AN INTRODUCTION TO HIGH-FREQUENCY
SOLID-STATE PIPE AND TUBE WELDERS

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INTRODUCTION

In the last few years the solid state welder has become the dominant choice for the high frequency pipe and tube making process, displacing the traditional vacuum tube welder. Solid state welders are available with power ratings range from 50 kW to 2000 kW. Their welding frequency can be tailored from 100 kHz to 400 kHz for most power ratings and as high as 800 kHz for low power units. Systems can be configured for the induction welding process, the contact welding process, or both. Load matching is as automatic as it is with vacuum tube units. Solid state welders have been applied and proven in all high frequency pipe or tube welding applications.

ADVANTAGES

The reasons for the revolutionary success of solid state welders are:

- **GREATER EFFICIENCY.** Solid state welders are typically over 80% efficient, compared with 65% efficiency for vacuum tube welders. This saves both electricity and cooling water, and often allows an existing vacuum tube welder to be replaced with a higher power solid state unit without incurring costly up-grading of the incoming electric or water supplies.

- **ENHANCED RELIABILITY.** They are more reliable because they contain no “finite life” components (such as a vacuum tube) and operate at significantly lower voltages (typically below 500 volts) so that voltage stresses on both the electrical components and insulation systems are greatly reduced. Lower voltages also reduce the potential for electrolysis and corrosion.

- **SAFETY.** They are safer for maintenance personnel because of the lower voltages in both the DC power supply and RF cabinets.

- **COMPACT DESIGN.** They are much more compact than vacuum tube units so that location and installation on the mill are greatly simplified.

With these advantages, the average pipe or tube producer has little difficulty justifying the replacement of an aging vacuum tube welder.

SELECTING A SOLID STATE WELDER

When purchasing a solid state welder, most of the main concerns and specifications are the same as for a vacuum tube welder. A major difference, however, is that a solid state welder is an inverter and a vacuum tube welder is an oscillator. The type of inverter circuit used in a solid state welder design, whether it is current fed or voltage fed, has significant impact on its features and performance. Also, type of solid state power devices employed impacts the range of available welding frequencies. The principle specifications for the welder are welding frequency, power rating, and efficiency. Other concerns include load matching, system packaging, modularity, installation restrictions, and on-going maintenance strategy.

Inverter Type - Current Fed or Voltage Fed:

Two fundamentally different circuits are employed in the RF generator sections of solid state welders. These are the current fed inverter circuit and the voltage fed inverter circuit which are illustrated in Figure 1. On the surface, these circuits appear to be very much the same. Both consist of a DC power supply section that converts the incoming three phase AC mains power to a DC voltage and a high frequency bridge composed of solid state power devices that converts the DC power into RF power at the welding frequency. The main differences between the two circuits are:

- In the current fed inverter, a large inductor connects the DC power supply to the inverter. If the output of the inverter is shorted, and this happens during arcing at the work coil, the inductor limits the output current and inherently protects the inverter from destruction. The voltage fed inverter, on the other hand, has a large capacitor between the DC supply and the inverter. In a coil arcing situation, the charge stored in this capacitor can destroy the solid state power devices if they are not protected against short circuits by additional protective circuitry. Additionally, the capacitor, which is physically quite large, must be mounted very close to the power FETs to minimize inductance. Thus the capacitor must be part of the RF generator assembly. On the other hand, there is no restriction on the location of the inductor in the current fed inverter, so it may be located in the DC power supply. The result is that the RF generator portion of a current fed inverter is considerably more compact than that of a voltage fed inverter.

- The current fed inverter has a low impedance output consisting of a parallel tank circuit (e.g. the output capacitance and work coil inductor are in parallel) where as the output of a voltage fed inverter naturally drives a high impedance, series tank circuit (e.g. the work coil and output capacitance are in series). As induction welding work coil loads have low impedances, the current fed inverter can drive them directly. With a voltage fed inverter, an RF output transformer is almost always required. This reduces both the efficiency and the reliability of the voltage fed inverter, and further increases the size of its RF section.

Thus it can be seen that solid state welders designed as current fed inverters will have the most robust tolerance of coil arcs, the smallest size, and the highest reliability. They will naturally provide the best match to the low impedance work coil loads encountered in induction pipe and tube welding.

Solid State Power Devices - MOS FETs or IGBTs:

Once the inverter circuit has been chosen, the second choice facing the solid state welder designer is the choice of power device. Two types of power devices are available for use as the switches in the solid state inverter - Metal Oxide Semiconductor Field Effect Transistors (MOS FETs) and Insulated Gate Bipolar Transistors (IGBTs). In a MOS FET, an electric field in the "capacitor" composed of the FETs's gate and silicon substrate controls the conductivity of a channel in the silicon substrate between the FET's output terminals. Varying the voltage applied to the gate terminal of the device varies this electric field, and the effect is to change the resistance between the output terminals from the low value of the silicon channel to a very high value where essentially no can flow between the output terminals. Thus changing the gate voltage of the FET controls the current flowing through it.

An IGBT is a combination of a FET and a bipolar transistor. The FET provides a high input impedance (one of the drawbacks of bipolar transistors) and is used to control the base current to the transistor. The base current controls the current between the transistor's output terminals. When no base current is present the transistor can pass only a very small amount of current. When enough base current is present, the transistor has a small voltage drop across its output, independent of current passing through it.

IGBTs are more efficient than FETs and can handle more current. This is because the current flows through the surface of the silicon in an IGBT as opposed to across the surface of the silicon as in the

FET. Thus fewer IGBTs than FETs are needed to achieve the same power rating, and the cost of the welder can be reduced.

However, the major draw back of IGBTs is their switching speed. At the current state of technology, this limits their usefulness to frequencies below 100 kHz. While IGBTs can be operated as high as 150 kHz, the switching losses reduce their ratings to be comparable with FETs. There is no particular advantage in using them in designs operating above 100 kHz And above 150 kHz their use is impractical.

As is explained in the next section, welding frequencies between 200 and 400 kHz are the best for all pipe and tube welding applications with the possible exception of tubes with very thick walls (greater than 13 mm). MOS FETs are the best choice for most solid state pipe and tube welders.

Welding Frequency:

Welding frequency is an important process parameter. Historically, about 400 kHz has proven to be a good frequency for most applications. This choice was arrived at as a result of scientific analysis, experimental studies, and the experience from pipe and tube producers. Recent theoretical work, backed by experimental results, has extended the understanding of welding frequency and has provided a solid foundation for its selection. [1]

In pipe and tube welding, two physical phenomena determine how much of the “vee” edge is heated during the welding process. The first is the electrical “skin effect”, or the tendency for high frequency currents to flow on the surface of conductors. This is characterized by the “electrical reference depth”. The second is the thermal conduction of heat away from the “vee” edge which can be characterized by a “thermal reference depth”. For a particular tube material, the “electrical reference depth” is a function of welding frequency, and the “thermal reference depth” is a function of the mill speed and “vee” length. If the “electrical reference depth” is reasonably less than the “thermal reference depth”, the result is a weld with the narrowest heat affected zone (HAZ) that is made with the minimum input power (highest efficiency from the welder) for that particular material, “vee” length, and mill speed. Increasing mill speed and reducing “vee” length both reduce the “thermal reference depth”, while increasing welding frequency reduces the “electrical reference depth”. If “vee” length is related to tube diameter, the modern theory of welding frequency can be used to determine the “best” welding frequency for a particular pipe or tube. This is illustrated for low carbon steel tube in Figure 2. Higher frequencies have proven to be better for very thin wall tube of copper, aluminum and brass. Somewhat lower frequencies have proven useful for welding stainless steels.

Figure 3 shows actual experimental data and analytically calculated results for 38.75 mm diameter by 1.47 mm wall low carbon steel tube, welded at different mill speeds and at welding frequencies between 100 kHz and 400 kHz. At 30 meters per minute mill speed, varying the welding frequency has minimal effect on the welding power requirement. This is because the “thermal reference depth” is somewhat larger than the “electrical reference depth”. However, as the mill speed is increased to 90 meters per minute significantly more power is required at the lower welding frequencies. In this example, a solid state welder operating at 200 kHz would actually be less efficient than a vacuum tube welder operating at 400 kHz if this tube were produced at 90 meters per minute. The most productive manufacturers of this size tube should definitely use higher welding frequencies to achieve the greatest efficiency.

Operating above the “best” welding frequency reduces the squeeze out necessary to obtain a good forge weld. The reduction in skelp width can result in considerable material savings while obtaining the highest weld quality. Conversely, working at too low a welding frequency can result in excessive squeeze out. This can yield brittle, cast weld structures of inferior quality.

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[1] For a complete discussion of welding frequency, see: Scott, P. F., The Effects of Frequency in High Frequency Welding, Tube Toronto 2000, 1996.

The magnetic flux concentration within the impeder is also affected by frequency. The higher the frequency, the lower the magnetic flux level. High welding frequencies make maximum use of the available amount of impeder material. Operating at lower welding frequencies can result in a requirement for more or higher quality impeder material. This is not to say that tubes can not be welded at lower frequencies, but that other parameters of the process may also have to be adjusted to obtain commercially competitive results.

Modern solid state technology has allowed welders to be developed for all welding frequencies, and are available to implement the most viable and cost effective tube production processes at the best welding frequencies.

Output Power and Efficiency Ratings:

Some confusion exists over welder output power ratings. Historically, makers of vacuum tube welders have rated the output power of their welders as that delivered to a calorimetric load. This rating is the most conservative and accounts for losses in the leads and work coil. This is also the rating that correlates with the welder power requirements given in the standard weld rate calculators. However, some suppliers of solid state welders rate their equipment as power delivered to the lead set or even as DC power supplied to the RF generator. These ratings can be significantly higher than those achieved by the calorimetric method. Therefore when choosing a solid state welder, it is important to understand which power rating the manufacturer is quoting. The alternative may be under-sizing the welder or making an unfair comparison between alternative product offerings.

The efficiency rating can also be misleading for the same reason. Conservative manufacturers define their rated efficiency as the total power delivered to a calorimetric load divided by the total input power drawn from the power line. Power lost in the lead set and work coil is also included in this rating. Again, some suppliers rate their efficiency only to the output of the RF generator. Practically, all well designed solid state welders are about 80% efficient in providing power to a calorimetric load with more than half the losses appearing in the leads and work coil. They are about 90% efficient in providing power to the output of the RF generator. Not understanding the manufacturer's efficiency rating method may produce projected savings that will not materialize after the equipment is installed.

Load Matching:

Load matching is more critical with a solid state welder than with a vacuum tube welder. This is because the high frequency generator in a vacuum tube welder is an oscillator with its own, self contained tank circuit that determines the welding frequency. On the other hand, a solid state welder is a resonant tuned inverter where the welding frequency is determined by the inductance of the work coil. This inductance is a function of the coil's geometry, the geometry and material of the tube being welded, and the characteristics of the impeder, all of which are difficult to predict for a particular tube welding situation. Furthermore, a solid state welder will only deliver its full power output at a particular voltage and current level which defines the output impedance of the welder. If the load provided by the work coil is different from this value, the welder's power rating can not be achieved. To correct for these conditions, load matching adjustment must be provided in the welder. The load matching circuitry transforms the actual impedance value provided by the work coil, tube, and impeder to the value needed to insure full power output from the welder at its rated frequency.

Most solid state welders with RF output transformers accomplish load matching by switching between multiple taps on the primary. The user selects the tap that does the best job of matching the work coil load to the inverter. The problems with this approach are that output power and frequency can not be matched independently and that the tap switching can only take place at low power levels. Thus, the load match can not be dynamically adjusted while the welder is operating to compensate for changes in the tube's material properties, which vary both as a function of weld temperature and from coil to coil, and for changes in the impeder's performance as it degrades over the production run.

A better solution to the load match problem is to use a network of variable inductors whose values can be adjusted at any power level. By providing a pair of inductors properly located in the output circuitry of the welder, both power output and welding frequency can be maintained independently. Also, the load match can be continually adjusted while the welder is operating to provide consistent welding throughout the production run.

Welder System Packaging:

Another important consideration in selecting a solid state welder is how the system is packaged. In general tube mills are a harsh environment for electronic equipment. Solid state welders should be ruggedly packaged in NEMA type, sealed enclosures and should not rely on contaminated plant air for cooling.

The interconnection method between the various equipment cabinets is also important. Some suppliers package their units with the DC power supply and RF generator in one cabinet and a load matching device in a separate cabinet that is mounted close to the tube mill. The interconnection is made by a special, water cooled RF cable whose length must be maintained below an absolute maximum value. A better, more flexible system has the DC power supply and RF generator in separate packages. Because of the small size of solid state devices, the RF generator can actually be made smaller than a conventional load matching network, and because the interconnection is a simple DC cable, there is no cable length restriction between the units. This not only simplifies the physical placement of the welder but provides on-going flexibility as the plant and mill layouts change over its life.

Modularity:

Modularity is a key difference between solid state welders and vacuum tube welders. Most modern solid state welders are constructed from standard modules and are configured for a particular power rating by changing the number of modules in the unit. Modularity contributes heavily to the serviceability of the welder. In the event of a module failure, it should be possible to quickly disconnect a defective module and operate the welder at reduced power. This is only practical, however, if the power rating of the individual modules is small enough so that the resulting power degradation is a small percentage of the welder's output. This is particularly true for welders in the 100 kW to 400 kW class. Modules should also be easily replaced, so the welder can be brought back to full power quickly. The manufacturer should exchange a defective module for a good unit so that plant personnel do not have to be trained in the details of solid state trouble-shooting and repair. Modularity also allows the welder to be configured for expandability, but sufficient facilities planning must be done in advance of the installation to ensure adequate electrical power, water, and floor space for the largest contemplated configuration.

Installation Considerations:

An installation plan for a solid state welder should be simpler than for a vacuum tube welder. Proper system design of the welder should impose no restrictions on the placement of the equipment on the plant floor. Because the RF component is significantly smaller than the vacuum tube oscillator, it should be easier to locate, and access to the mill for roll changes should be improved. The lower electric power and water consumption should reduce facilities costs as well as lower on-going operating costs.

Maintenance:

The maintenance strategy for a solid state welder is easy to implement and should result in reduced down time and lower maintenance expense. An extensive spare parts inventory for a solid state welder costs significantly less than that for the comparable vacuum tube unit, and there is no expensive vacuum tube to replace at regular intervals. It is important that maintenance personnel are trained on the solid state unit, but this training is for familiarity. A properly designed solid state welder, where all electronic repair can be accomplished by replacing a defective module or circuit board, reduces the detailed knowledge necessary to fix the unit, minimizing mill down time. Because of the high reliability of solid state components, the number of outages should be negligible. Further, the welder system should have over-all diagnostic capability that reports fault conditions to the operator, and the modules and circuit boards should contain self-diagnostics to aid in pin pointing the source of fault conditions.

SUMMARY

There are good reasons why solid state welders have displaced vacuum tube welders in the pipe and tube industry. These include higher efficiency, higher reliability, improved safety, and more installation flexibility. However, all solid state welders are not the same. The pipe or tube producer must be careful to understand which welder properly implements the target production process and to correctly interpret sometimes misleading specifications. This is best accomplished by working with proven suppliers that have a serious, long term commitment to the pipe and tubing industry.

FIGURES

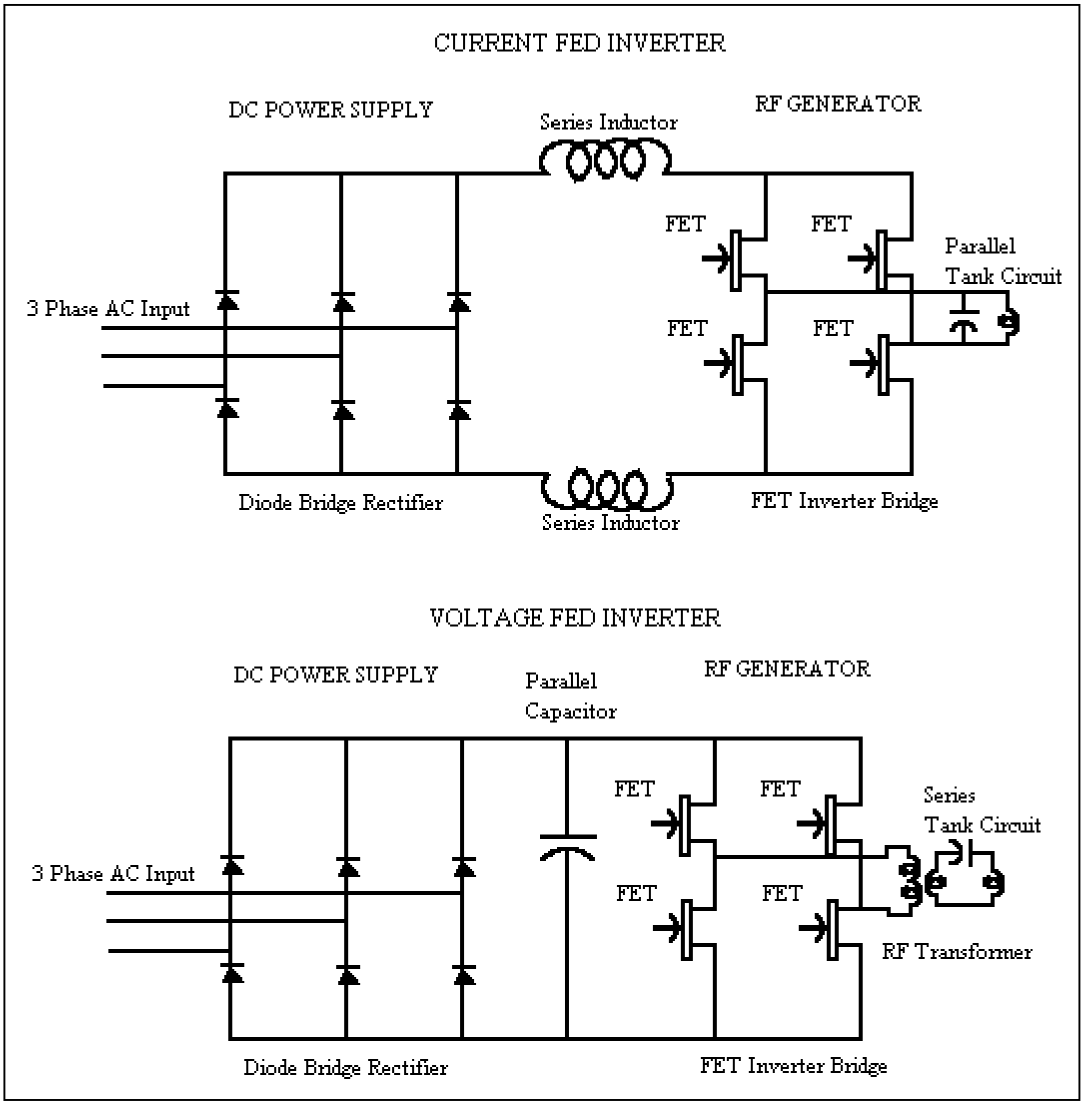

Figure 1 - Diagrams of Current Fed and Voltage Fed Inverters

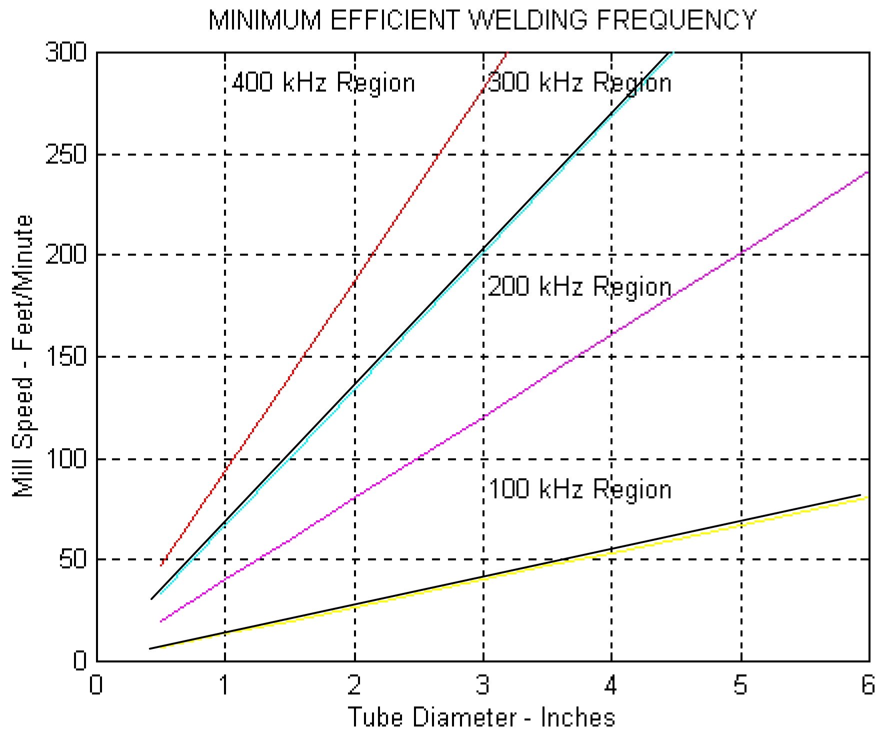

Figure 2 -= The "Best" Welding Frequency for Low Carbon Steel

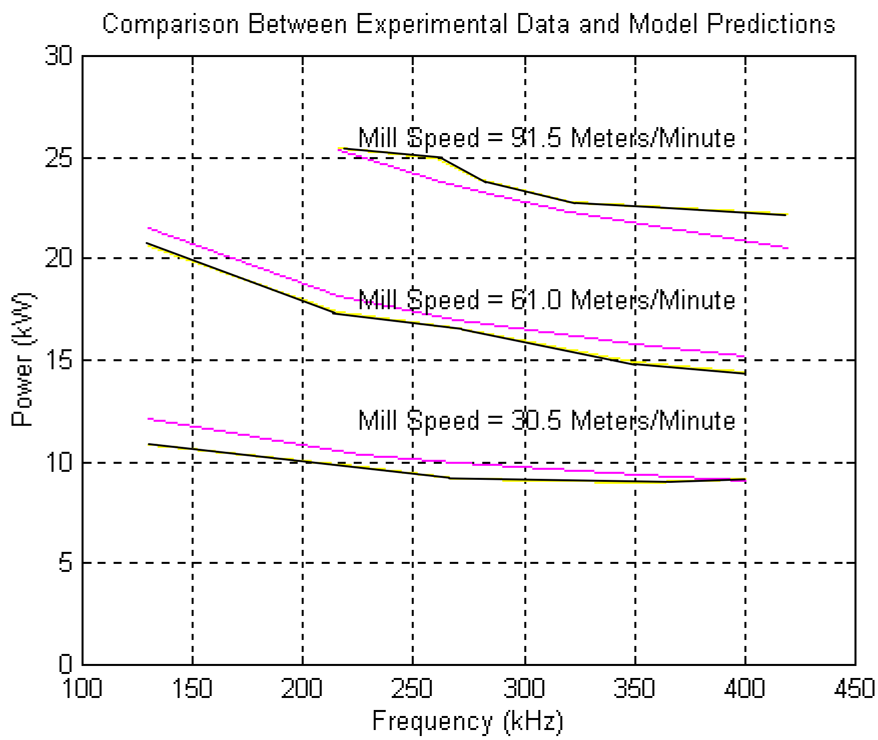

Figure 3 - How Weld Power Varies with Mill Speed and Welding Frequency