Fast Thyristors for Induction Heating Solutions

Induction heating is one of the key metal industry applications using high-power resonant converters. The power range of such converters goes up to 10 MW and there is no more efficient alternative as switching device than the bipolar fast thyristor. ABB provides for years fast switching thyristors and further expands its portfolio for high-power resonant inverters. **Ladislav Radvan, ABB s.r.o. – Semiconductors, Switzerland**

Induction heating is based on three basic effects: electromagnetic induction, skin effect and heat transfer. Electromagnetic induction was first discovered by Michael Faraday in 1831. An electrically conducting object (usually a metal) can be heated when placed in an inductor that is part of a resonant circuit. An alternating current flowing through the inductor's coil generates an oscillating magnetic field. This in turn induces Eddy currents (also called Foucault currents) in the object which, by means of resistive (Joule) heating, heats up the object. According to Lentz's law the direction of the inductive current is opposite that current that generated the magnetic field which induced the inductive current.

In addition to this, the high frequency used in induction heating applications gives rise to a phenomenon called skin effect. This skin effect forces the alternating current to flow in a thin layer close to the surface of the object. The effective resistance of the object is increased which greatly increases the heating effect. As the skin effect is frequency dependent, the frequency can be used to specify the heating depth. Although the heating due to Eddy currents is desirable in this application, it is interesting to note that transformer manufacturers need to avoid this phenomenon in their transformers. Laminated transformer cores, powdered iron cores and ferrites are all used to prevent Eddy currents from flowing inside transformer cores.

The effects described above render induction heating many advantages compared to other heating methods. Induction heating is cost effective due to the lower energy consumption. Heat is generated directly in the heated object without any interfaces. Heating is contactless and therefore very clean. Induction heating is a fast process offering improved productivity with higher volumes. The heating energy can be easily and precisely regulated and the whole object or just parts of it can be heated by frequency adjustments. Figure 1 shows the typical converter power requirements and operating frequency as a function of induction heating furnace capacities.

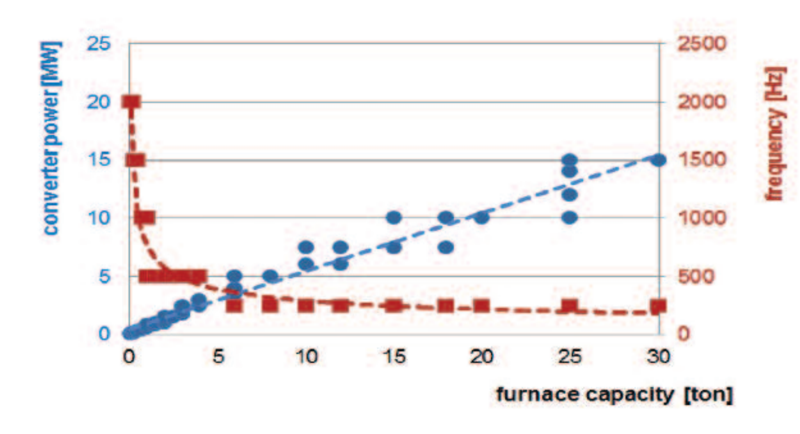


Figure 1: Typical converter power and operating frequency as a function of induction heating furnace capacities

Switching Techniques for Resonant Inverters

The most efficient way to feed induction coils with an alternating current is by integrating it into a resonant circuit, forming a resonant inverter.

Generally, semiconductor switches are operated in the hard-switching mode in various types of pulse width modulated (PWM) DC/DC converter and DC/AC inverter topologies. One disadvantage of PWM schemes is that the exact time at which the power is switched on or off is given and cannot be controlled and optimized to reduce losses.

A way to improve the efficiency of power inverters is to reduce the switching losses. One big advantage of resonant inverter topologies is that they make use of soft-switching techniques which allow to minimize switching losses. There are two different modes at which active switches as transistors are operated, depending on the device type.

Zero Voltage Switching (ZVS) technique means that the transistor is switching at the moment when the voltage is close to zero. This method eliminates turn-on losses caused by parasitic capacitance $C_{Gate\text{-}Source}$ and is often used for MOSFETs.

Zero Current Switch (ZCS) is the more preferred method for IGBT modules and even necessary when using fast thyristors (circuit commutation). This technique reduces turn-off losses as the current does not flow through the device before or at the moment of switching and the tail current – typical for bipolar devices – is eliminated. Benefits of soft switching techniques are not only the loss reduction and highly efficient energy conversion, but also the limitation of electro-magnetic interference (EMI) (less di/dt and dv/dt is generated in the switching process).

Circuit Topologies for Resonant Inverters

Figure 2 depicts a quite popular topology: the voltage source inverter (VSI) in the ZVS mode using a medium frequency (10 – 25 kHz) IGBT switch. The LCL resonant tank allows to easily adapt to variable loads without the need for a transformer. R1

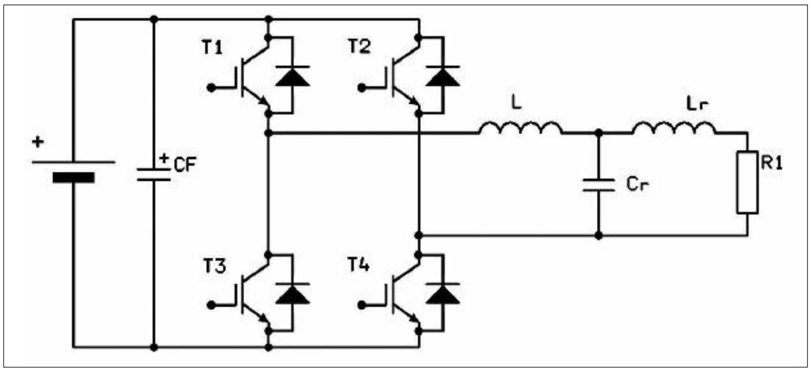


Figure 2: **Voltage source inverter with inductive coupling (ZVS mode) and parallel resonant circuit**

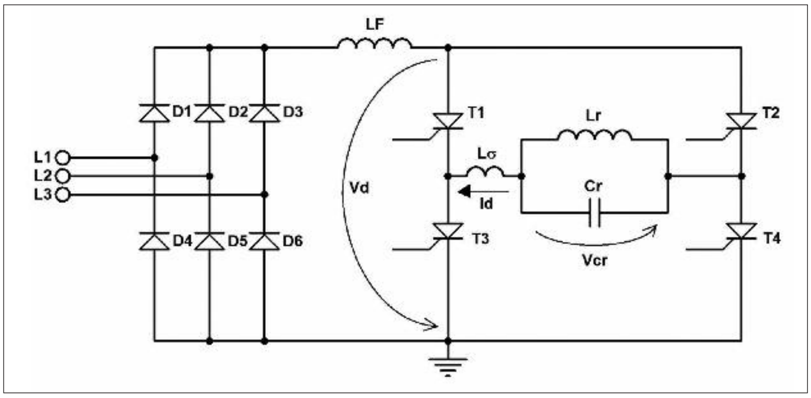


Figure 3: **Current source inverter (ZCS mode) and parallel resonant circuit**

represents the heated object. Typical applications applying such circuits are surface hardening, bending or welding. ABB offers a wide range of IGBT modules in different industrial standard housings and topologies for this application.

Induction melting systems in the 10 MW range traditionally and exclusively use current source inverters with fast switching thyristors in presspack housings. A frequently used circuit topology is shown in Figure 3, with a standard input 3-phase controlled (or uncontrolled) rectifier, a big serial inductance and an H-bridge in the inverter part. The LF choke is for current stabilization and filtering purposes. A control unit must enable a capacitive phase shift between the inverter output current I_d and the resonant load voltage V_{Cr} (basic operation condition necessary for the thyristor recover process).

Only the positive half-wave of the AC voltage is applied to the thyristors, after the minimal turn-off time has elapsed. L_r at the same time enables the commutation process of T_x. The inverter output current id has a rectangular shape changing its polarity by activating T1/T4 or T2/T3 (diagonally). The energy is thus periodically pumped into the parallel resonant circuit and the inverter output voltage V_{Cr} has a sine waveform at the resonance frequency and di/dt is limited by the parasitic inductance Lσ and by the voltage V_d. Higher output power converters need higher power thyristors or usually use several discrete thyristors connected in series.

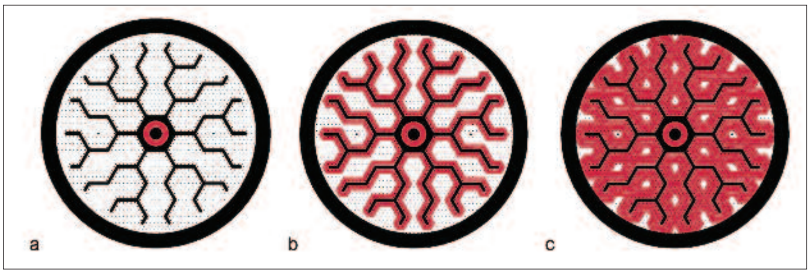
Device Features

ABB Semiconductors offers a wide range of fast thyristors with a total of 21 different types, optimized for different operation frequencies. The fast thyristor portfolio comprises standard fast thyristors (up to 1 kHz) and medium frequency thyristors (up to 10 kHz). Common to all fast thyristors are

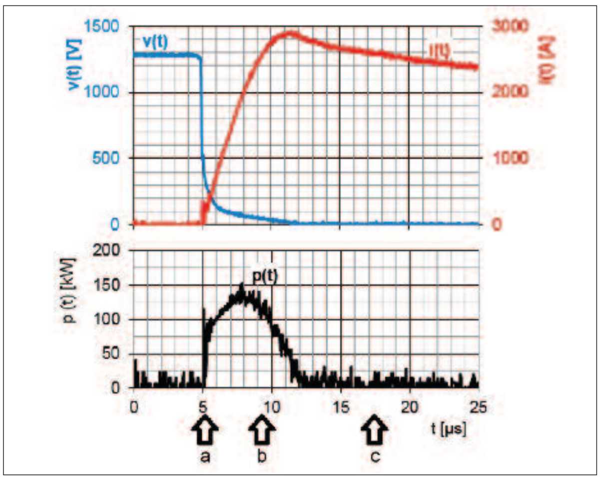
- amplifiying & distributed gate structure
- carrier lifetime control technology
- optimized carrier concentration profile for maximum current rating
- special cathode-gate design for faster on-state current spreading and effective operation in the specified frequency range.

All thyristors feature the alloyed technology where the Silicon wafer is directly alloyed to the molybdenum disc which renders the device more robust against surge and peak powers generated at occasional hard-switching conditions. Moreover, the alloyed molybdenum disc helps to stabilize the junction temperature and acts as an energy buffer.

The latest product is the 2 kV fast thyristor based on a 3-inch Silicon wafer. It is offered in two options: the 5STF 28H2060 and the 5STF 23H2040. The first one has an average on-state current I_{TAV} of 2.8 kA and a turn-off time t_q of 60 µs. The latter has an average I_{TAV} of 2.3 kA and a t_q of 40 µs. These thyristors feature a very efficient cathode area usage. Figure 4 shows how the current spreads in the cathode during turn-on. Thanks to the massively distributed gate structure over all the whole cathode area the turn-on losses are nearly eliminated. The central auxiliary thyristor serves as a gate signal for the distributed gate electrode of the main thyristor. The large cathode area around the distributed gate is immediately activated and switching losses are efficiently reduced.



ABOVE Figure 4: **On-state carrier spreading during thyristor switching**



RIGHT Figure 5: **Waveforms related to the three carrier spreading stages of Figure 4**

Figure 5 shows thw waveforms during thyristor turn-on (600 A/µs) and calculated power loss (arrows below relate to Figure 4), $T_j = T_{jmax}$.

Further design features implemented in these two new fast thyristors are

- minority carrier life-time reduction
- cathode shunt network to protect the thyristor against parasitic turn-on at high dv/dt
- concentration profile optimization to achieve low on-state losses.

Figure 6 shows thyristor turn-off and blocking voltage measurement curves at different turn-off times t_q. Parasitic turn-on occurs at turn-off times equal or below 21 µs, which is well below the specified value of 60 µs, thus demonstrating a good datasheet value margin. State-of-the-art fast thyristors feature an optimal balance between fast spreading of the carrier distribution over the whole cathode area at turn-on and a thyristor immunity against high dv/dt. In the event of an applied blocking voltage the remaining charge in the device as well as the additional capacitive current must be extracted by the shunt network and must not act as an internal or false gate signal. Such a current amplitude at high dv/dt can be as high as several tens of amperes. The high power resonant inverter is exactly the type of system where the inverter requirement naturally meets the fast thyristors' properties.

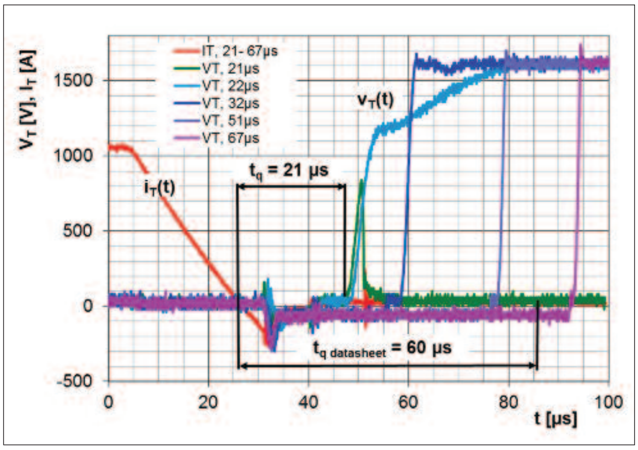


Figure 6: Turn-off and blocking voltage measurement curves at different turn-off times, 500 V/µs, $T_j = T_{jmax}$

Application Examples

It has been proven for years that the heavy metal industry relies on the reliability and performance of fast thyristors. And as in many other market segments also in the heavy metal industry there is a general trend towards increased power and power density, higher efficiency and productivity. Fast thyristors are one of the key enablers to follow these trends. The most powerful applications are melting and pouring in the heavy metal industry with furnace capacities of up to 50 tons and inverter powers of up to 50 MW.

Some applications in the medium power range are surface hardening or quenching for the production of cogwheels, arbors, valves, rails, etc. Further examples are preheating for material forming or before welding, induction welding, stress revealing after welding, steel tempering or annealing. Also induction bending (800 kW level) to shape big tubes for power plants or "I-shape" steal support forming are frequent applications.