Selecting the Correct Size Inverter for DC Welding

Harry Bissell, Product Design Engineer
Reno Boilard, Director of Marketing
Welding Technology Corporation

Abstract:

Unlike AC resistance welding controls that uses a large (one-size fits all) SCR assembly as the power switch for controlling applied heat, DC resistance welding controls uses an elaborate inverter circuit that comes in various sizes. Because there is substantial cost differences between the various sizes of inverter circuits, there becomes a need in understanding how to correctly size an inverter for the correct application; whether one is welding aluminum or steel, with coatings or bare, in spot weld mode or seam weld mode, and more. This paper focuses on several issues starting from the weld nugget zone then back through tooling, then onto many important weld transformer considerations, then finally onto the inverter control. In the end, an effective simple to use tool for determining proper inverter size for required applications is presented.

Introduction:

The use of resistance welding by means of direct current (DC) has always promoted cost benefits to users for improving welding quality.   There has been acceleration in the use of this technology due to major improvements in the technologies that resulted in lower costs with enhanced reliability. Although the costs have reduced, they are still considerable. As a result, it is extremely important for selecting the proper size equipment for such welding applications.

This paper attempts to simplify the overall scope of the technology so as to achieve an understanding of the methods to make proper selection of equipment. As with all cases of resistance welding, sizing must begin at the spot-weld and work our way back through the tools, then the welding transformer, then finally the welding control. The following sections are discussed to convey this understanding.

- A) AC Welding System
- B) DC Welding System - Fundamental Differences
- C) Secondary Resistance
- D) Bell Curve of Inverter Operation
- E) The role of the Transformer in Inverter Welding
- F) Duty Cycle issues
  - Welding Transformer
  - Inverter
    - Diodes
    - Capacitors
    - IGBTs
- G) Tools for Determining Inverter Selection

A. AC Welding System:

To understand the fundamental differences between AC and MFDC (inverter) welding, a review of the nature of the AC welding system is in order. AC welders consist of a voltage source, usually a single-phase (220V, 480V or 575V typical) sine wave voltage source, a thyristor phase controlled switch, and a welding transformer to lower the secondary voltage to an approximately correct level to create a resistance weld. (Figure 1)
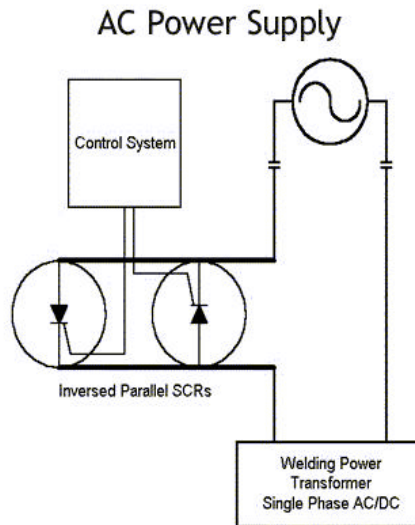

Figure 1: AC Welding System

The phase control of the applied sine wave actually forms, to some extent, a variable voltage source feeding the primary of the transformer. This model holds for low and high firing angles where the slope of the sine wave is changing rapidly. Near the peak of the sine wave, the slope of voltage changes slowly. During this time, changes in firing angle will apply roughly the same voltage for a different total time.

The mechanism for controlling weld heat is a combination of variable voltage over a large portion of the sine wave, and a variation in the time that voltage is applied as well. This gives the AC welding system a substantial window over which it can control the power delivered to the weld nugget. The addition of taps on the transformer primary can extend the range of this system by changing the effective voltage at the secondary.

Thyristors used for phase control in AC welding systems are a very mature technology, available in a very wide range of voltage and current capabilities. A welding system that fails to deliver enough energy to the weld nugget can often be retrofit with a larger thyristor with minimal impact to the system as a whole.

B. The DC (inverter) welding system:

Inverter welding systems consist of a three-phase (220V, 480V or 575V typical) sine wave voltage source. This source is applied to a three-phase full wave rectifier consisting of six (or more) diodes or thyristors. The output of this rectifier is a DC voltage equal to the peak of the applied sine wave voltage, with about 18% ripple from the overlapping of the three-phase voltage source. (Figure 2)
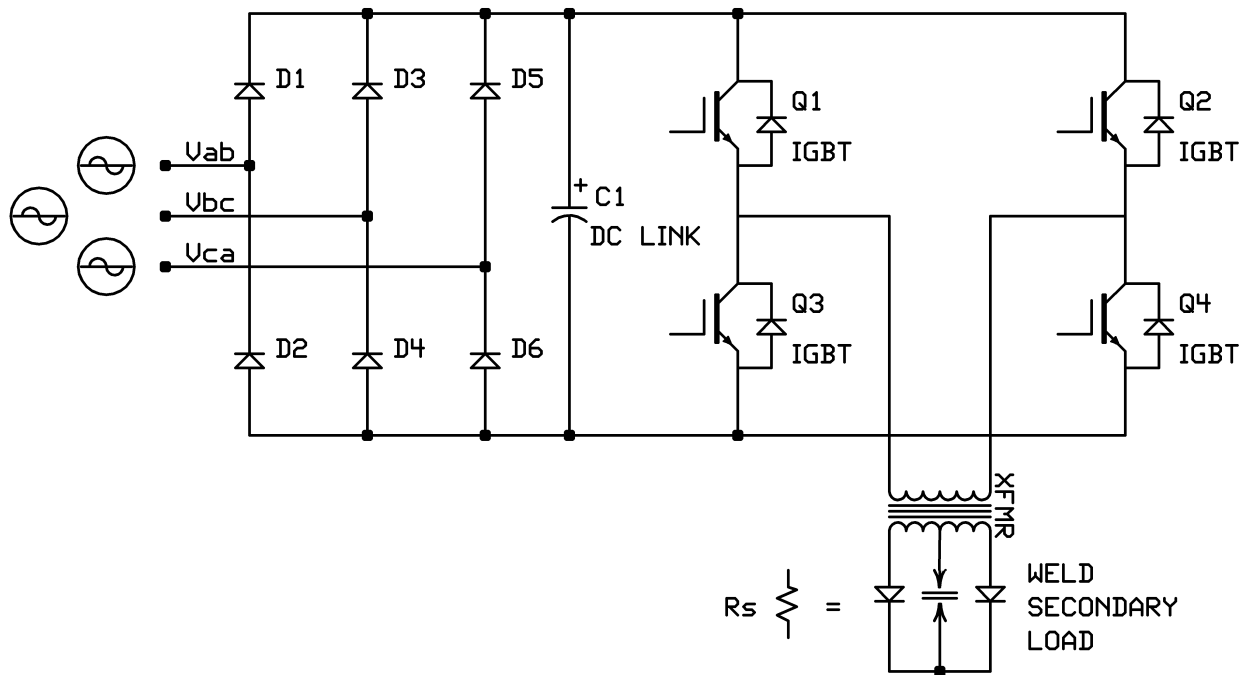

Figure 2: DC Welding System

This rectified voltage is applied to a capacitor called a "DC Link". The DC Link functions as both a filter and a snubber. The capacitor reduces the peak current requirements of the rectifier diodes, and absorbs any voltage overshoots resulting from the line and load inductances when devices turn off.

The DC link forms the voltage source for the Inverter. The inverter is a single-phase full bridge, also known as an H-bridge for the arrangement of the switching devices. The switching devices are most commonly Insulated Gate Bipolar Transistors (IGBT). These devices are switched on in alternating pairs to produce an AC voltage in the weld transformer primary. The switching frequency is much higher than the AC line frequency, allowing the weld transformer magnetic core to be greatly reduced in size and weight.

The fundamental difference in the AC phase control and Inverter control welding systems is the nature of the voltage source. The phase-controlled system can deliver an essentially variable voltage to the weld transformer. The Inverter system delivers an essentially fixed voltage to the weld transformer.

C. Secondary Resistance:

Secondary Resistance is probably the most important and most frequently overlooked quantity in the Resistance Welding process. The science of Resistance Welding owes its very name to this parameter. Secondary resistance is the same in both AC and Inverter welding systems. Voltage, Resistance, and Current are still slave to Ohms Law; however, differences in the method of controlling the process make the DC system more sensitive to resistance.

Lets consider a simple analogy. Consider the weld load as a 50W light bulb. We can light that bulb with either 120VAC (RMS) or 120VDC and it will be equally bright. Power of 50 watts divided by 120V gives a current of 0.416 amps and a resistance of 288 ohms. This resistance is fixed. It is a property of the load itself and we cannot change it.

If we want to reduce the power to this load, we can only do so by effectively changing the voltage we apply to it. In the Phase Control method described above, we do so through a combination of changing the actual applied voltage and changing the percentage of time that we apply the voltage. Shifting the firing point of the Thyristor relative to the AC sine wave can give a fairly smooth variation in the power we deliver to the load. (Figure 3)
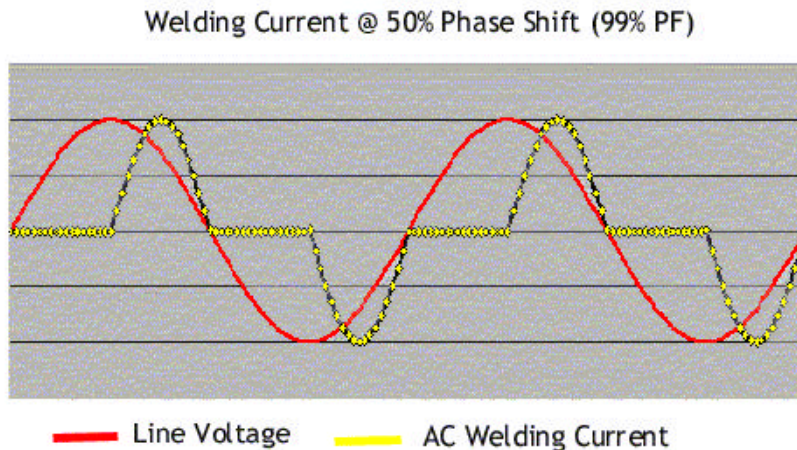

Figure 3: AC Phase Control Output

The MFDC (Mid Frequency to DC) case is much different. The input voltage is always 120V and we do not have a means of changing it. The load resistance is 0.416 ohms and we have no means of changing that either. The only thing that we can control is if the voltage is delivered to the load, or not. You could get half power by flipping the wall switch on and off with equal times. If we did it fast enough, it would give the illusion of the light bulb being only half bright. (Figure 4)
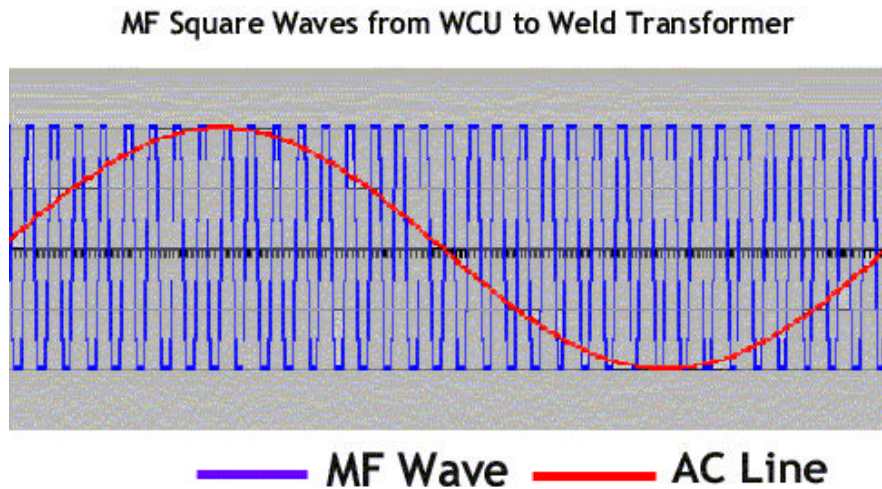

Figure 4: MFDC Phase Control Output

There is no control over applied current in this example. When the switch is on, the current is 0.416 amps. When the switch is off, the current is zero. There is no way to turn the switch halfway on.

Inverter welders control the energy delivered to the weld in this same fashion, by changing the amount of time the fixed voltage is applied to the fixed resistance of the load. Current is not controlled in a linear fashion; it is either zero or whatever current is drawn by the applied voltage and the load resistance. Ohm's law is always respected.

D. The Bell Curve of Inverter Operation.

Control of weld energy by changing the time that voltage is applied to the load gives three distinct areas of operation. We will call these three regions the Ideal Operating Range, Secondary Resistance Limiting, and Primary Current Limiting.

Inverter weld controls operate at some switching frequency, typically between 400 and 2000Hz. The vast majority of applications use a frequency of 1000 to 1200Hz. This frequency is high enough to allow weld transformers to be reduced in size by removing magnetic core material. The same amount of conductor area must be maintained for a given output power. Raising the frequency higher reaches a point of diminishing returns, the size cannot be further reduced and parasitic losses from switching become greater.

5

Establishing a frequency of operation also fixes the time that the inverter can be turned on. When this time is reached, the Inverter must shut off the pair of IGBT that are conducting, wait until they turn fully off, then the other pair of IGBT can be switched on. We will refer to this period as "ON" time"

At 1000Hz, the period of total time is 1ms (1000us). Each half cycle would then be 500uSeconds, and the IGBT ON time cannot exceed this calculated maximum.

Ideal operating range would be achieved where the ON time is a substantial fraction of the total half cycle time, with Inverter Primary Current within the normal range for that inverter capacity. Some room must be allowed to accommodate additional energy required by stepper programs or changing resistance conditions.

If the ON time reaches the half cycle maximum, without reaching the Inverter Primary Current limit, the condition of "Secondary Resistance Limiting" occurs. No more energy can be delivered to the weld load. The fixed voltage of the Inverter supply, and the resistance of the weld load, simply will not draw any additional current from the inverter even if the inverter stayed on forever. In practice, this is seen as a condition where increasing the weld heat from the inverter control does not cause any increase in energy delivered to the load.

Changing the resistance of the metal to be welded is usually not an option. The only solution is to increase the voltage at the secondary, by choosing a different transformer tap (if applicable) or by replacing the transformer with a unit that has a lower turns ratio (higher secondary voltage).

If the inverter reaches the requested current at a short on time, the welding system will become difficult to control. The resolution of heat settings will make it hard to control the process. Small changes in requested weld energy will cause large variations in actual energy. Overall weld secondary current may be reported at a lower than normal value, as the delivered energy will be a small fraction of the total half cycle period. The inverter may reach a Primary Current Limit and shut down to protect the inverter components. (Figure 5)

In this case, the secondary resistance is too low. One possible solution would be to increase the primary current capacity of the inverter. As noted earlier, this is not as simple as retrofitting a larger thyristor to an existing control. Inverters are a unified system and increased current usually requires changing the rectifier bridge, DC link capacitors, and IGBTs... or in other words... changing everything. Another possible solution would be to decrease the secondary voltage by choosing a different transformer tap (if applicable) or by replacing the transformer with a unit that has a higher turns ratio (lower secondary voltage)
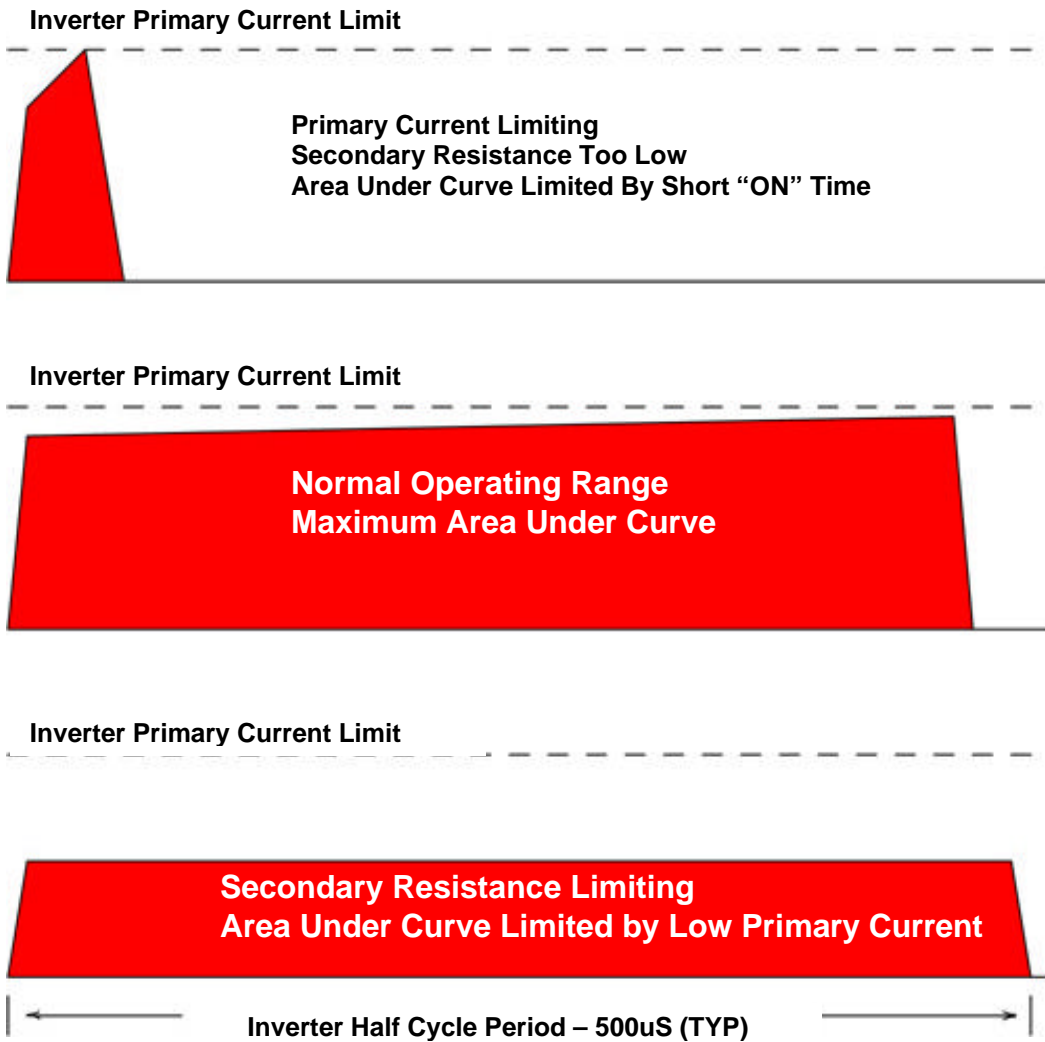
Inverter Primary Current Limit

Primary Current Limiting
Secondary Resistance Too Low
Area Under Curve Limited By Short "ON" Time

Inverter Primary Current Limit

Normal Operating Range
Maximum Area Under Curve

Inverter Primary Current Limit

Secondary Resistance Limiting
Area Under Curve Limited by Low Primary Current

Inverter Half Cycle Period – 500uS (TYP)

Figure 5: Primary Current Limiting, Normal Operating Range or Secondary Resistance Limiting

E. Role of the Transformer in Inverter Welding:

The fixed voltage output of the Inverter welding control requires that we abandon any simple assumptions about transformers. The transformer is best thought of as an impedance, or power-matching device between the inverter (fixed voltage) and the weld secondary load (fixed resistance).   Many users make the simple assumption that if they have an Inverter with 1000 primary amp capacity, and a 50:1 transformer turns ratio... that they will achieve 50KA secondary current. They are often surprised to find that such a system may deliver far less energy than that due to the mismatch from ignoring the actual secondary resistance. Inverter weld controls and transformers are expensive items, specifying the incorrect unit can be a disaster.

Simple rules of thumb used in sizing AC weld systems, such as specifying a transformer by KVA rating should be avoided in Inverter welding systems. It is outside of the scope of this paper to advise on the correct transformer size for a particular application. Manufacturers of these transformers are the best resource for making sizing decisions; they may be able to assist a user who is unsure of their secondary resistance. Careful consideration in the planning stages can avoid costly mistakes in the actual application.

F. Duty Cycle Issues:

Once the correct transformer is selected for a particular application, an ideal Inverter control size can be chosen. This selection process is more complex than the typical AC welding system.

AC welding systems have two major components that need to be selected for proper thermal management, the Weld Transformer and the Thyristor switch. AC Weld transformers are constructed of copper and ferrous material, nothing that is subject to rapid thermal failure. Thyristors have a simple construction and as such are quite robust.

DC welding systems have many components that must be appropriately sized to assure proper operation and to achieve their expected lifetimes.

MFDC Transformer - A full discussion of this component is outside the scope of this paper, but a short overview will aid understanding the issues involved. MFDC transformers have two parts to their thermal ratings. The transformer itself has duty cycle very similar to its AC counterpart. The core and windings usually have their duty cycle specified with an averaging time of one minute. The Secondary Rectifier assembly (diodes) are considered as a separate case. These diodes may be damaged by short applications of very high power, and must have their own power de-rating curves. A secondary current and number of cycles of acceptable "conduction time" (on time) are given. At low current levels, the diodes may be operated in continuous fashion. At high current levels, they may be capable of conducting for only a few tens of milliseconds. Transformer rating curves as shown in Figure 6 have a "family" of curves detailing the characteristics at a number of operating points. The actual application must be examined before specifying a transformer.

Figure 6: Typical RoMan MFDC Transformer rating curves

Inverter – The manufacturer's duty cycle curve as shown in Figure 7 specifies the rating of an inverter. The following parameters usually form the basis for this specification.

- Operating Current
- Maximum conduction time
- Expected life

The basis of these specifications can be best understood if we look at the physical characteristics of a number of the inverter components. In short Diodes (or Thyristors), IGBTs, and Capacitors.
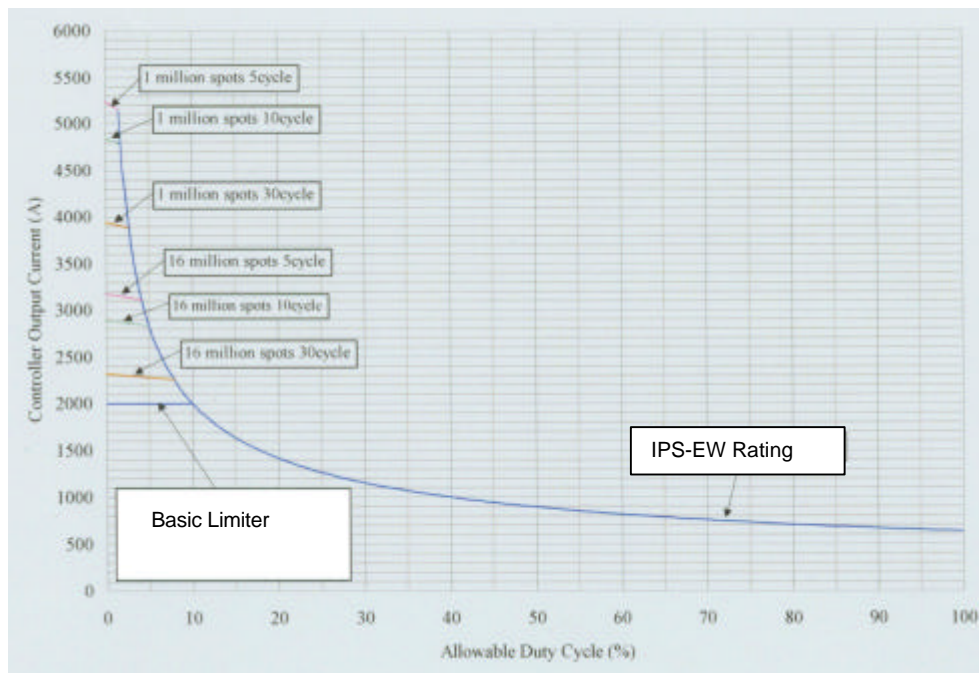

Figure 7: Typical Inverter Rating Curve

Diodes

Diodes in inverter applications have similar characteristics to those of Thyristors. As two terminal devices (anode, cathode) they can be constructed in such a way that any heat generated in the silicon can be removed rapidly. Diodes (or thyristors) are typically used for line voltage rectification and are subject to similar conditions as would be found in an AC welding process. Usually they are not the critical factor in duty cycle rating.

Capacitors

Capacitors are a vital component in Inverter controls. They serve as a power reservoir, lowering the peak demand on the rectifier diodes and absorbing transient voltages caused by AC line and weld load inductances. Many Inverter weld controls use Electrolytic capacitors. This form of capacitor contains a chemical (electrolyte) that causes an oxide layer (dielectric) to form on an Aluminum foil plate. These capacitors have a finite life based on drying of the electrolyte. Their life expectancy is cut in half by each ten degree Centigrade change in operating temperature. Internal resistances cause heating in Inverter applications and can shorten life further. Failure mode for these capacitors is generally catastrophic and they must be removed from service when their useful life expectancy is exceeded. Maximum voltage ranges for Aluminum electrolytic capacitors are usually in the 450VDC range (some are specified to as high as 550VDC). The voltage rating usually requires that capacitors be operated in series to get an acceptable working voltage rating. Dielectric breakdown can occur with overvoltage transients, and usually causes catastrophic failure.

Insulated Gate Bipolar Transistors (IGBTs)

Insulated Gate Bipolar Transistors (IGBTs) are very different devices from Thyristors. All but the very smallest of these devices are manufactured in modular assemblies consisting of a number of matched transistor die (chips) and a number of diode die (chips) mounted to a common heat sink area. They are isolated from this heat sink by a thin layer of some thermally conductive, electrically insulating material such as Alumina (aluminum oxide ceramic). The individual die has a multitude of wires bonded to them to make the electrical connections. These are attached to lead frames inside the modules and eventually are terminated at external points.

There are two major wear mechanisms in these modules, both related to heat and therefore current. IGBTs eventually die from failure of the bonding wires, or thermal fatigue of the insulating ceramic material. Both failure modes are usually progressive. Failure of bond wires can occur from thermal fatigue (they get too hot and unsolder from the die) or from mechanical fatigue (they are subject to vibration from mechanical and electromagnetic sources). One failure will increase the load on other bonds, which tend to fail faster from the increased stress, as the remaining bond wires have to carry the additional load of the failed connection.

Fatigue (cracking) of the insulating substrate is another failure mechanism. Understanding of the principles involved is critical in Inverter Welding, as the ratings of the devices themselves are affected by the nature of Resistance Welding loads.

Thermal Fatigue in IGBTs results from the different coefficient of expansion for the different materials. The silicon die becomes hot during device conduction time. This heat causes expansion of the silicon die, the insulating ceramic layer, and eventually the copper heat sink / mounting base. These materials expand at different rates. The amount of actual mechanical stress (and the amount of subsequent damage) depends on the temperatures involved, and the time that those temperatures are maintained.

Copper has a (linear) thermal coefficient of expansion roughly five times that of Silicon. The insulating material is chosen to meet the requirements of thermal conductivity, electrical isolation, and an attempt to match the coefficient of expansion of the silicon and the copper. This thermal fatigue mechanism leads to a special region of operation used in Resistance Welding Inverters.

Transient Thermal Impedance is the characteristic used to model the performance of the IGBT in the region of operation where the Silicon has risen to an elevated temperature, but the copper has not changed temperature. This region is characterized by application of short pulses of energy separated by relatively long periods of idle (cooling) time. Simply put, during a short pulse (like that of a Resistance Weld spot) the heat stays in the silicon, causing less expansion that would occur in a longer pulse.

There is a time constant associated with the Transient Thermal Impedance operating area. This constant varies in specifications from as short as 120ms (6 line cycles @ 50Hz) to as long as 700ms (42 line cycles @ 60Hz) depending on manufacturer. The shorter time constant may be appropriate for some materials (such as Aluminum) but would not be applicable in most bare of coated steel applications. Variance also exists in the specification of expected product life. Some products are specified at as few as one million weld spots, others at ten million spots. The user must take care to evaluate products based on similar conditions, in fact the actual conditions that they will use in their application.

Manufacturers of IGBTs test their devices to categorize their expected lifetime. These tests yield estimates of lifetime based on steady state temperatures, typical of their common applications in motor drive controls and uninterruptible power supplies. Published figures underestimate the life expectancy in pulsed applications by one to several orders of magnitude.

G. Tools for Determining Inverter Selection:

It is of critical importance that the end user of Inverter Resistance Welding Controls has access to data from manufacturers that allow them to intelligently compare the relative merit of various inverter units. To date there is no one universal standard for making such comparisons.

The easiest way for a user of inverter resistance welding controls to choose the correct inverter size is to map out the intended application with the inverter duty cycle rating chart as shown in figure 7.

Stepper Max (%)	**10%**	*This is the maximum current added by the stepper over the base weld current*
Weld Current	**20000**	*This is the base welding current (I secondary)*
Heat Cycles	**12**	*Number of "heat" cycles in one welding pulse*
Cool Cycles	**0**	*Number of "cool" cycles in one welding pulse*
Pulses	**1**	*Number of 'pulses" in one weld*
Transformer Turns Ratio	**50**	*Welding Transformer turns ratio : nn : 1*
Time between welds	**1.95**	Time in seconds from the start of one weld to the start of the next (maximum = 2 seconds)

Figure 8: User Application Data

In order to ascertain that the chosen inverter will operate within acceptable range of operation, the user is required to map out a point on the chart that is below the curve. In order to determine the operating current and the application's inverter duty cycle, the user is required to input the information shown in figure 8 above.

Since we are concerned about the worst-case application, the user is to input the maximum values that apply. The data inputted into figure 8 will yield results as shown in figure 9.
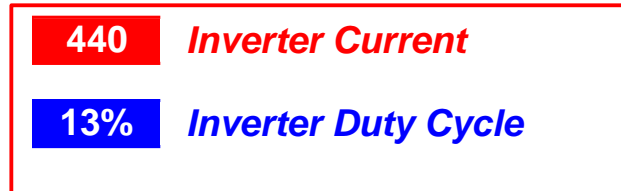

Figure 9: Calculated Application Point

The calculated application point could now be transposed to the inverter duty cycle rating charts to determine if the selected inverter is suitable for the application. In the example shown in figure 10, the application point is above the acceptable limit of the selected inverter. The value of 440 amperes operating at 13% inverter duty cycle is above the IPS-BW inverter. The user will have to choose a larger inverter unit for the application involved.
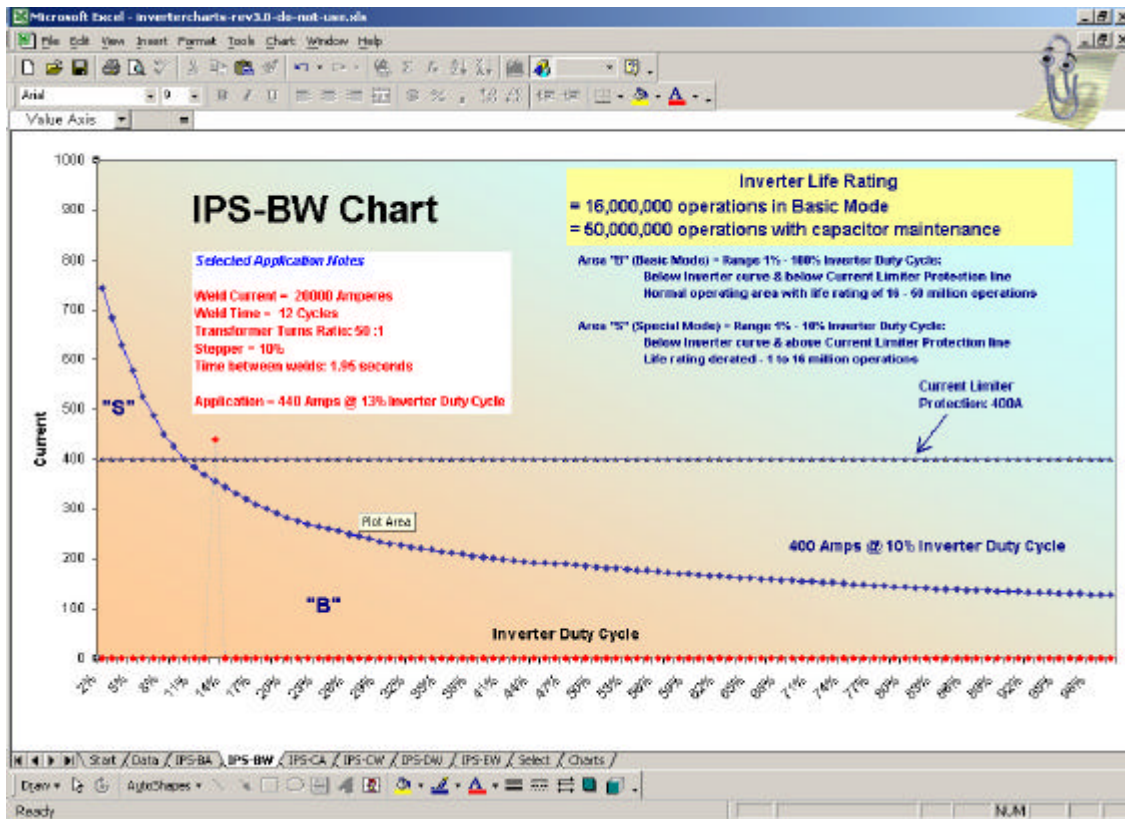

Figure 10: Application Point Above Limit

12

The duty cycle calculation (13% in this example) is based on the worst-case situation within a 2-second interval for pulses that are within the specifications of the manufacturer. For example, the charts shown in this document are rated at a 30 cycle welding pulse. Should the user enter 31 cycles or more as the weld time, the duty cycle will automatically be valued at 100%. For welding cycles of 30 cycles or less, the duty cycle is calculated by the number of ON cycles during a 2-second interval.

In the example above, there is 1.95 seconds between starts of welds (or 117 cycles base on a 60Hz timing). Therefore, there is 15 cycles of ON cycles during 120 cycles hence the inverter duty cycles is measured to be 12.5% (rounded up to 13% on the chart).

The inverter primary current is measured to be 440 amps. It is calculated as 20,000 amperes secondary plus 10% additional for stepper then divided by a Turns ratio of 50.
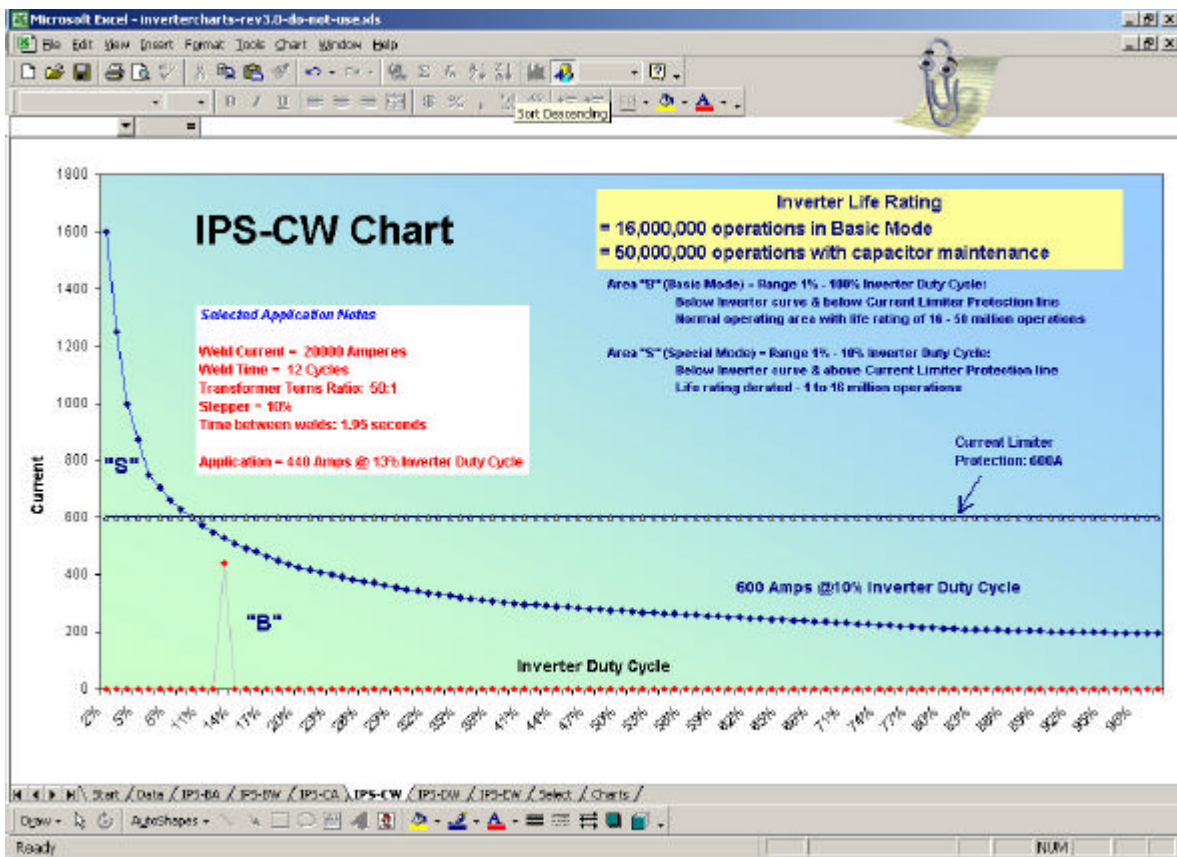

Figure 11: Application Point Within Limit

By selecting a larger inverter, the user's application point will find itself within acceptable operating limits.

Summary:

Selecting equipment for producing spot-welds using resistance-welding process requires careful attention in proper sizing. Always begin at the spot weld location to determine the welding current requirements in terms of ampacity, welding time, and force.

Next, determine the tooling requirements for providing the current, time and force to the spot weld. This is essential for determining the correct type and size of welding transformer.

Once the welding transformer has been selected, a weld control is selected. If the selected transformer is a single phase AC or single phase to DC power transfer device, the thyristor base welding control is selected. The thyristor based welding control is practically a one-size fit all where the major sizing criteria would be reserved only for sizing of circuit breakers and isolation contactors.

If the selected transformer is a Mid Frequency to DC power transfer device (MFDC weld transformer), the inverter based welding control is selected. The inverter based welding control comes in various sizes. The choice of size of inverter is based on the intensity of current draw through the inverter and the inverter's duty cycle of operation.   Selection tools are available from manufacturers for validating the choice of inverter for the intended application.   The user maps out the worst-case application point within the inverter specification chart.

References:

1) Roman Manufacturing Inc.,

> http://www.romanmfg.com/
> http://www.romanmfg.com/sizing.htm

TXSELECT is a piece of software written to aid in the selection of a transformer for an application.

2) Welding Technology Corporation,

> http://www.weldtechcorp.com/
> http://www.weldtechcorp.com/documentation/index.html

INVERTER SELECT is a piece of software written to aid in the selection of a suitable size inverter for user specified applications.