

High Frequency Induction Heating

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Abstract

This paper presents a new High Frequency converter for induction heating. The converter has a diode rectifier and automatic matching. It uses a patented timesharing principle for high frequency use of IGBTs (*ref. [1]*) in order to reach 350 kHz. The paper focuses on the benefits the converter structure has in some typical application.

Introduction

Solid state converters for induction heating are built with different types of switches depending on frequency range: thyristors for frequencies up to about 10 kHz, IGBTs up to about 100 kHz and PowerMOS up to about 400 kHz. IGBTs have several strengths compared with PowerMOS: better ruggedness, more power from each module and lower price. However, it is necessary to derate considerably to reach high frequencies due to much higher switching losses.

An important feature of induction heating converters is their ability to adapt to the variations in the load. The induction coil is electrically represented by an inductance in series with a resistance. The inductance requires reactive power and the resistance needs active power. The converter is the source for the active power and the compensation capacitor for the reactive power. The solid-state converters have taken over for fixed frequency motor-generator sets and, with the possibility of tuning the output circuit to its resonance frequency, the balance between production and consumption of reactive power could be made as an automatic adaptation. This is the standard today.

Load matching

When a metal is heated from room temperature to a suitable temperature for forging, melting, heat treatment, etc., the resistivity of the metal changes typically by a factor 4 - 5. Steel, with ferromagnetic properties at low temperature, turns to nonmagnetic behavior above the Curie temperature. In induction heating processes, the induction coil is often made to cover a certain range in work-piece dimensions. From the equation describing power transfer to the work piece (*ref. [2]*), we see that the load resistance is proportional to the work-piece diameter, and to the square root of work piece resistivity and relative permeability. Due to saturation effects, the effective relative permeability of magnetic steel is dependent on the field strength in the coil. This means that the change in load impedance, when the work piece temperature passes the Curie temperature, is larger at moderate than at high power densities and larger at high frequency than at low frequency. A consequence of this characteristic is that the induction heating equipment has to deal with a range in load resistance. For one coil and work piece, the range is about 1:2 in the non-magnetic case, and sometimes more than 1:4 in case of steel being heated above the Curie temperature, at moderate power density and high frequency.

A normal approach to this is to equip the system with some means of adjusting load impedance to the best setting and accept output power below nominal in part of the heat cycle. A different approach is to equip the inverter with extended capacity to supply higher voltage or higher current than nominal as illustrated in *figure 1*.

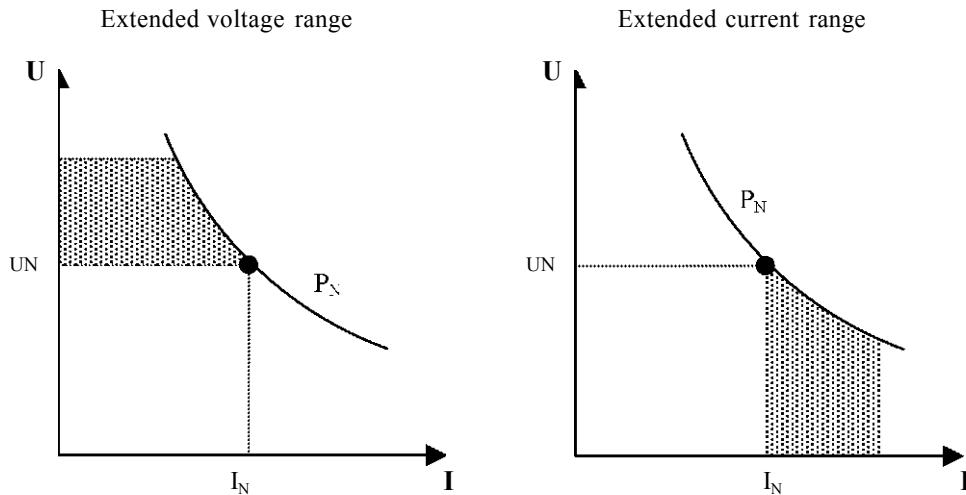


Figure 1. Automatic matching, voltage and current extension

A system with such extended capacity in either voltage or current we describe as having **automatic matching** capability.

Any system could be given an automatic matching capability just by derating the nominal power, but for systems with a controlled rectifier, an unmatched load means a reduced power factor on the mains supply. Automatic matching therefore functions best when this load adaptation has no bad influence on the mains supply power factor. This is the case when the converter has an uncontrolled (diode) rectifier, or a voltage extension above maximum rectifier voltage.

Converter structure

The use of IGBTs in an inverter for induction heating improves ruggedness and flexibility compared with a solution with MOSFETs. This inverter technology is put into a converter topology with diode rectifier and automatic matching, as illustrated in figure 2. This creates an induction heating generator with several strengths. This paper presents these features in more detail and shows their importance in a few typical applications.

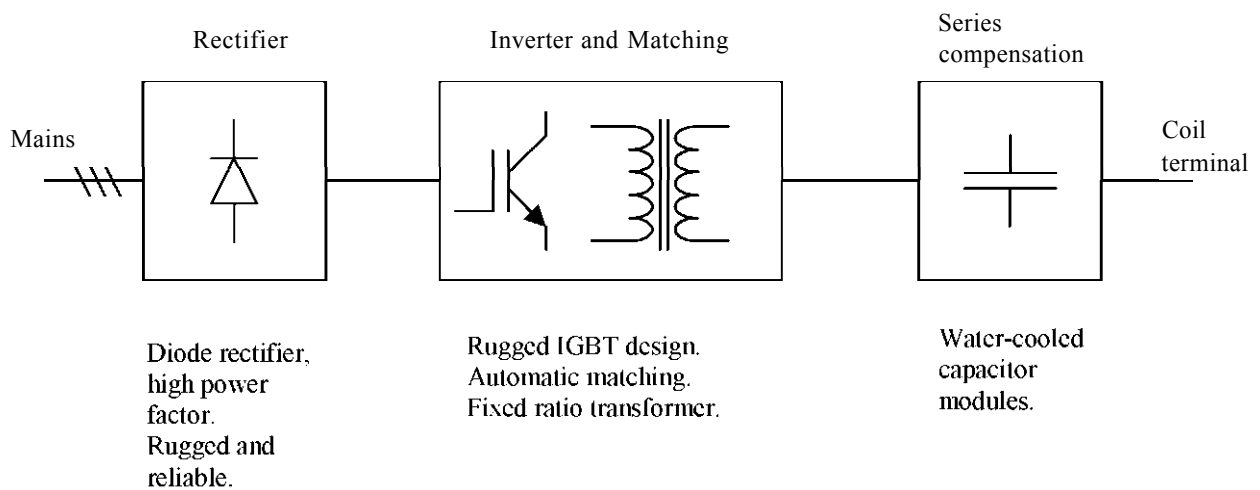


Figure 2. Converter structure and brief presentation of the converter's parts

The diode rectifier is rugged and reliable. The mains power factor is close to 0.95 independent of matching condition and output power. The diode rectifier bridge is passive; it continuously feeds the inverter with a constant DC voltage. The converter's start and stop process is an inverter function only and not affected by the rectifier and the phase of the mains.

The inverter uses IGBTs as switching elements. A patented switching pattern is used to reach frequencies up to 350 kHz. The advantage of IGBTs compared with MOSFETs is mainly their rugged properties: If a coil short-circuit occurs, the load resonant frequency increases. This causes the current zero crossing to occur before the voltage switching (see figure 6). This type of switching, termed capacitive switching, destroys an unprotected MOSFET. The action taken to avoid this situation creates disadvantages in a MOSFET inverter. In an IGBT inverter, the problem is removed in the first place. The IGBT device handles capacitive switching in a short time, and overheating is the only limitation that requires monitoring. Coil short-circuit events are handled excellently (See figure 6).

The NPT production technology used in IGBTs also gives less parameter spreading between the chips compared with the situation for MOSFETs. This makes paralleling of switching elements safer.

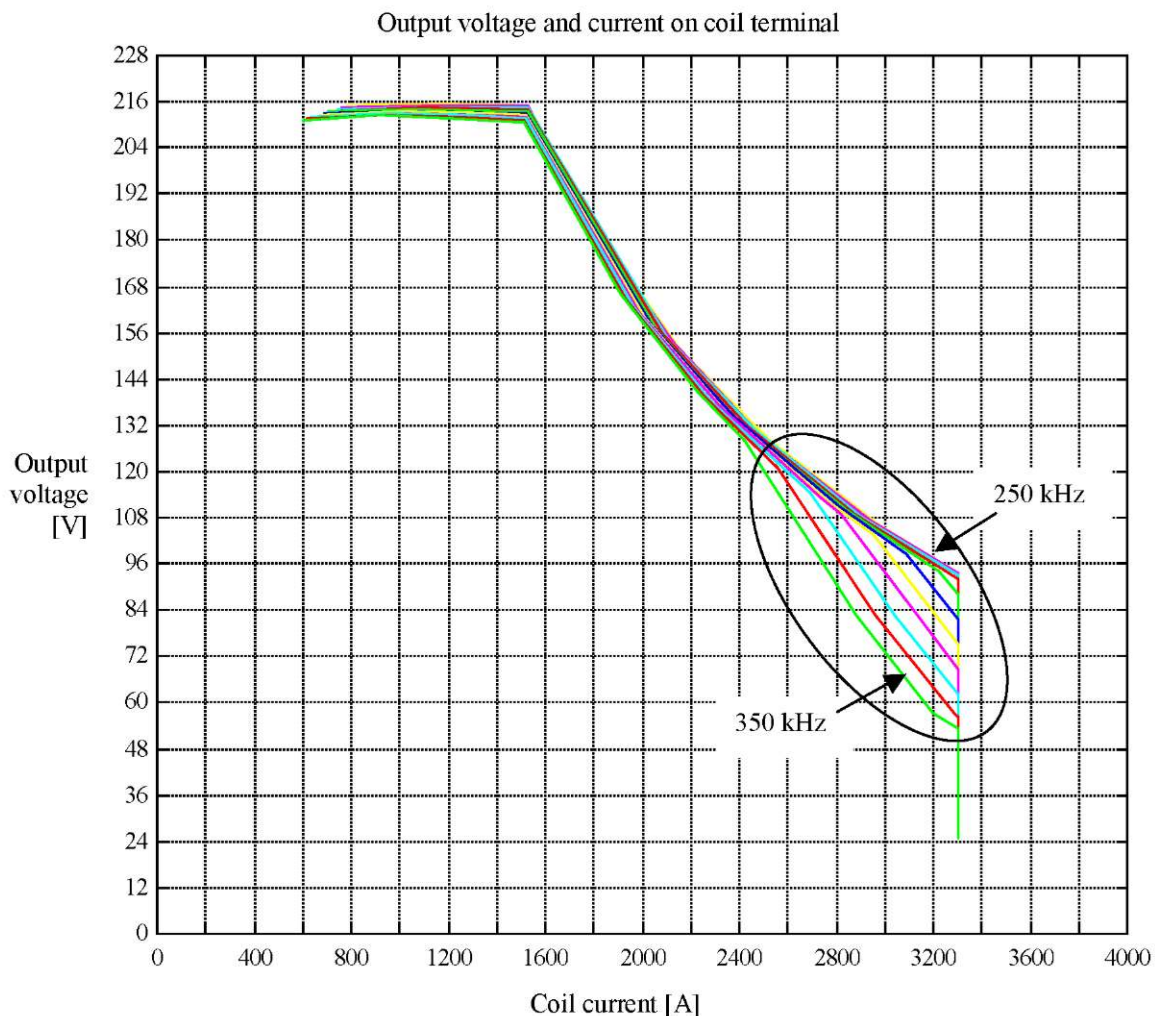


Figure 3. Maximum simultaneous output voltage and current for a 300kW 300kHz converter

The converter has automatic matching, by means of an extended current range, and a fixed ratio transformer. The solid-state inverter continuously adapts to the load resistance and instantly compensates for any load variation within the specified range as the converter is running. Because this

new switching pattern gives reduced losses when output the output voltage is reduced, the extended current range is achieved with just minor over-sizing of the inverter switches.

Figure 3 shows maximum simultaneous values for output voltage and current at the coil terminal. The figure shows the calculated values for the new 300kW, 300kHz, two-turn-coil, tube welding converter. The different lines are for frequencies from 250-350 kHz in 10 kHz steps.

The output capacitor modules are designed and made by EFD. These are low inductance, high current modules particularly designed for induction heating purposes. The numerous internal capacitor elements are water-cooled from each side in order to secure high current and high reactive power operation.

Applications

To sum up, the strengths of this converter structure are:

- Rugged, uncontrolled (diode) rectifier with high and load-independent power factor.
- Automatic frequency adaptation and automatic matching with almost 200% extended current range.
- Short ramp-up time, fast regulators and precise switch-off.
- Rugged and compact design. Improved safety margin at short-circuit, both on coil terminal and internally.

In the following, we look at the impact these features have in some applications.

Strip heating

Heating of steel strips below the Curie temperature with induction heating is a very efficient and well controllable process. Applications are drying of flux, paint curing, tempering, blue annealing, boosting, tin reflow, preheating before galvanization, and galvannealing. Many of these processes are continuous in which different strip dimensions are welded together to form a continuously running strip. A change in strip width causes a particularly large change in load resistance. Features such as a fast change of power setpoint, or a maintained high mains power factor at different load impedances, are important in a continuously running process.

Hardening

Contour gear hardening using single-shot heating has many advantages. This process requires a very high, but short, power pulse. The IGBT derating technology makes it possible to supply large current and power for a short time.

Wide automatic matching range is also an important property in hardening applications. As the heated item passes the Curie temperature, the steel becomes non-magnetic, and the impedance drops significantly. A converter with a wide automatic matching range will be able to deliver high power to the different impedance below and above the Curie temperature.

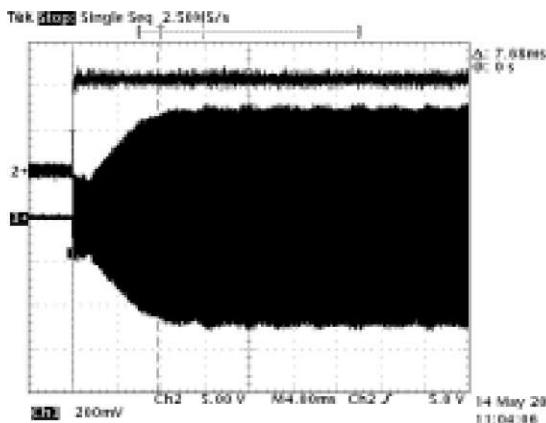


Figure 4.

The two curves in the plot are power reference (2) and output current (3).

Timebase is 4 ms/div.

The power reference is close to 100%.

Starting frequency = 300 kHz

Working frequency = 250kHz

To ensure stable hardening quality, it is necessary to have both precise power pulse duration and short ramp times during start and stop. The use of a diode rectifier makes the start and stop process independent of line voltage phase. In the start up process shown in *figure 4*, the current reaches its steady state value within 8 ms.

Tube welding



Figure 5. Longitudinal tube welding converter and the welding process

Converters for longitudinal welding of tubes in pipe production meet a variety of load conditions. A few of the typical load changing mechanisms are:

- Load impedance for one tube dimension is dependent on line running conditions and impeder quality. Thus, wide matching range is generally needed.
- Large tubes require higher power, but at somewhat lower demand for frequency.
- Small tubes may require large current and high frequency, but less power.

The converter is designed with relatively low internal inductance. This makes the resonant frequency respond to coil layout. A larger coil will make the frequency drop, which is the desired response for a larger tube.

When the welding process is running, metal slivers from the process can short-circuit the weld Vee, or make contact between the coil and the pipe. The short-circuited current path lowers the coil inductance, making the load resonant frequency increase. This causes immediately capacitive switching. In an IGBT inverter, capacitive switching is, as discussed, handled properly and ruggedly. *Figure 6* shows two pictures of the converter output during a coil short circuit. The coil short circuit is harmless to the converter.

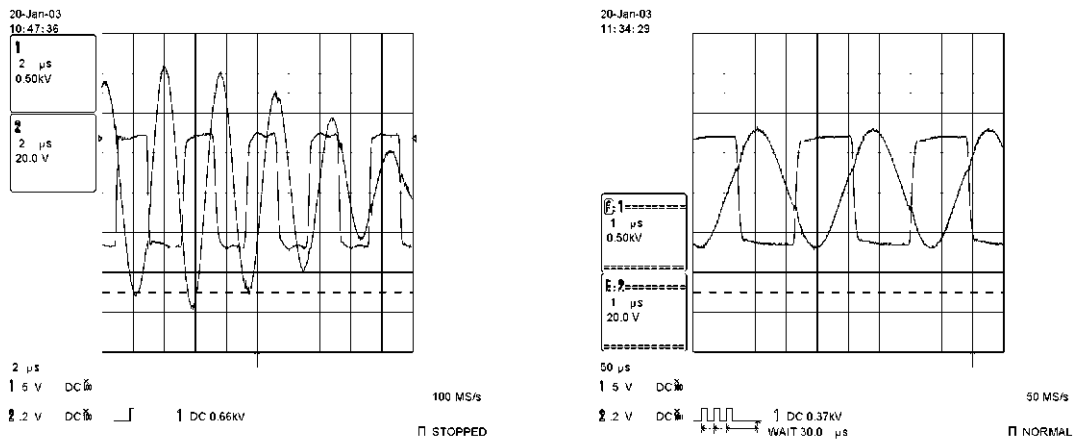


Figure 6. Coil short circuit event.

Left picture shows output voltage and current as the coil short circuit occurs. The phase-angle changes from normal voltage lead to voltage lag, or capacitive switching. Right picture shows output voltage and current just before the converter stops due to capacitive switching alarm.

Conclusions

The presented high-frequency converter, with diode rectifier, automatic matching and IGBT-based inverter, has many important features.

The diode rectifier gives high power factor on the mains, regardless of matching condition and power level. This is important in continuous processes, like strip heating. The diode rectifier does not participate in the converter's start and stop processes, causing fast and accurate start and stop. This is important in hardening application, where precise power pulses are needed.

The wide automatic matching range is important in nearly all applications. When heating metal, the resistivity changes as temperature rises, causing the load impedance to change. If steel is to be heated above the Curie temperature, the change is larger. This is the case, for instance, in hardening applications. In longitudinal tube welding, the load impedance changes with the line setup. One converter will also cover different tube dimensions having different load impedance.

The IGBT inverter handles coil and internal short circuits very well. This is also important in longitudinal tube welding where metal slivers from the process often cause temporarily partial short circuits.

References

(Patent)

- [1] Patent number NO312388, PTC/N001/00397.

(Textbook)

- [2] Induction Heating Handbook, John Davies and Peter Simpson, McGraw-Hill Book Company Ltd, Berkshire, England, 1979, Ch. 12.