Enhancing the efficiency of induction heating plants through Silicon Carbide MOSFETs

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Frequency converters are power electronic devices or systems that convert electric energy with given parameters (voltage, frequency, number of phases) into electric energy with different parameters. Such power conversions are for example required for induction heating. Therefore, this kind of power supply plays an important role in advanced thermoprocessing plants for both energy efficiency as well as overall costs.

Modern silicon carbide (SiC) semiconductor devices offer remarkable advantages over conventional silicon (Si) components, especially with regard to power losses, size and weight as well as reduction of heating of the semiconductors [1]. This comparative study investigates the differences between silicon IGBTs, silicon MOSFETs and silicon carbide MOSFETs in high-end frequency converters for induction heating applications.

FUNCTION OF THE FREQUENCY CONVERTER

In order to use the principle of induction heating, usually a high frequency current needs to flow in the induction coil. For its generation, a frequency converter is necessary that converts the line current with a frequency of 50 or 60 Hz into a current of a much higher frequency of several hundred hertz to several hundred kilohertz (**Fig. 1**). The output frequency is selected depending on the application such that the workpiece is heated efficiently and with an optimum temperature distribution. For example, high frequencies are used for hardening because only the surface of the part to be hardened needs to be heated to the austenitizing temperature.

Electric power is usually converted in two steps: First, the line current is rectified and then the resulting direct current is converted into alternating current of the desired frequency by an inverter. The main components of the rectifier are diodes or silicon controlled rectifiers. For inverters, the preferred choice are transistors because they are fully controllable, i.e. they can be both turned on and off. Of the various types of transistors available, IGBTs (insulated-gate bipolar transistors) and MOSFETs (metal oxide semiconductor field effect transistors) are the relevant options for this application. The latter ones are used predominantly to generate high frequencies of several hundred kilohertz. Compared to IGBTs, they turn on and off faster; on the other hand, the undesired voltage drop during the turned on state is higher.

SILICON CARBIDE TRANSISTORS IN POWER ELECTRONICS

A transistor is an electronic device for controlling the flow of electric current. Transistors, no matter whether IGBTs or

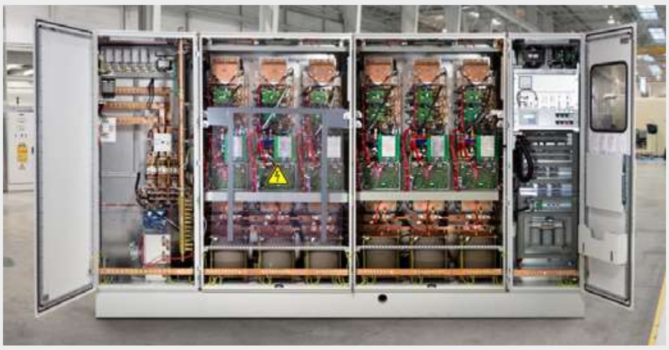

Fig. 1: Modern IGBT frequency converter in a modular design for induction heating applications (source: SMS Elotherm)

Fig. 2a: Silicon MOSFET, silicon carbide MOSFET identical

Fig. 2b: Silicon carbide MOSFET (source: Cree)

Fig. 2c: Silicon IGBT for frequencies up to 100 kHz (source: Infineon)

MOSFETs, are traditionally made of silicon (Si). Some years ago, silicon carbide (SiC) was introduced as a semiconductor material for power electronics. Since then, it has attracted much attention for the many benefits it provides. The technology for the production of SiC power semiconductors for industrial use has made great progress in the last years and will continue to evolve in the coming years, both technically and commercially. First, bipolar transistors and junction FETs made of silicon carbide were available commercially. Later, MOSFETs appeared on the market. While until recently only single MOSFET chips for small currents were available, manufacturers now offer power modules that can be used in a feasible manner in converters in the medium kilowatt range.

As a result, the advantages of the new technology are available to induction heating power supplies. Compared to silicon transistors, those of silicon carbide are superior in several respects. For one, SiC transistors produce less power loss. This applies to all sources of power loss occurring during the operation of transistors: in the on state (conduction losses), in the off state (blocking losses), during switching (switching losses) and for triggering the transistor (driving losses). Besides, the thermal conductivity of silicon carbide is greater than that of silicon by a factor of three, so that the created heat can be dissipated much more effectively.

Both properties together, the lower power loss and therefore higher energy efficiency as well as the reduced heating during operation, result in the same chip area being able to carry and switch more current. Hence, SiC components can be housed in smaller cases with lighter, thinner and cheaper heat sinks.

PROCEDURE OF THE INVESTIGATION

From the wide range of SMS Elotherm frequency converters, two models were selected to test the latest generation SiC MOSFETs from different manufacturers. The SiC MOSFETs (**Fig. 2a** and **Fig. 2b**) were compared experimentally with both Si MOSFETs (Fig. 2a) and Si IGBTs (**Fig. 2c**). The relevant criteria for the evaluation were the current and voltage waveforms during switching as well as the total power loss caused by the components when operating at different operating points and at different output frequencies. The comparison with Si MOSFETs was carried out in a high frequency (HF) converter for output frequencies above 100 kHz. The reference for the performance in the medium frequency (MF) converters for output frequencies up to 100 kHz are the Si IGBTs currently used there.

COMPARABILITY OF THE TRANSISTORS

In general, power semiconductors are defined by their blocking voltage and their maximum permissible continuous current. The following comparisons are thus based on transistors which are similar in these parameters and which are also contained in the same case respectively. It should be noted however, that with increasing frequencies the rated current (ampacity) of a transistor becomes less and less important as the operating limits of a semiconductor module are not only given by the current, but also by the maximum heat loss that can be dissipated.

The following comparison, based on information obtained from the data sheets of components, shows what this means for the current rating and heat dissipation of comparable transistors in the different technologies: when comparing components with similar current rating and the same package, it can be noted that a Si MOSFET can dissipate much more heat than a Si IGBT since the chip area of the MOSFET is larger by a factor of 2-3 [2]. A silicon carbide MOSFET is significantly smaller than a comparable silicon MOSFET so that it can dissipate fewer losses despite the better thermal conductivity. Its maximum allowable power dissipation is at the level of a Si IGBTs (**Fig. 3**).

COMPARISON WITH SILICON MOSFETS

For many years, SMS Elotherm has been using Si MOSFETs in HF converters ranging from 100 kHz to 600 kHz. In such a power unit, Si MOSFETs with a blocking voltage of 1,000 V are compared to 1,200 V SiC MOSFETs. A semiconductor manufacturer provided SiC MOSFET modules with the same case and a similar current rating as the Si MOSFETs. The SiC MOSFETs are far superior in terms of switching speed and on-state resistance ($R_{DS(on)}$). As mentioned previously, the required SiC chip is considerably smaller than its silicon equivalent. On the one hand, this makes SiC MOSFETs economically interesting already today because the price difference compared to conventional MOSFETs is low. On the other hand, fewer losses can be dissipated since the thermal resistance between junction and case is larger. For high-frequency induction heating converters, in which the losses are the limiting factor, this may appear to be a disadvantage at first. But what is the overall balance? The study seeks answers to questions about the differences in efficiency and power output per transistor. Finally, the new technology will be tested for its present operating limits.

The lower on-state resistance of the SiC MOSFET reduces the conduction losses compared to Si MOSFETs (**Fig. 4**). This becomes especially noticeable in resonant switching applications even at high switching frequencies because switching losses are minimized through zero voltage switching (ZVS) and zero current switching (ZCS) and therefore the conduction losses are the largest contributor. However, this alone is not enough to compensate for their higher junction-to-case thermal resistance. In order to achieve the power output of conventional Si MOSFETs in the application at hand, the switching speed had to be increased. In principle, this is easily possible with SiC MOSFETs. Due to the relatively low gate capacitance, very fast switching transients can be obtained even with low-power gate drivers. Yet it has been found that even the switching speed of conventional MOSFETs often cannot be fully utilized since this leads to massive problems. The fast switching favors unwanted coupling into the converter's system and measurement electronics. In addition, the influence of the parasitic commutation inductance, which can never entirely be avoided in the inverter design, increases. Rapidly switching off can create voltages spikes, and in conjunction with parasitic capacitances high-frequency oscillations can occur. A high switching speed thus poses increasing demands on the inverter design and the immunity of electronic components. With the increase in the switching speed and the solution of the associated electromagnetic interference issues, the losses could be reduced by one-third in this application.

When this is considered together with the fact that fewer losses are permitted, one concludes that the maxi-

Fig. 3: Comparison of the power loss that can be dissipated for transistors with equal current rating (normalized)

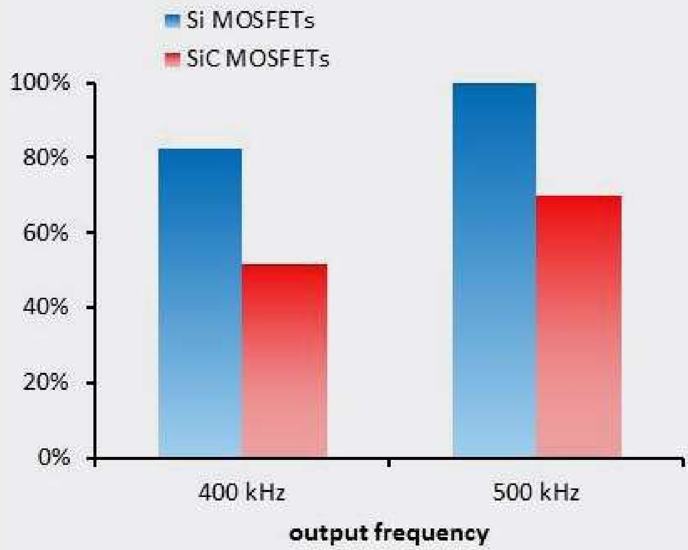

Fig. 4: Normalized power losses in Si and SiC MOSFETs at different output frequencies

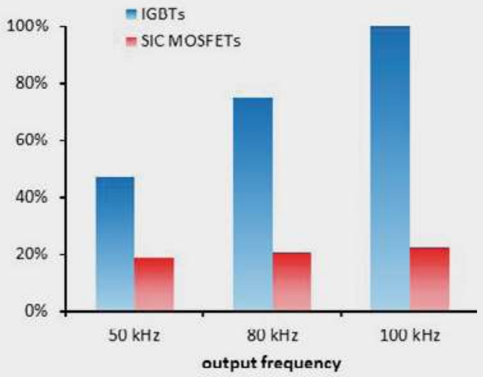

Fig. 5: Normalized power losses of IGBTs and SiC MOSFETs at different output frequencies

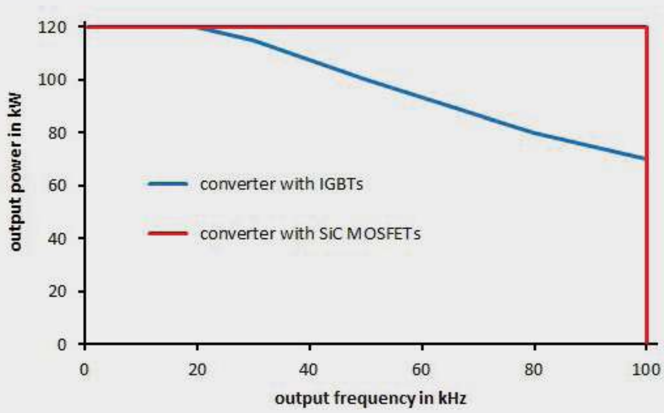

Fig. 6: Converter output power de-rating curve

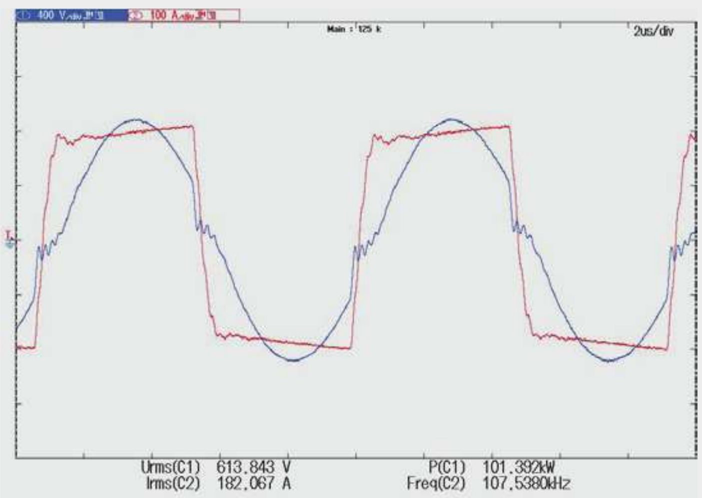

Fig. 7: Output voltage (blue) and current (red) waveforms

mum power output per transistor is similar. An inverter with a given power and frequency rating thus requires the same number of transistors made of either Si or SiC. For the improved efficiency of the silicon carbide inverter, currently about 1.5 times the cost of silicon version has to be expected.

It should be mentioned that, using silicon carbide, the same power rating can be attained at a higher efficiency with the same number of transistors in the same module, but with a smaller chip area. However, the commercially available SiC MOSFET chips are still in the same case today that also contains the much larger Si MOSFETs. In fact, the case could be fully used thermally by placing a larger area SiC MOSFET. Such a component would offer a higher current rating at a lower price than its silicon counterpart of the same size. Meanwhile, from a thermal point of view, both would be similar. In conjunction with the reduced losses, one can expect a considerably higher power output from a SiC MOSFET compared to a Si MOSFETs in the same module. Fewer transistors result in a more compact design, which leads to smaller parasitic inductances, and as a result permits a higher switching speed.

COMPARISON WITH SILICON IGBTS

SMS Elotherm MF converters for output frequencies of up to 100 kHz are equipped with IGBTs that allow very fast switching and have low switching losses [3]. Nevertheless, the converter output power at high frequencies (above 20 kHz) is limited by the power losses in the inverter IGBTs. These losses are mainly caused by the switching actions. For this reason, especially at high output frequencies, a considerable advantage is expected from employing silicon carbide MOSFETs.

At an output frequency of 100 kHz, the power loss in the inverter with SiC MOSFETs is barely 28 % compared to Si IGBTs. Even at lower frequencies, a significant advantage of the SiC-MOSFETs is observed, even though the difference to the Si IGBTs is smaller. **Fig. 5** shows the power losses in the inverter transistors at different output frequencies for both IGBTs and MOSFETs.

As can be seen, the power losses in the IGBTs strongly depend on the output frequency. Therefore, at high frequencies the output power must be reduced so as to not destroy the semiconductors due to overheating. With the SiC MOSFETs, however, the resulting power loss is on the one hand almost independent of the output frequency and, secondly, substantially lower than that caused by the IGBTs. Thus, a high efficiency can be achieved at all output frequencies. It not necessary to reduce (derate) the converter output power at high frequencies (**Fig. 6**).

If, for example, an output power of 120 kW at frequencies above 20 kHz is required, a larger converter would need to be selected. In these cases, the silicon carbide

MOSFETs offer the distinct advantage that the inverter is able to provide the full output power even at high output frequencies and the additional expenses for a higher power converter do not arise.

But not only at the time of purchase, but also during operation, silicon carbide MOSFETs offer economic benefits: because of the much lower losses in the inverter, a converter efficiency of up to 99 % is possible. This leads to a reduced energy consumption of the overall system. In addition, the lower cooling requirements save space and costs. Utilizing silicon carbide MOSFETs in place of IGBTs is an innovation that clearly pays off both technically and financially.

Another advantage of the SiC MOSFETs compared to IGBTs is their faster switching behavior, in particular when switching off. As a result, the output current and voltage waveforms of the inverter are nearly ideal (**Fig. 7**). This indicates that the power semiconductors in the inverter are operated with optimal performance and no adverse effects occur which could, for example, lead to excessive electromagnetic disturbance or reduce the reliability under certain circumstances.

To conclude, the results clearly prove that MOSFETs made of silicon carbide are far superior to silicon IGBTs, which are until now the usual choice, in inverters in the mid-kHz range.

CONCLUSION

Modern power conversion systems are necessary to meet the increasingly stringent energy efficiency standards and to reduce the overall system cost for the user. These goals, together with an increase in performance and output power, are difficult to achieve with conventional semiconductor materials, so the introduction of new components made of silicon carbide offers many unprecedented possibilities.

Silicon carbide MOSFETs unite the advantages of low forward voltage and fast switching in a single component. In contrast, when using semiconductors made of silicon, one has to opt for one feature by selecting IGBTs or MOSFETs as the type of transistor and suffer the poor performance of the other property.

The comparison with Si MOSFET at frequencies above 100 kHz indicates that the same power yield can be achieved with a reduced power dissipation and a much smaller chip area. A reduction in the size of the inverter, however, is only possible if the transistor module is thermally equally well used as with the Si technology. This means that the chip area of the SiC MOSFETs must be adjusted to the power that the module is able to dissipate. This is not necessarily guaranteed for SiC MOSFETs of equal current rating.

Overall, the ongoing progress in manufacturing technology will cause SiC transistors to more and more replace conventional Si components in high-frequency induction systems. The heating plants do not only become more energy efficient, but also cheaper and more compact.

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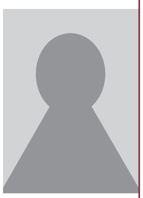

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