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Study of Power Loss Reduction in SEPR Converters for Induction Heating through Implementation of SiC Based Semiconductor Switches

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***Abstract* – This paper presents a power loss analysis for a Single Ended Parallel Resonance (SEPR) Converter used for induction heating. The analysis includes a comparison of the losses in the electronic switch when the circuit is realized using a conventional Silicon (Si) based IGBT or when using Silicon Carbide (SiC) based MOSFET. The analysis includes modelling and simulation as well as experimental verification through power loss and heat dissipation measurement. The presented results can be used as a base of comparison between the switches and can be a starting point for efficiency based design of those types of converters.**

***Keywords* – Induction Heating, SEPR converter, SiC MOSFET, Power Losses.**

1. Introduction

Induction heating is a modern and efficient technology for heat processing. It has a broad field of implementation that encompasses devices for both industrial and household applications. Its main principle of operation includes the generation of variable magnetic field that induces eddy currents in the load to be heated. The induced currents are then converted to heat due to the Joule effect. This leads to a very efficient heat transfer. [1]

The magnetic field required for the induction heating is produced by specially designed inductor (heating) coil. The current that powers this inductor is generated by a resonance power electronics converter. This makes the power electronics converter a key element for the efficiency of the induction heating process.

Various power electronics converter circuits can be used as power supply for the induction. The circuit topology is usually selected based on the required power and the specifics of the application. For powers up to 1500W where a flat inductor is used, the SEPR converter (Figure 1) is a suitable solution. [2],[3]

This converter issimple and efficient, low cost solution. When implemented it is usually powered by the standard single phase electric grid. The grid voltage is then rectified by a bridge rectifier – D1÷D4. The unfiltered rectified voltage is then fed to the converter through a small DC link capacitor – Cf. The converter is composed by: an electronic switch – S (in the case of figure 1 an IGBT); an antiparallel diode - D; and a resonant tank – Cr and Lr – where Lr is the induction heating coil.

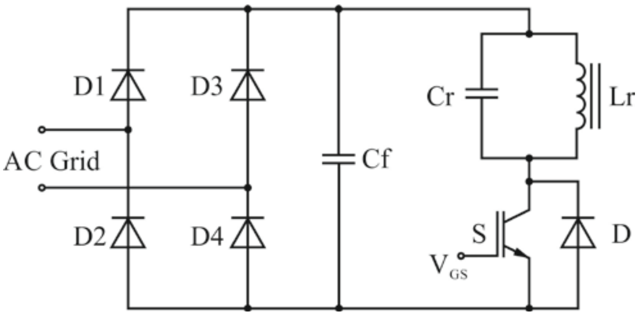

Figure 1. Basic topology of SEPR converter

The efficiency of this circuit will be determined by the lossesin: the rectifier the electronic switch and the antiparallel diode; the equivalent series resistance of the capacitors Cf and Cr; the specifics of the inductor and the load. A significant place of possible improvementon power losses and efficiency can be found with the design of the heating coil and the proper selection of the electronic switches – S and D.

The current paper aims at comparing and analyzing power losses within the semiconductor switches, where for the circuit the conventional Si based IGBTs are replaced with new SiC based MOSFETs. It is expected that through the introduction of SiC MOSFETs, the losses in the circuit can be improved compared to the conventional IGBTs.

The suggested analysis includes: modeling and simulations – presented in Section 2 of the paper; experimental verification through direct loss measurement and thermal analysis – presented in Section 3; and relative conclusions that can be drawn from the analysis presented respectfully in Section 4.

2. Modeling and simulation

For the initial loss analysis, a model of the circuit presented inFigure 1 was developed. The model parameters were derived from an existing industrial induction heating device. The parameters of the device set in the model are presentedinTable 1.

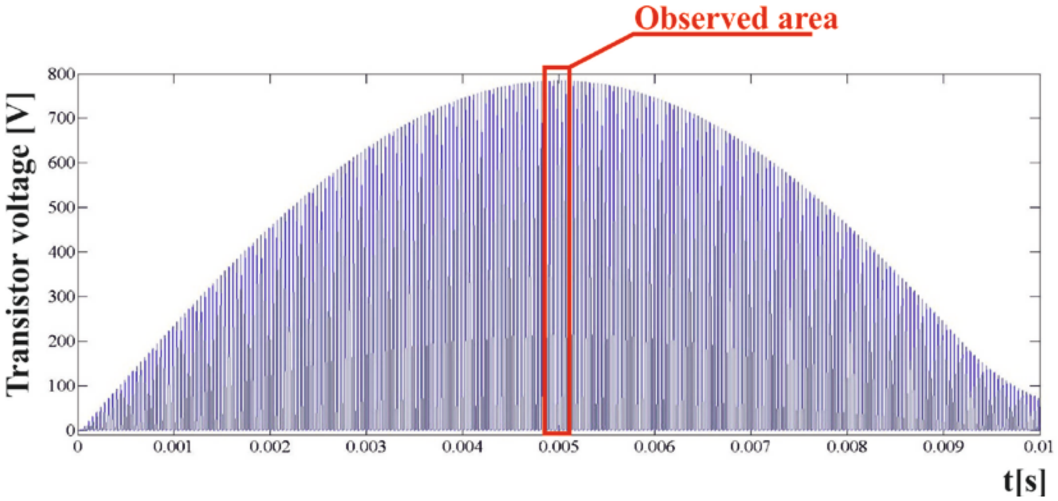

Figure 2. Observed area within a half period of the supply AC voltage

Table 1. Model parameters for the SEPR converter

Parameter	**Value**
Power	1800W
Input voltage	230V/50Hz
Operating frequency	25kHz
Component	**Value**
Filter capacitor Cf	330pF
Resonant capacitor Cr	8µF
Inductor type	Flat inductor

Table 2. Model parameters for the semiconductor switches

Transistors			
Component		**IGBT**	**MOSFET**
Power Ratings	Maximum voltage	1350V	1200V
	Average current	20A	24A
On-state parameters	resistance/ voltage drop	1.9V	0.08Ω
Switching parameters	Input capacitance	1500pF	1915pF
	Reverse transfer capacitance	45pF	13pF
Diodes			
Component		**For IGBT**	**For MOSFET**
On-state parameters	Forward voltage drop	1,8V	3,1V
Switching parameters	Peak reverse current	23A	20A
	Reverse recovery time	320ns	220ns
	Rate of change of current	-100A/µs	-100A/µs

The transistors that are compared are: IHW20N135 - a SI based IGBT specifically developed for inductive heating applications – the transistor includes an antiparallel diode; CMF20120D – a SiC based MOSFET with power ratings satisfying the circuit requirements. The parameters that are included in the model for both transistors and their antiparallel diodes (for the IGBT an integrated diode and for the MOSFET a parasitic body diode) are presented in Table 2.

The descried semiconductor switches are modeled using:

- For the MOSFET – Shichman and Hogedes equations for an insulated filed effect transistor [4], [5]. Relevant to the analysis the model includes both conduction and switching losses.
- For the IGBT a combined model of a MOSFET at the input and a BJT at the output is used. The MOSFET is modeled based on [4] and [5], while the BJT is modeled using [6] and [7]. Relevant to the analysis the model includes both conduction and switching losses.
- Antiparallel diodes for both transistors are modeled using [6] and [7]. The diodes models include both conduction and reverse recovery losses.

Circuit modeling is developed in specialized computation software – in the given case MATLAB.

The simulation is carried for one full period of the input grid voltage. Results are taken only for the peak voltage over a half period of the grid voltage – figure 2. For this area, due to the higher voltage and current,the power losses will be higherand thus a better distinction and comparison between the switches included in the circuit could be made.

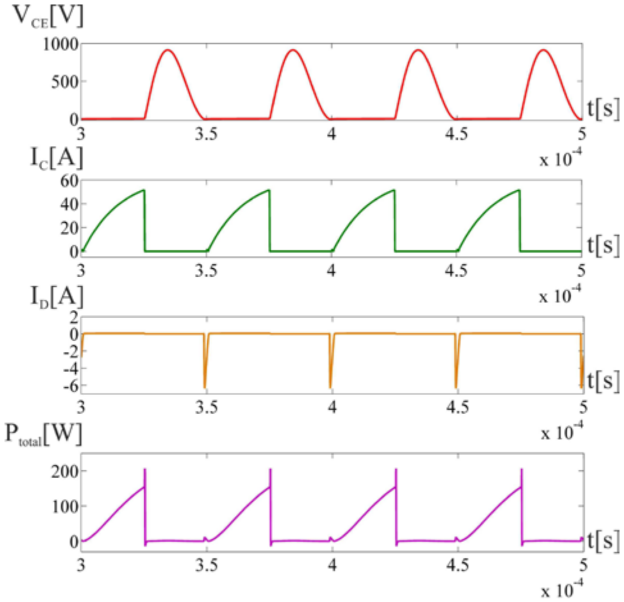

Figure 3. SiIGBT simulation waveforms

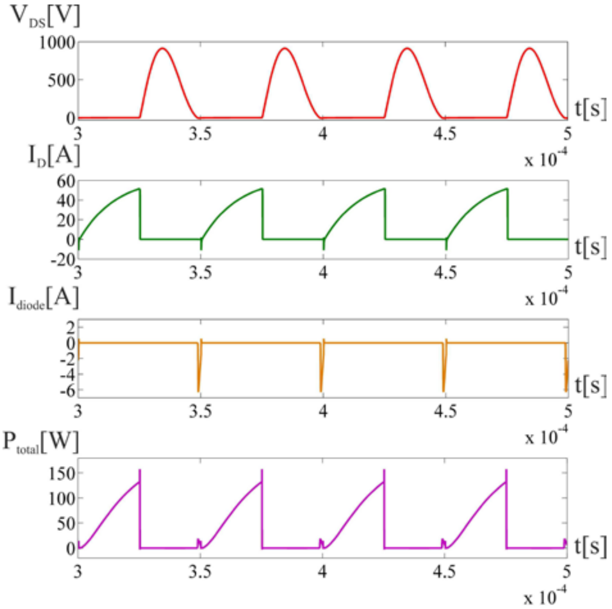

Figure 4. SiC MOSFET simulation waveforms

The simulation results from the implementation of the model are presented in figure 3 when a Si IGBT is used and in figure 4 when a SiC MOSFET is used. At the figures:

- For figure 3: V_{CE} is the voltage on the IGBT and its antiparallel diode; I_C is the current trough the IGBT; I_D is the current through the antiparallel diode; P_{total} is are total losses as sum of the losses through the both the IGBT and the diode;
- For figure 4: V_{DS} is the voltage on the MOSGET and its antiparallel diode; I_D is the current trough the MOSFET; I_D is the current through the antiparallel diode; P_{total} is are total losses as sum of the losses through the both the MOSFET and the diode;

The calculated average losses obtained through the use of the model and the simulation are presented in table 3.

Table 3. Average power losses summary –simulation values

IGBT	
Component	**Value**
IGBT turn on losses	0,0275W
IGBT conduction losses	25,5165W
IGBT turn off losses	26,9846W
Integrated diode losses	1,1972W
Total IGBT losses	53.7258W
MOSFET	
Component	**Value**
MOSFET turn on losses	1.4651W
MOSFET conduction losses	24.4503W
MOSFET turn off losses	18.3079W
Body diode losses	1.3593W
Total MOSFET losses	45.5823W

It can be seen from the simulation results that by replacing conventional IGBT with a SiC based MOSFET the converter can benefit from loss reduction and general efficiency improvement. The loss difference is generally concentrated in the turn-off losses, due to the slower turn-off of the IGBT and its tailing current. Turn-on losses, where for the circuit Zero voltage commutation is obtained, are negligible for both types of switches while conduction losses are close where the MOSFET benefits slightly from its lower resistance compared to the voltage drop of the IGBT.

Those effects are further studied in the following section where experimental verification is presented.

3. Experimental verification

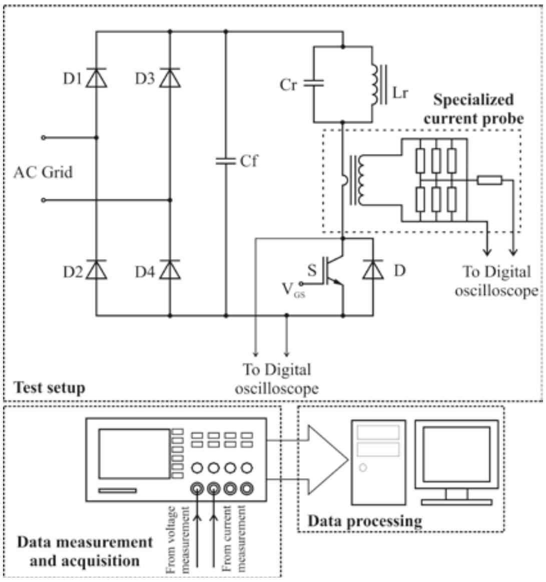

Figure 5. Experimental test setup

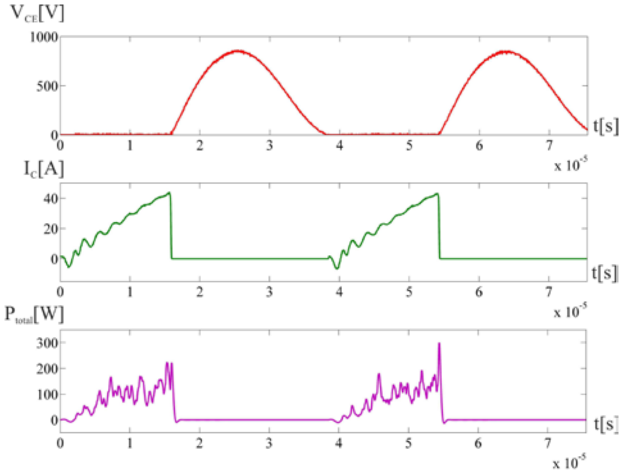

Figure 6. Si IGBT experimental waveforms

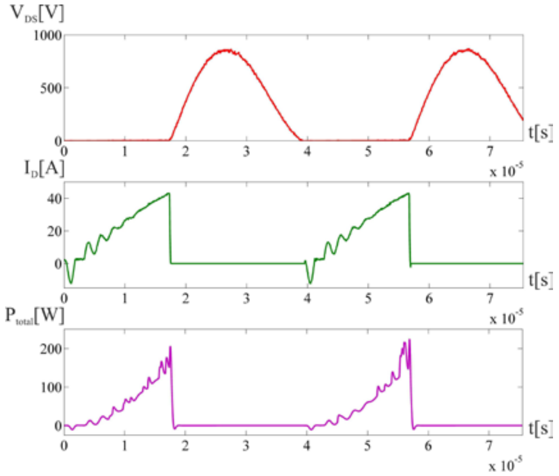

Figure 7. SiC MOSFET experimental waveforms

The circuit and the suggested comparison was further studied by two types of experiments.

Power loss measurement

The first experimental study includes measurement of the real losses.

Waveforms and data related to the losses, and presented further on, is measured and recorded using the experimental setup from figure 5. In this experimental setup an industrial induction heating device is used. Currents and voltages on the switches are measured, where the conventional IGBT used in the initial configuration of the device is directly replaced with a SiC based MOSFET. The current in the circuit is measured with a specialized current probe, designed specifically for power loss measurement [8]. The voltage is measured using conventional voltage probe. Data form the measurement is recorded using conventional digital oscilloscope. Afterwards the power losses are obtained by multiplying the measured current and voltage, switching and conduction losses are separated [9].

Table 4. Average power losses summary – experimental values

IGBT	
Component	**Value**
IGBT turn on losses	0.7755W
IGBT conduction losses	28.9676W
IGBT turn off losses	29.544W
Integrated diode losses	0.3635W
Total IGBT losses	59.65W
MOSFET	
Component	**Value**
MOSFET turn on losses	0,0118W
MOSFET conduction losses	23,0884W
MOSFET turn off losses	19,652W
Body diode losses	0,2032W
Total MOSFET losses	42,9554W

Results from the measurements are presented as waveforms in figures 6 and 7 – respectively for IGBT and MOSFET. Presented parameters for the waveforms use the same symbolic representation as those shown in figures 3 and 4. Additionally the average losses are presented in table 4.

It can be seen from the presented results that the experiment verifies the simulation. Obtained results show the possibility to reduce losses through the utilization of SiC based MOSFETs.

It has to be noted that for the experimental study the same driver was applied for both the MOSFET and the IGBT. Losses on the MOSFET can be even further improved if a specialized SiC MOSFET is used.

Thermal study

In addition to the power loss measurement a thermal study of the experimental setup was made. The thermal study includes a recording of the thermal field of the heatsink for the electronic switch for the time required for temperature stabilization – in the given case of the study 7 minutes. The same heatsink was used for both the IGBT and the MOSFET. The study is conducted using thermal imaging camera.

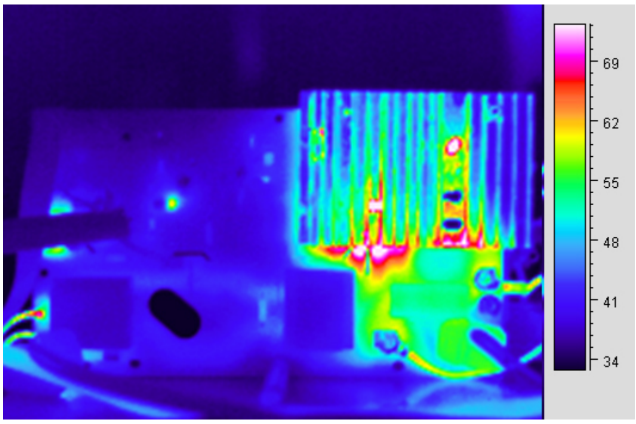

Figure 8. Thermal field with IGBT

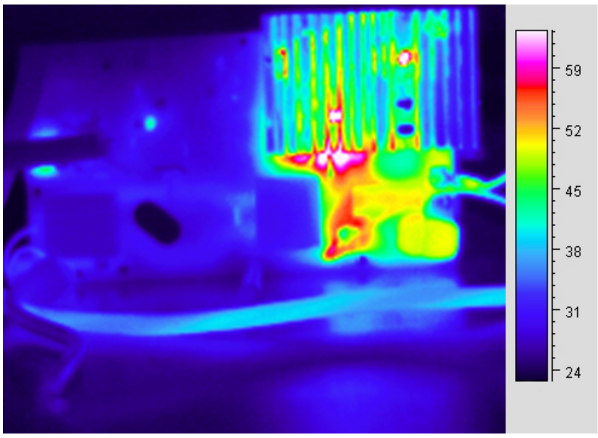

Figure 9. Thermal field with MOSFET

Results in figure 8, figure 9 and figure 10. Where: Figure 8 and figure 9 present distribution of the thermal field at the end of the study (7th minute), respectively for IGBT and MOSFET; and figure 10 presents the average temperature on both switches over the studied time.

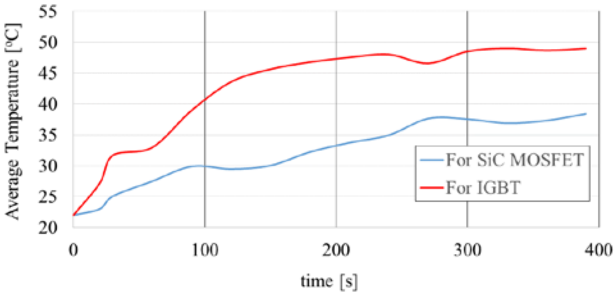

Figure 10. Average temperature on the heatsink

This study gives further verification for the power loss improvement of the topology when a SiC MOSFET is used instead of conventional Si IGBT. The thermal study also provides information on the thermal parameters for the given power. It is clear that the loss reduction can significantly affect the size of the heatsink for the SiC MOSFET, due to its lower temperature.

Conclusion

Based on the developed models, conducted simulations and experiments and on the obtained results, the following conclusions can be made:

- Presented simulation and experimental approaches provide relatively close data for the studied semiconductor switches. Those approaches can be used in further circuit design and switch selection.
- Both simulation and experimental results show the advantages of SiC based switches. SiC offers lower losses and thus better overall efficiency of the induction heating process. If price drop in SiC based switches continues they can be considered as a replacement for conventional IGBTs when building SEPR converters.
- The analysis shows that losses are concentrated in the turn of process of the device. Where the MOSFET switches are faster than the IGBT.
- Presented results are for the same driver for both IGBT and MOSFET, losses can be even further improved if a specialized SiC MOSFET driver is applied.

Acknowledgements

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