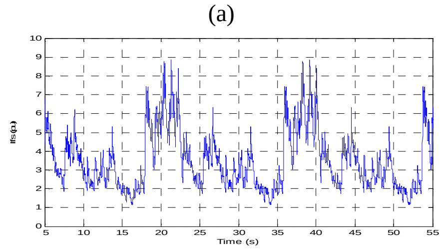
C. Globular

Figure 8(a) shows the instantaneous voltage and current in the transformer primary side and also the welding arc voltage and its *v x i* characteristics. The *v x i* characteristic curves regarding to the transfer modes for short-circuiting and pulsed modes indicates a greater stability of the arc welding on the primary side of the welding machine transformer.

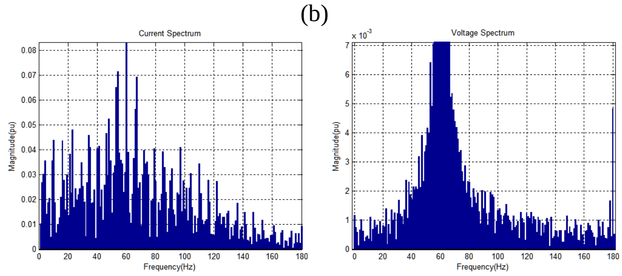
In the globular transfer mode, the drop has a diameter larger than the electrode. In some cases it may be that the drop touches the weld pool and short-circuit occurs. This occurrence may be observed in time of 4.09 *ms* (arc voltage in figure 8(a)), where the current increases from a value close to 120 *A* to a pulse current of 420 *A*.



(a)



(b)



(c)

Fig. 8. Oscillograms of the test globular transfer mode: (a) Voltage, current and characteristics *v x i* on primary side and low voltage welding side; (b) I_{sf} (*pu*); (c) Current spectrum on the transformer primary side; (d) Voltage spectrum on the transformer primary side.

The same can be seen in the primary current, where the pulse current is higher than the pulse values prior to short-circuit.

Figure 8(b) shows the instantaneous flicker sensation, indicating its better performance in relation to short-circuiting mode, but still worst than the pulsed mode.

D. Spray

Figure 9(a) shows the instantaneous voltage and current in the transformer primary side and also the welding arc voltage and its *v x i* characteristics. The *v x i* characteristics of the spray drop transfer mode shows that this kind of welding process is more stable than the others.

The current level on the primary side and in the arc welding is higher than the other tests (pulsed, short-circuiting and globular). However, the spray transfer mode is more stable.

The instantaneous flicker sensation presents reduced values oscillating between 0.74 and 4.7 *pu*. Figure 9(c) shows the current spectrum and voltage.

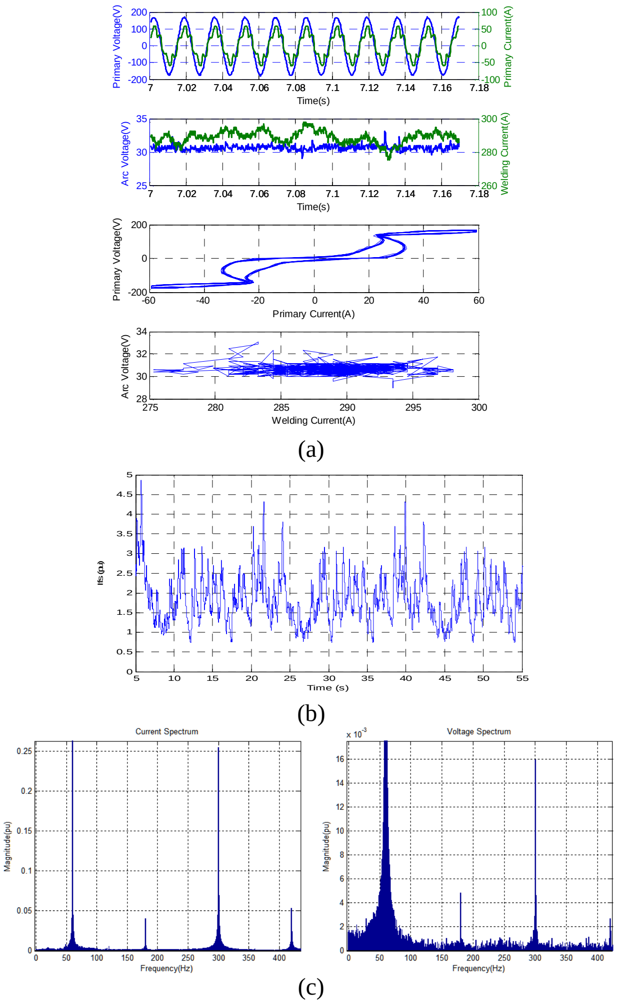


Fig. 9. Oscillograms of the test spray transfer mode:(a) Voltage, current and characteristics *v x i* on primary side and low voltage welding side;(b) *Isf* (*pu*);(c) Current spectrum on the transformer primary side;(d) Voltage spectrum on the transformer primary side.

Table IV – Results from tests with P-GMAW – Primary Voltage

	Primary Voltage			Pulse Frequency = 1/(tb+tp)				
	34.5 Hz		*45.5 Hz*		*51.8 Hz*		*55.6 Hz*	
	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)
	2.2	9	3	15	3.5	9	4	5
	3.2	26	4.5	105	3	112	2	50
	1.4	43	2	150	2.2	163	4	115
	3.2	94					2	170
h	Load	No Load	Load	No Load	Load	No Load	Load	No Load
3^{rd}	7.5	7	7.5	7.7	7	7.5	8	7
5^{th}	17	19	16	19	18	21	16.5	20
7^{th}	7	6	7.5	7	6	5	6.2	6
	64.5 Hz		68.7 Hz		75.2 Hz		86.2 Hz	
	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)	Mag. (‰)	ih (Hz)
	3.8	4	3.8	8	3	14	4.5	25
	5	124	3.8	128	3.2	134	5	145
h	Load	No Load	Load	No Load	Load	No Load	Load	No Load
3^{rd}	7	7.2	6.9	7	7.3	7.5	5.8	6.2
5^{th}	16.5	19.5	16.5	20	16.8	20	16.6	19
7^{th}	7.1	5.5	6.9	6	6.5	7.6	6.5	6.5

Table V – Results from tests with P-GMAW – Primary Current

	Primary Current			Pulse Frequency = 1/(tb+tp)				
	34.5 Hz		*45.5 Hz*		*51.8 Hz*		*55.6 Hz*	
	Mag. (pu)	Fih (Hz)	Mag. (pu)	Fih (Hz)	Mag. (pu)	fih (Hz)	Mag. (pu)	Fih (Hz)
	0.225	9	0.35	15	0.25	9	0.35	5
	0.304	26	0.17	30	0.19	43	0.15	50
	0.157	43	0.35	105	0.26	112	0.35	115
	0.314	94	0.15	150	0.18	163	0.14	170
h	Load	No Load	Load	No Load	Load	No Load	Load	No Load
3^{rd}	0.075	0.24	0.075	0.23	0.042	0.23	0.07	0.235
5^{th}	0.42	0.14	0.4	0.14	0.38	0.14	0.4	0.14
7^{th}	0.15	0.06	0.15	0.06	0.14	0.051	0.14	0.06
	64.5 Hz		68.7 Hz		75.2 Hz		86.2 Hz	
	Mag. (pu)	Fih (Hz)	Mag. (pu)	Fih (Hz)	Mag. (pu)	fih (Hz)	Mag. (pu)	Fih (Hz)
	0.35	4	0.3	8	0.25	14	0.31	25
	0.12	68	0.08	77	0.08	89	0.04	110
	0.38	124	0.29	128	0.24	134	0.29	145
h	Load	No Load	Load	No Load	Load	No Load	Load	No Load
3^{rd}	0.06	0.23	0.08	0.29	0.06	0.23	0.02	0.23
5^{th}	0.38	0.135	0.4	0.13	0.38	0.13	0.35	0.14
7^{th}	0.12	0.06	0.14	0.06	0.13	0.055	0.1	0.055

Table VI – Results from tests with P-GMAW – Primary Current

	Primary Voltage						Primary Current					
	Short circuiting Test#9		Globular		Spray		Short circuiting test#9		Globular		Spray	
	Mag. (‰)	Mag. (‰)	Mag. (‰)	Mag. (‰)	Mag. (‰)	Mag. (‰)	Mag. *(pu)*	Mag. *(pu)*	Mag. *(pu)*	Mag. *(pu)*	Mag. *(pu)*	Mag. *(pu)*
h	Load	No Load	Load	No Load	Load	No Load	Load	No Load	Load	No Load	Load	No Load
DC	10.3	10.9	0	0	0	0	0	0.048	0	0.026	0	0.026
3^{rd}	8.56	9.37	4.64	4.95	5.4	5.3	0.07	0.230	0.066	0.228	0.0385	0.23
5^{th}	15.3	17.9	15.7	16.8	15.8	16.6	0.36	0.146	0.346	0.135	0.248	0.132
7^{th}	6.36	6.71	4.2	4.87	2.66	5.73	0.081	0.053	0.112	0.046	0.05	0.049

7. Conclusion

The paper has presented an experimental investigation about the welding machine operating in the GMAW process, considering four different metal transfer modes: short-circuiting; pulsed; globular; and spray. The welding machine has a strong nonlinear behavior in all process, injecting current harmonics and interharmonics in to the local electric utility. For the particular case of interharmonic frequencies, the presented results have shown that a strong correlation between the GMAW pulsed mode frequency and the interharmonic current generation. The voltage fluctuations also have different behavior for different types of GMAW drop transfer modes. In this sense, the GMAW spray mode presents the lowest magnitudes for instantaneous flicker sensation at the primary side of welding machine transformer. In addition, the *v x i* characteristics about the different GMAW drop transfer modes indicates that the spray transfer mode presents greater stability in comparison to the other processes. Finally, the general conclusion about the present work is that de power quality could be better or worst depending on the considered GMAW drop transfer mode.

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