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Simulation Study of Silicon Carbide MOSFET based Inverter for Electric Vehicle Application using MATLAB

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Abstract: Silicon Carbide semiconductor has huge benefits over Silicon semiconductor and is best to apply for inverters in electric vehicle applications. The objective of this study is to develop the Silicon Carbide MOSFET-based inverter while analysing the comparison with the conventional Silicon MOSFET and calculate their loss calculation in the inverter. In this method, the simulation has been done through MATLAB software to construct the Silicon and Silicon Carbide MOSFET model including inverter design. Final outcome of the simulation gave similar results as the previous research. Accordingly, Silicon Carbide MOSFET-based inverter has a lower switching and conduction loss than the Silicon MOSFET-based inverter due to its low on-resistance. This study is best to improve by emphasizing other factors such as adjusting various temperatures to obtain a wider observation on the performance as well as operation of the inverter.

Keywords: Silicon Carbide, MOSFET, Electric Vehicle

1. Introduction

An increasing part of the market share is dominated by electrified vehicles (EVs). Electric vehicles while being driven with electric power emit zero emissions of carbon dioxide (CO_2) and air pollutants as it does not require any fuels such as petrol or diesel [1]. EVs require power electronic devices capable of efficient and effective operation at elevated temperatures to fulfil consumer standards of range, charge-time and effectiveness.

The inverter is essential to the performance of the vehicle as it distinguishes how the vehicle drives and the end user perceives the vehicle [2]. Inverters form critical parts as it is one of the key components in the electric vehicle system. Silicon Carbide semiconductor has gained wide interests and meets the demanding needs of automotive inverter drive applications. Their properties make it possible to build some powerful transistors and diodes that map well into the inverter design requirement. SiC materials have superior characteristics in comparison to Silicon materials such as wide bandgap energy that allows higher operating temperature, large thermal conductivity as well as high critical breakdown

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electric field [3]. The study aims to demonstrate the modelling and simulation of SiC MOSFET based inverters with reliability studies on the system to enhance the performance for EV application. Therefore, the system is examined and implemented using MATLAB software.

1.1 Analytical and experimental evaluation of SiC-inverter nonlinearities for traction drives used in electric vehicles

In the permanent magnet synchronous motor drive system with a SiC MOSFET based inverter, researchers propose to investigate the voltage and current distortions and compare them with the Si insulated-gate bipolar transistor based inverter using both modelling and experimentation aspects in MATLAB. A set of parameters of the switching devices determines a comprehensive modeling of the inverter distortion voltage. The voltage distortion of the inverter of SiC MOSFET is smaller compared with Si insulated-gate bipolar transistor based inverter resulting in higher switching speed, lower on-resistance and lower output capacitance [4].

1.2 Evaluation of potentials for Infineon SiC-MOSFETs in automotive inverter applications

In MATLAB, the implementation of the simulation model is carried out using analytical and map-based models for all electric drivetrain components such as inverter and electric machine. SiC MOSFET allows lightweight and devastatingly practical inverter systems for automotive applications. The desired SiC MOSFET chip area is significantly reduced compared to insulated-gate bipolar transistor-based inverters like the Hybrid-PACK Drive. By using SiC MOSFET, which can eventually optimize the vehicle cooling system, the needed cooling effort at the level of the inverter system can be reduced [5].

2. Materials and Methods

This section discusses the basic processes of project work including the chosen materials, software and methods used as well as covers the detailed explanation on simulation developed using MATLAB for the model development of SiC and Si MOSFET based inverter.

2.1 SiC and Si MOSFET

Table 1 shows electrical characteristics between both Silicon and Silicon Carbide MOSFET under a junction temperature at 25 $^\circ C$ and these parameters were taken from data sheets for Silicon [6] and Silicon Carbide [7].

Table 1: Parameter specification for SiC MOSFET and Si MOSFET

Parameter	SiC MOSFET	Si MOSFET
Static drain - source on - state resistance, $R_{DS(ON)}$	0.12 ohm	0.27 ohm
Drain current, I_{ON}	10.0 A	7.8 A
Turn - on switching loss, $E_{M(ON)}$	61 μJ	156 μJ
Turn - off switching loss, $E_{M(OFF)}$	41 μJ	156 μJ
Gate source voltage, V_{gs}	18.0 V	10.0 V
Input capacitance, C_{iss}	1200 pF	830 pF
Reverse transfer capacitance, C_{rss}	13 pF	68 pF
Output capacitance, C_{oss}	90 pF	170 pF

SiC MOSFET presents the potential for low switching losses and providing comparable conduction losses as well [8]. In addition, low on-state resistance and rapid switching speed capability of SiC active switches can further minimize power loss and thus increase power device performance.

2.2 Loss calculation

Losses in inverters for electric vehicle application is caused by conduction and switching phenomena which raise the operating temperature of the devices as well as affecting their characteristics [9]. Table 1 is used as a reference to calculate the losses in the inverter. Hence, most of the parameters used in SiC MOSFETs are significantly smaller than conventional Si MOSFETs [10]. Eq. 1, 2, 3 and 4 [11] shows the conduction and switching loss calculation for SiC and Si MOSFET based inverters as the following:

$$P_{TOTAL} = P_{SWITCHING} + P_{CONDUCTION} \qquad \textit{Eq. 1}$$

$$P_{TOTAL} = 6(P_{SWITCHING} + P_{CONDUCTION}) \qquad \textit{Eq. 2}$$

$$P_{CONDUCTION} = R_{DS(ON)} \times I^{2}{}_{ON} \qquad \textit{Eq. 3}$$

$$P_{SWITCHING} = fs\left(E_{M,ON} + E_{M,OFF}\right) \qquad \textit{Eq.4}$$

3. Results and Discussion

The results and discussion section presents the simulation results of materials selected for this project such as Si and SiC MOSFET. SiC and Si MOSFET are modelled using Simulink and the output as well as transfer characteristics are simulated by extracting the parameters from each datasheet for various voltages. The inverter circuit is set up in order to observe the switching pulse and output waveforms as well as validate the difference between them. Thus, loss calculations for switching and conduction are calculated using MATLAB code in order to measure the power dissipated in Si and SiC MOSFET based inverters by analysing the results [12].

3.1 Output and transfer characteristics of Si and SiC MOSFET

Output characteristics show the variation of the drain current with respect to the drain-source voltage with a junction temperature at 25 °C. Drain current, I_D vs drain-source voltage, V_{DS} measured at numerous gate voltages ranging from 6 Volts to 22 Volts in order to get the output characteristics of Si and SiC MOSFET. The output characteristic of Silicon curves (dashed lines) and Silicon Carbide curves (solid lines) shown in Figure 1 is compared at various voltages with variation of the Drain current I_D versus drain-source voltage V_{DS}.

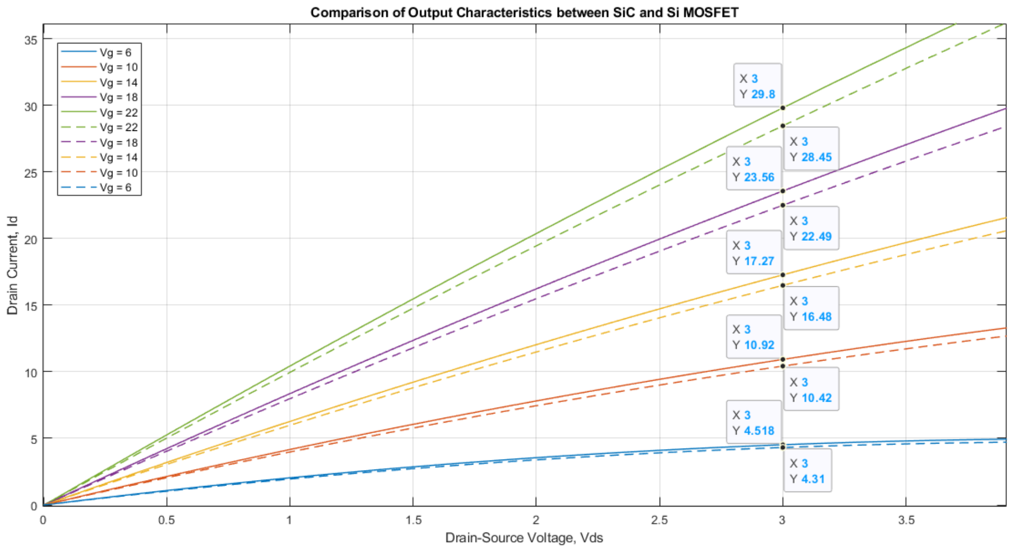

Figure 1: The comparison of output characteristics between SiC and Si MOSFET

The curves of the simulation models match the datasheet curves really well. Figure 2 shows a comparison of the datasheet-based transfer characteristic curve to the simulation curve of the presented Silicon and Silicon Carbide model at different voltages from 6 Volts to 22 Volts. From the observation based on the figure shown, for example, when voltage at 22 Volts, the difference between Si and SiC MOSFET at 3 Volts for drain current are 1.35 A while when voltage at 18 Volts, the difference between Si and SiC MOSFET at 3 Volts for drain current are 5.22 A.

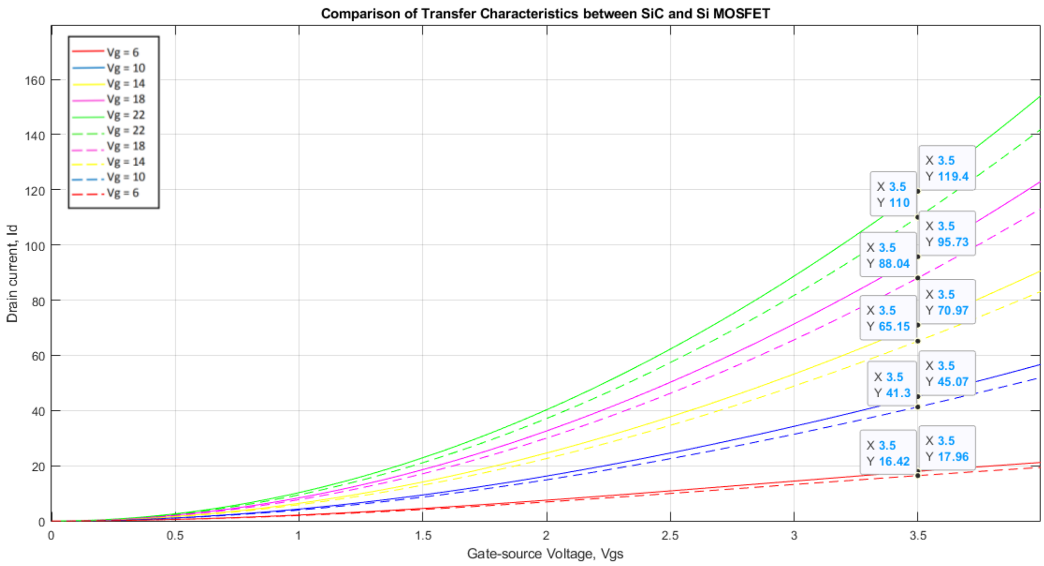

Figure 2: The comparison of transfer characteristics between SiC and Si MOSFET

The legend indicates two different line styles such as solid and dash line. The red line shows voltage at 6 Volts, blue line illustrates voltage at 10 Volts, yellow line indicates the voltage at 14 Volts, purple line demonstrates voltage at 18 Volts and the green line implies voltage at 22 Volts. From the observation based on the figure shown, for example, when the voltage at 22 Volts, the difference between Si and SiC MOSFET at 3.5 Volts for drain current are 9.4 A while when the voltage at 18 Volts, the difference between Si and SiC MOSFET at 3.5 Volts for drain current are 7.69 A. The model curves are in satisfactory correlation with the datasheet curves.

3.2 Gate pulse and output waveforms of Si and SiC MOSFET based Inverter

The Simulink model of 180-degree inverter with a DC voltage of 350 Volts as shown in Figure 3 was built along with the series of RLC loads [12].

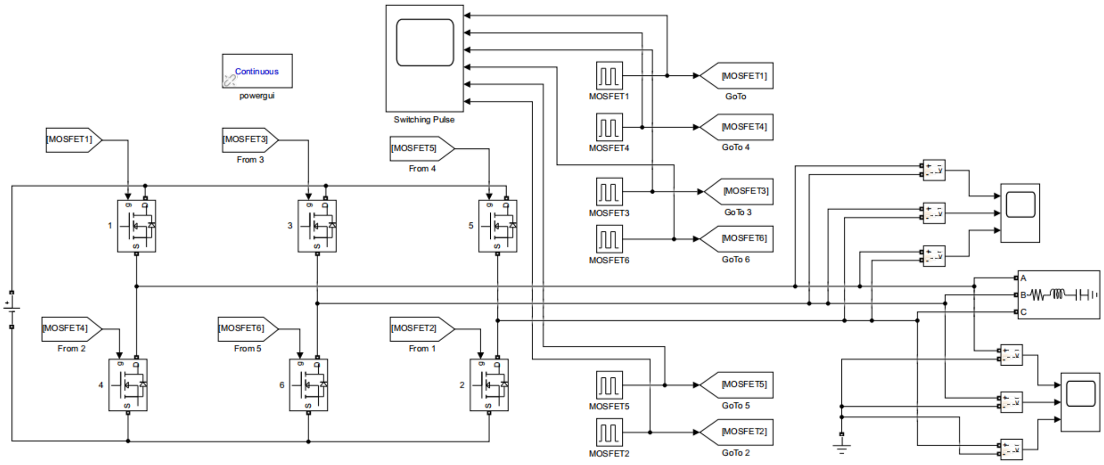

Figure 3: Simulink model of a full circuit inverter

Figure 4 shows the gate pulse of an inverter to indicate the amplitude at 5 Volt versus period at 20 milliseconds. Each pulse generator is connected to six MOSFET switches whose parameters are adjusted based on the type of material used whether the conventional Silicon or Silicon Carbide. Thus, pulse width is set at 50 percent of the period and switching frequency, f_s at 50 Hertz. The positive half cycle of any phase demonstrates in the output when the upper switch of that phase is in conduction mode (ON). Then, the negative half cycle of any phase demonstrates in the output when the lower switch of that phase is in conduction mode (ON). Two switches are available in one arm which will never be activated at the same time.

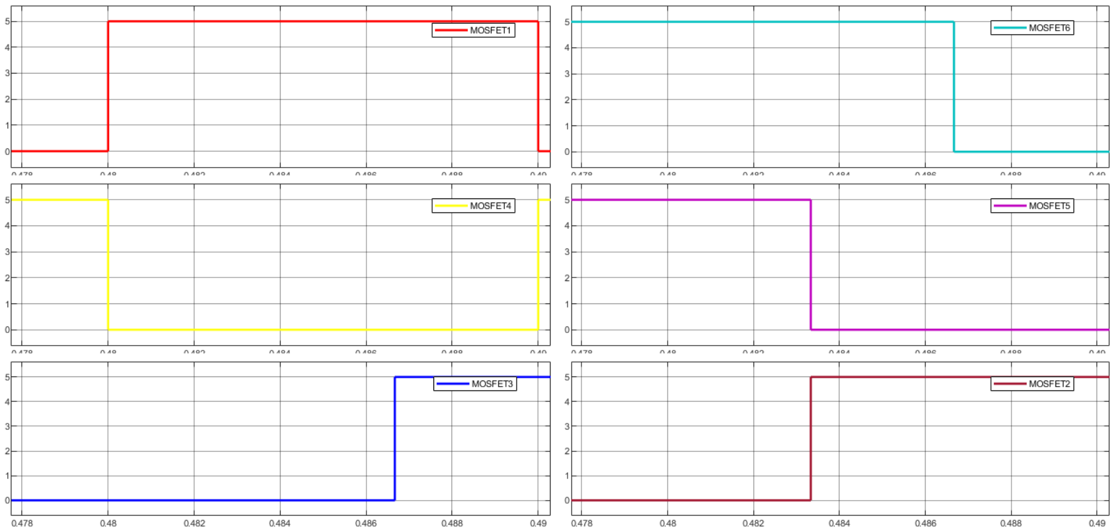

Figure 4: The gate pulse of a full circuit inverter for Si and SiC MOSFET

In this mode of operation, the switching pulses of 1 and 4, 3 and 6, and 5 and 2 are designed completely opposite to each other [12]. For example, when MOSFET-1 is turned on, MOSFET-4 would be turned off. Figure 5 shows the phase-to-phase voltage of SiC and Si MOSFET based inverter with variation of the line voltage, V versus time, s which proved that the peak line voltage is approximately 350 Volts.

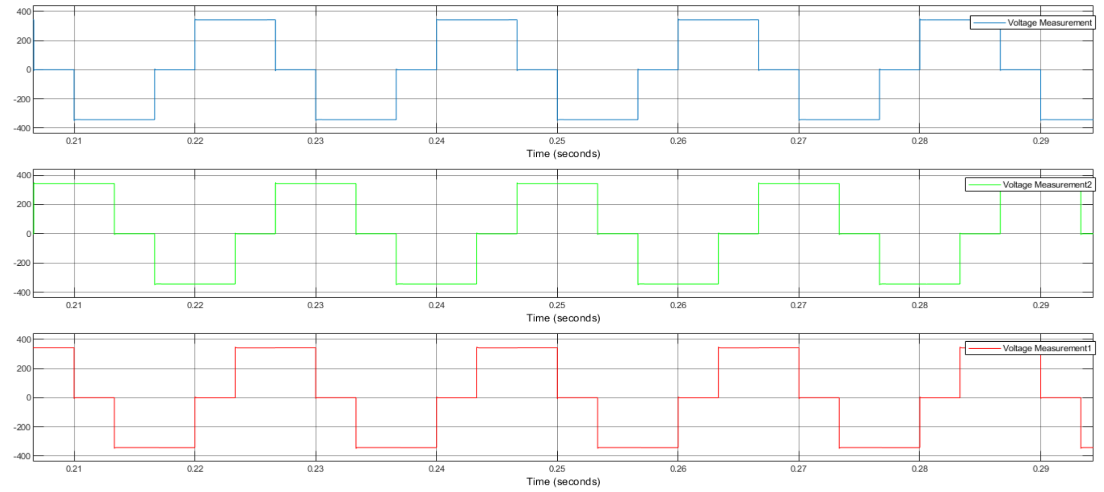

Figure 5: Line voltage of an inverter

Figure 6 shows the phase-to-ground voltage of SiC and Si MOSFET based inverter with variation of the phase voltage, V versus time, s which proved that the peak phase voltage is approximately 230 Volts.

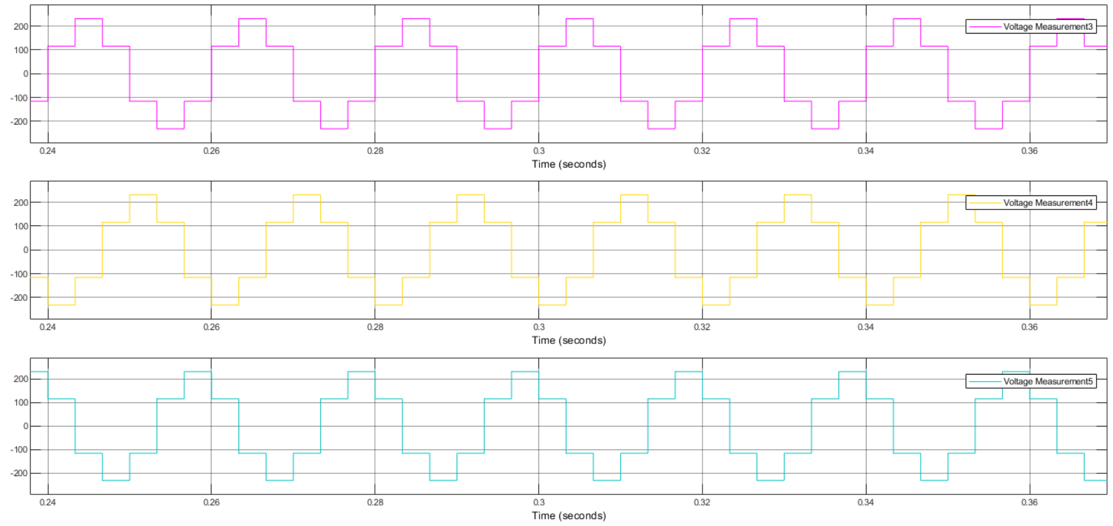

Figure 6: Phase voltage of an inverter

3.3 Loss calculation of switching and conduction for SiC and Si MOSFET based Inverter

The comparison between Si and SiC MOSFET based inverter for loss calculation in Table 2 has proved that the use of Silicon Carbide can reduce more losses in the operation of an inverter compared to Silicon [11].

Table 2: Comparison of loss calculation between Si and SiC MOSFET based inverter

Parameter	SiC MOSFET (W)	Si MOSFET (W)	Loss reduce (%)
Conduction loss	1.2000	1.6427	26.95
Switching loss	5100 μ	15599 μ	67.31
Total loss inverter	7.2031	9.8654	26.99

The total loss in SiC MOSFET inverters may be influenced by a smaller value in parameters used in SiC MOSFETs than in conventional Si MOSFETs. Figure 7 demonstrates the comparison of SiC and Si MOSFET based inverters with variation of the switching frequencies in Hertz versus inverter loss in Watt. As a result, it was observed that using SiC MOSFET for inverters can minimize losses as compared using the conventional Si MOSFET. The higher the switching frequency, the higher the losses produced by Si MOSFET compared to SiC MOSFET inverters [13].

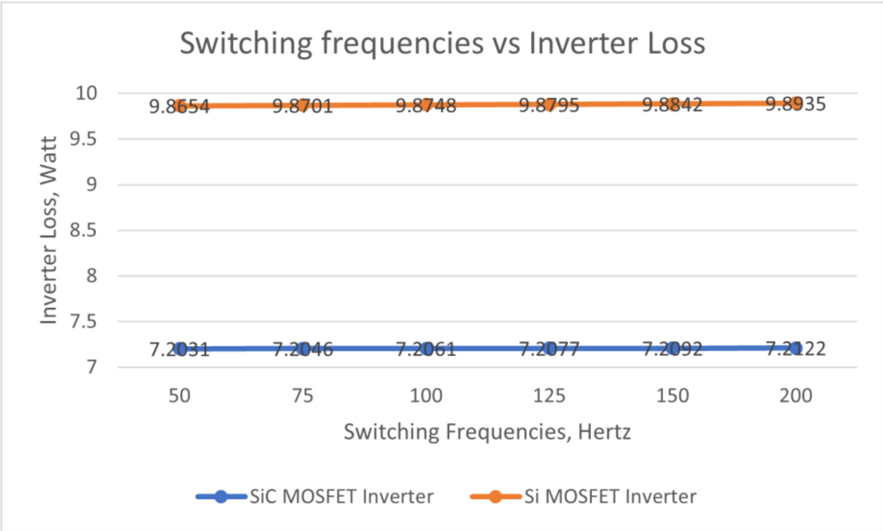

Figure 7: Switching frequency versus inverter loss in Si and SiC MOSFET based inverter

In comparison to Si MOSFET-based inverters, SiC MOSFET-based inverters clearly exhibit lower power loss at 350 DC Volts. In EV applications, the implementation of SiC MOSFET devices will help to lessen power loss and boost inverter efficiency. This can lead to better inverter design optimization while making it possible for both high operating frequency and high voltage rating [10]. The EV application is the best example of implementing silicon carbide over silicon. While driving an electric vehicle, the hardware system is built to accommodate the full power capability of the vehicle as it is necessary in both silicon and silicon carbide-based designs. Silicon carbide becomes far more efficient in terms of its way of handling the same load design specifications in a much smaller size than Silicon. Hence, the overall inverter system's performance can be achieved by nearly 80 percent [8].

4. Conclusion

SiC MOSFET based inverter for electric vehicle application has been evaluated experimentally by simulating and realizing the model using MATLAB. The simulation results indicate that MATLAB outperforms other simulation platforms when it comes to design models as well as calculating switching losses in semiconductor devices. The result indicated that the SiC MOSFET-based inverter has a lower switching and conduction loss than the Si MOSFET-based inverter due to its low on-resistance. According to both loss observations, the overall total loss of the SiC MOSFET-based inverter is significantly lower than the Si MOSFET-based inverter. The SiC device has demonstrated the expected performance which exhibits great potential to replace the conventional Si devices especially in the semiconductor fields and is very much in line with the current emerging technologies in electric car applications. Some recommendations that can be used to improve this project are Silicon Carbide can be substituted with other powerful semiconductor material such as Gallium Nitride for better comparison in many aspects and various temperatures can be applied to analyse and observe the different conditions that might happen based on the simulation and modelling results.

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