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Evaluation of DC-DC Power Converters For 3.5kw Micro-Butt Welding Applications

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Abstract

Most of the industrial welding applications involving of electronic circuits such as AC-DC, and DC-AC and AC-DC converters. This paper assesses the different DC-DC power converter topologies suitable for micro butt welding focusing on resistance type of welding. The objective is to compare different types of DC-DC converter circuits and finally set criteria to select most suitable. They will be compared taking into account volume, weight, cost, easy to implement and functionality. As a result, it will be designated those that fit better for the application. To conclude, simulation of different power converter topologies and some experimental results on a half-bridge converter confirm the study and the selection procedure followed.

Introduction

Micro butt welding is an effective way to reliably join small-scale parts n electronics industry and instrument making. The introduction of power electronics in the welding process has improved many aspects of the machine. Size and weight have been reduced. The machine is easy to handle and access and for the low power types up to 3.5 kW. This advance has been possible due to the introduction of power electronic topologies that allow processing the energy with higher efficiency and frequency (in the range from 20 kHz to 200 kHz). This allows diminishing remarkably the size and weight of the magnetic components used in these machines, which suppose the main part of the weight and volume of the final machine, jointly with the heat sinks. However, all the electronic topologies are not valid in this type of application. In this paper the most suited PWM-controlled topologies are discussed.

Power devices improvement in size and capacity (the heat sinks are reduced), added to the development of controllers have allowed added functions in machines that facilitate their use and obtaining a greater weld quality. Additionally, it extends the expected life of the machine. This ease of use improvement contributes as well so that nonqualified users can handle them without problems. Currently, part of the market tends to introduce them as a do-it-yourself work tool.

The majority of previously mentioned work is to generate a suitable DC-DC converter for manual metal arc welding (MMA) and spot welding to achieve the better welding quality [1-7]. This article presents an evaluation of different switched power supplies topologies applied to micro butt welding which deals with welding of two pieces of wires.

General Description of Micro Butt Welding

The micro butt welding system used for joining of two pieces of wire in the range of 9mm to 16mm diameter and deals with high welding quality by relating the welding parameters such as welding current, dynamic electrical resistance, temperature of the material at the surface, and electrode movement during welding. The welding control objective is to assure uniform quality of the weld joint by providing the proper pressure between two wire clamping and maintaining the required welding current through the work pieces. By using the clamping arrangements, the operator can maintain the alignment of pieces so that required pressure between the two surfaces will be built up. The operator can select the material type with size and trigger the power supply, welding current is established, the joint surfaces are heated, and finally wires are welded with high mechanical strength, welding method is extremely efficient.

The micro butt welding system includes welding power apparatus, movable clamp and grinding wheel (Fig 1).

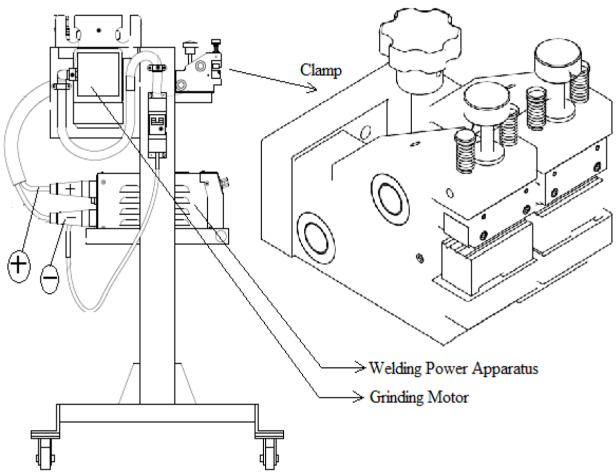

Figure 1: Setup used for micro butt welding includes Welding power apparatus, clamp and grinding wheel.

The welding power apparatus uses DC-DC converter connected to a 370V DC bus obtained from boost converter. The input supply is rectified and boosted with 370V DC using a power factor correction boost converter. The rectifier and boosting circuit is common to all of them and it will not be considered in the evaluation.

The welding current is provided by an inverter that is connected a dc-link capacitor and transformer with a high turns ratio. The current is rectified at the secondary side of the transformer (Fig 2). The voltage between the two pieces of electrodes is in the range of only a few volts 5V DC.

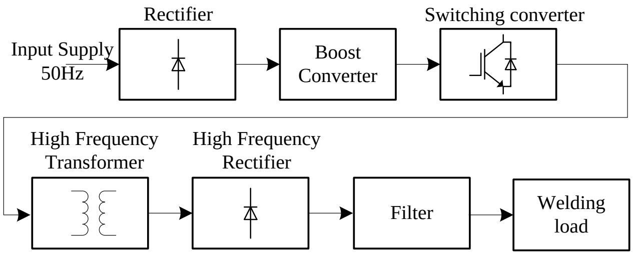

Figure 2: Block Diagram of Micro-Butt Welding Power Apparatus

The equivalent electrical circuit model of micro-butt welding load is shown in Fig 3, which consists of resistance offered by fixed & movable clamp, left & right side of work pieces and faying interface. The ohmic value of welding load is considered as very small maximum of 1mΩ.

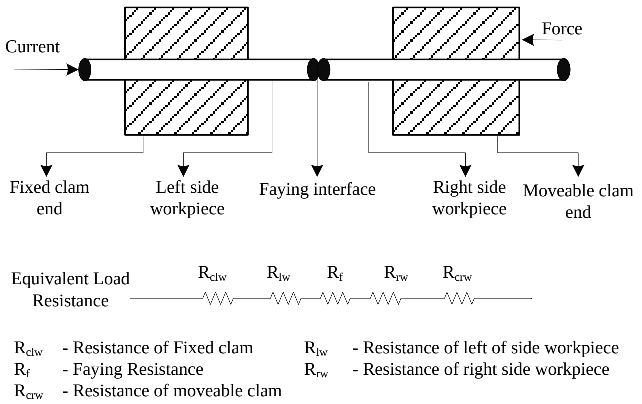

Figure 3: Equivalent electrical circuit model of micro-butt welding load.

General Comparison of Dc-Dc Topologies

A. Introduction

The power electronics topology used in this application must have, derived from the previous analysis, the following general characteristics:

- It must provide galvanic isolation form the main, where the machine supplies from.
- It must regulate the DC current (150A-600A), with 5V DC.
- It must support and control the short circuits.

The criteria for comparison are based on functionality, volume, weigh and cost. In this way, operating mode, voltages and currents in devices, heat sinks, and the magnetic components are taken into consideration because of their incidence in the final volume and cost.

The study focuses on the machines so-called commercially as “inverter”. The topology is a DC-DC converter connected to a 370V DC. There are several DC-DC electronic topologies with different operating modes (PWM, resonant) and other interesting functions, as power factor compensation. In this paper non-resonant topologies are only compared because micro butt-welding machine operating functions are easily implemented on conventional PWM control method.

B. Electrical isolation

Taking into account the galvanic isolation specification, all non-isolated topologies are excluded for evaluation (buck, boost, buck-boost). Only two switch forward, half-bridge and full-bridge converters are considered.

C. Power Electronic Switching devices

If electronic switching devices are considered, the following parameters are relevant for comparison [8] and have been included in Table I:

F_{sw}/F_{out}	:	Transistor switching frequency and output frequency ratio.
Q_n	:	Number of transistor in the topology.
$V_{Q\_off\_max}$	:	Maximum transistor voltage in T_{off} interval.
$I_{Q\_on\_max}$	:	Maximum transistor current in T_{on} interval.
D_n	:	Number of diodes including output diodes.
$V_{D\_off\_max}$	:	Maximum diode voltage in T_{off} interval.
$I_{D\_on\_max}$	:	Maximum diode current in T_{on} interval.
N	:	Transformer turns ration (N_2/N_1)

Table 1: Important Parameters VS DC-DC Converter Topologies

Parameter	*Forward*	*Two switch forward*	*Push-pull*	*Half bridge*	*Full bridge*
F_{sw}/F_{out}	1	1	0.5	0.5	0.5
Q_n	1	2	2	2	4
$V_{Q\_off\_max}$	$2*U_{bus}$	U_{bus}	$2*U_{bus}$	U_{bus}	U_{bus}
$I_{Q\_on\_max}$	$(I_O*N)+I_m$	$(I_O*N)+I_m$	$(I_O*N)+I_m$	$(I_O*N)+I_m$	$(I_O*N)+I_m$
D_n	3	4	2	2	2
$V_{D\_off\_max}$	$V_{bus}*N$	$V_{bus}*N$	$2*V_{bus}*N$	$V_{bus}*N$	$2*V_{bus}*N$
$I_{D\_on\_max}$	I_o	I_o	I_o	I_o	I_o

The Table I shows the characteristic's parameter of different topologies as the function of DC bus voltage (U_{bus}), transformer turns ratio (N), maximum of magnetizing current (I_m) and the average DC output current (I_o).

It is assumed that the forward converter has a third winding, with the same number of turns as the primary winding used for resetting the magnetizing flux. Thus, the maximum duty cycle is 0.5 and maximum voltage in the transistor is $2*U_{bus}$. In the push-pull converter the inverse voltage in the transistors is high ($2*U_{bus}$). Due to this high voltage and the added complexity in building the primary winding, it will not be considered in the evaluation. However, the maximum voltage of two transistor forward converter is clamped to U_{bus} by the diodes, and the third winding is not necessary. In half-bridge and full-bridge converter it is assumed that the transformer has a centre-tapped secondary and two diodes as rectifier, for these current levels, this solution is cheaper and robust than using a four diodes rectifier.

Exclude the current ripple, the maximum current of half-bridge, full-bridge and two transistor forward converters are given in (1).

$$I_{Q\_on\_max} = I_o (N_2 / N_1) + I_{mag} \quad (1)$$

The difference is in the turn's ratio (N) necessary to get the same output current I_o. In the next paragraph the three converters, two switch forward, half-bridge and full-bridge converters are compared. It is looked for the best match to the proposed application. The turn's ratio (N) is discussed deeper.

D. Magnetics Transformer operation

Half-bridge and full-bridge are ahead of other converters when the transformer is considered. They both supply AC voltage to the transformer, thus, first and third quadrant of B-H magnetic characteristic are used. It yields to less transformer size when compared to two switch forward converter that only uses the first B-H quadrant. Transformer size is very important for this welding application because these machines are portable and the size affects the weight and cost.

On the other hand, Table I shows that the ratio between the switching frequency and the output frequency (F_{sw}/F_{out}) is halved in these two converters, thus the same switching frequency yields in less output inductor rating and, consequently, less weight, size and cost for the same output current ripple in I_o.

Two-Switches Forward Vs Half Bridge Vs Full Bridge Converter

The full-bridge, two switches forward and half-bridge converters are shown in Fig 4, 5 and 6 respectively. According to the general characteristics shown in Table I and their discussion, it can be concluded that two switch forward, half-bridge and full-bridge are the best scored. Table II includes three aspects that get involved directly in the operation, the average output voltage V_o, the maximum of the instantaneous output voltage V_{o_max} and additional cable inductance [8].

Table 2: Output Voltages Vs Maximum Instantaneous Output Voltages Vs Output Inductance

Parameter	*Two switches forward*	*Half bridge*	*Full bridge*
V_o	$D*N*V_{bus}$	$D*N*V_{bus}$	$2* D*N*V_{bus}$
V_{o_max}	$N*V_{bus}$	$N*(V_{bus}/2)$	$N*V_{bus}$
Output inductance	*Additional inductance Required*	Cable inductance is sufficient	Cable inductance is sufficient

To compare three machines having the same output current I_o, sets the output voltage V_o common for all three machines. The first row in Table II sets the turns ratio assuming the same maximum duty cycle Dmax (= 0.5).

$$(N_2/N_1)_{H.B} = (N_2/N_1)_{2SWFW} = 2* (N_2/N_1)_{F.B} \quad (2)$$

The micro-butt welding application demands very low output voltage at the secondary winding, in order to get this the no. of turns at secondary of transformer is one for all the converters and the primary no of turns are given in (3).

$$(N_1)_{H.B} = (N_1)_{2SWFW} = (1/2)* (N_1)_{F.B} \quad (3)$$

Substituting (2) in (1), neglecting the ripple current through the filter inductor at the output and assuming the transformer magnetizing current to be negligible in both circuits, the transistor currents.

$$(I_{Q\_on\_max})_{H.B} = (I_{Q\_on\_max})_{2SWFW} = 2*(I_{Q\_on\_max})_{F.B} \quad (4)$$

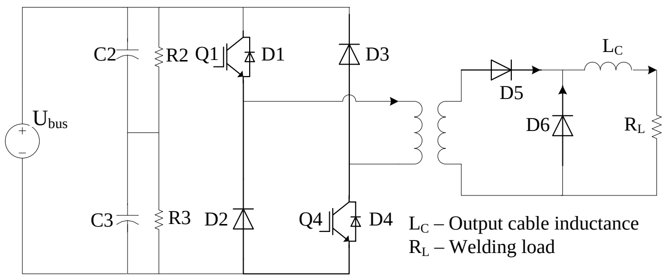

Figure 4: Two switch forward converter.

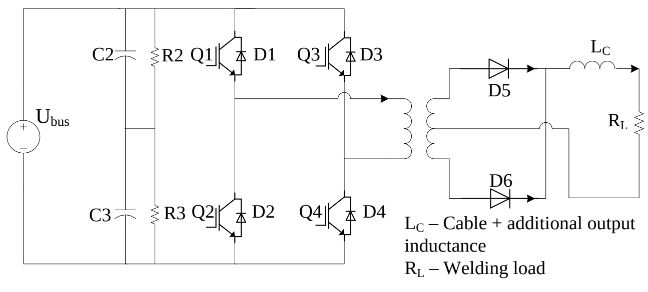

Figure 5: Full-bridge converter

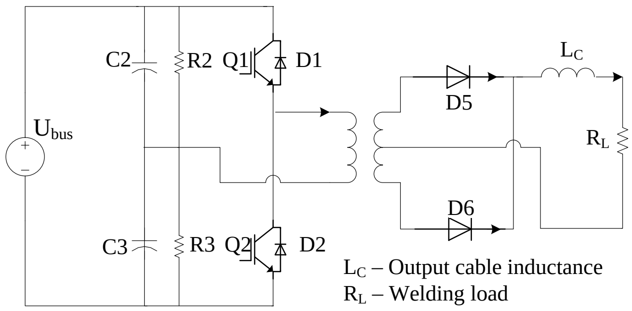

Figure 6: Half-bridge Converter

In case of full-bridge the primary turns (N_1) is twice as that of two switches forward converter and half-bridge also which uses double number of devices. This results in double number of transistors carrying half of current in the full-bridge converter.

In case of two switches forward converter only half of the time this converter can transfer energy to the output; this will increase the RMS current through the primary switch. With same reason, the voltage-second on output inductor is much higher in two-switch forward converter compared with half bridge and full bridge converter. The maximum instantaneous output voltage of two switches forward converter is equal to 2Vo (Dmax = 0.5). So, the capacitor will charge to the maximum stand-by voltage. Also the output inductor is required in case two switches forward converter and it reduces the output current ripple but in case of half-bridge and full-bridge the cable inductance itself is sufficient.

The half-bridge converter is opted by considering above drawbacks of full-bridge and two switches forward converter. The half-bridge can be best selection since the application requires very few volts on secondary side also which allows more compact design, less volume and weight in the machine.

Simulation and Experimental Results

Half-bridge, full-bridge and two switches forward converters are studied using OrCAD PSpice simulation. The various parameters are fixed for all the converters, which are dc-link capacitor 470µF, dc-link voltage 370VDC, switching frequency 40 kHz, output cable inductance 1µH used for the simulations. The turns ratio 37:1 for full-bridge, 18.5:1 for half-bridge and two switches forward converters are used for the simulations which satisfy design criteria of (2). In order to get the same level of ripple as that of half-bridge and full-bridge, output inductance 8µH is used for two switched forward converter in the simulation. The transformer primary winding voltage ±185VDC for half bridge, ±370VDC for full bridge and two switches forward converter are shown in Fig. 7 (a). The transformer primary currents are shown in Fig. 7 (b). The transformer secondary winding voltages are shown in Fig. 7 (c). The voltage across the rectifier outputs are shown in Fig. 7 (d).

To validate the conclusions obtained, there has been developed an experimental prototype of a micro-butt welding machine based on the half-bridge converter. This prototype could be marked to deliver 600A output current. Fig. 8 Channel 1 shows the applied AC voltage to the primary winding of the transformer and Fig. 8 Channel 2 shows the current in the primary winding. The parasitic inductance becomes apparent in the slope of the transitions and the oscillations in off time.

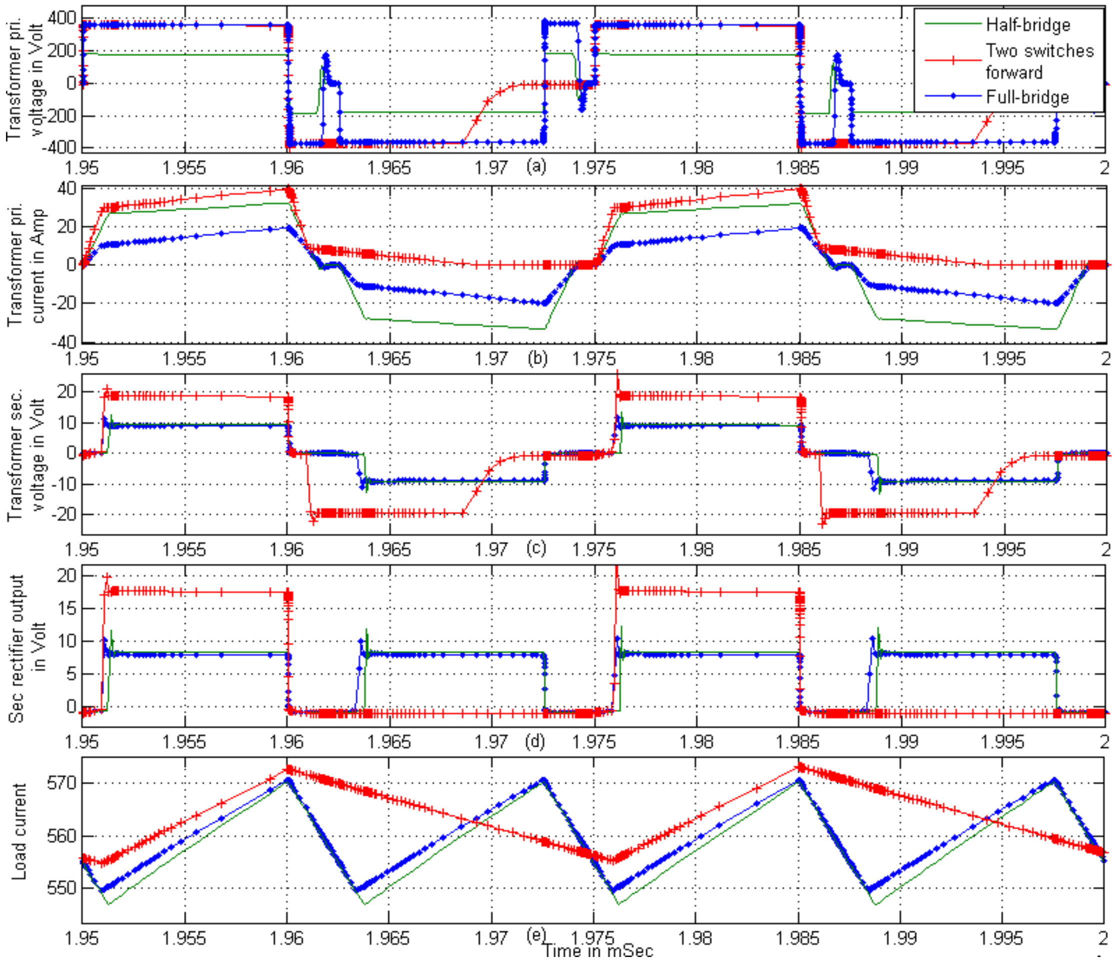

Figure 7: Simulation results. (a) Transformer primary voltages (b) Transformer primary currents, (c) Transformer secondary side voltages (d) Voltage across the rectifier outputs (e) Load currents.

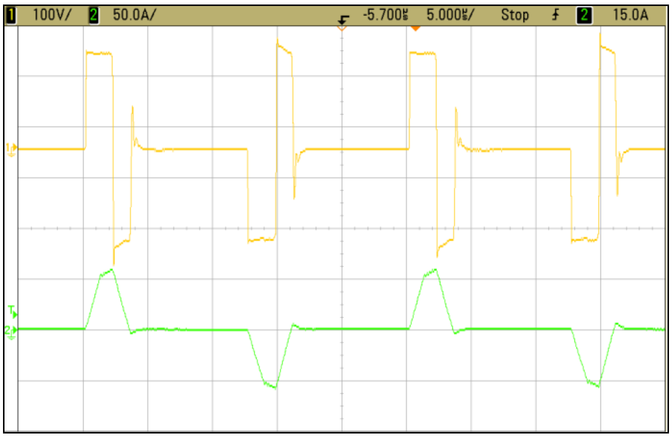

Figure 8: Transformer Primary Voltage and Current of Half-Bridge Converter

Figure 9: Rectifier output voltage and load current of half-bridge converter (500mV/100A for Channel 1)

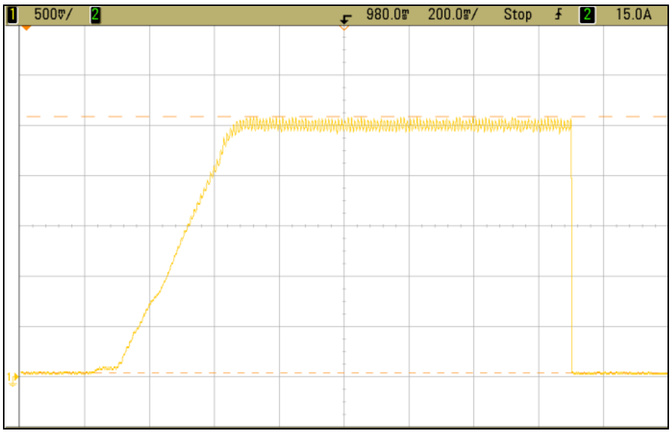

Figure 10: Half-bridge converter complete cycle of the load current (500mV/100A for Channel 1).

The transistors switching frequency is 40 kHz, thus, the ripple frequency in the output voltage (V_o) and current (Io) are twice (80 kHz). This output current and voltage are depicted in Fig. 9 of Channel 1 & 2 respectively where the ripple can be observed. The Fig. 10 shows the load current of 600A during complete welding process. The complete welding process takes place within 1.5Sec. Fig. 11 shows the prototype built and tested. The power apparatus is split in to three sections, upside is the control PCA, right side is the power PCA for capacitor bank and IGBT, left side is the power PCA for output rectifier and middle part consists for control transformer and high frequency power transformer.

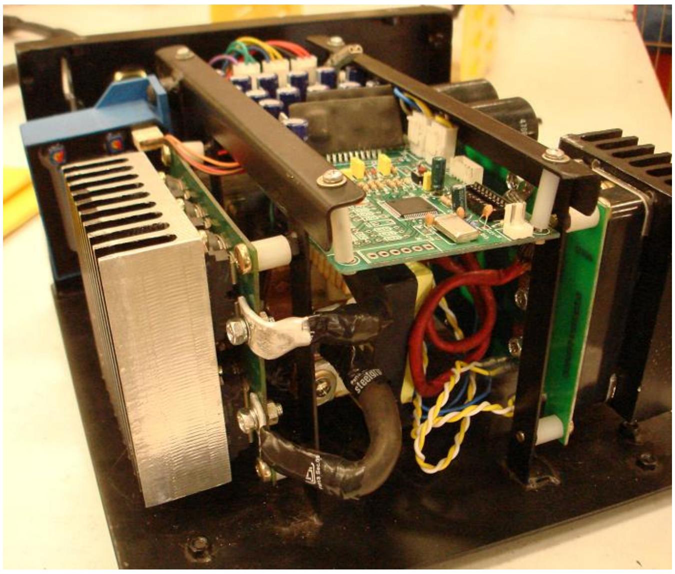

Figure 11: Prototype based on the half-bridge converter rated for 600A of output current and 5V of average output voltage.

The different types of wires like steel, aluminum and copper with different sizes are welded with experimental prototype and the welded samples are shown in Fig.12.

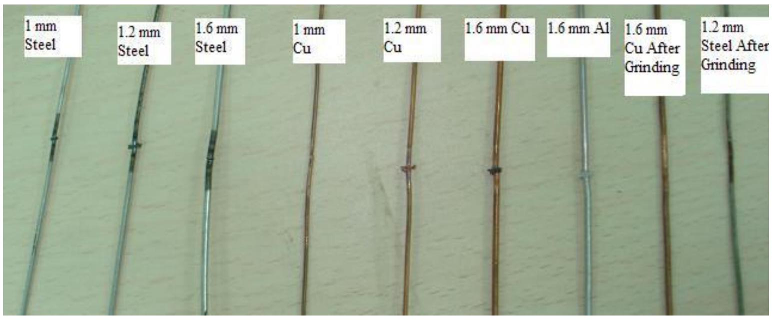

Figure 12: Welding samples of different types and different sizes.

Conclusion

There have been shown the functional requirement of micro-butt welding machine, focusing on those aspects that take part in the power electronic design of the DC-DC converter. Besides, it has been shown a simple electric model of the micro-butt welding load. The characteristics have been compared and used as criteria to select the topology that better suits for this application. From the comparison emerges that the half-bridge converter as the most suitable. Also the simulation results are evaluated for full-bridge, two switches forward converter and half-bridge converter. Finally, the experimental prototype of a half-bridge converter has been developed and used to verify that expected theoretical behavior and confirming the evaluation carried out.

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