Field test of a silicon carbide metro propulsion system with reduced losses and acoustic noise

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Abstract
Results are reported from a successful field test with a silicon carbide (SiC) metal-oxide-semiconductor field-effect transistor (MOSFET) traction inverter. The train has been operated over a 3-month period in the Stockholm metro system. Increased traction inverter power density has been achieved, with volume and weight reductions of 51% and 25%, respectively. Lower power losses permit the use of car motion cooling. A sound pressure level reduction of 9 dB(A) was measured in the field with the higher inverter switching frequency permitted by using SiC. Complementing tests have been performed in the laboratory to compare thermal performance of silicon and SiC in the same power semiconductor housing. Propulsion system power losses are reduced by 19% with SiC. Acoustic noise reductions while increasing switching frequency are also reported.

1 | INTRODUCTION
Mankind has to face several great challenges regarding use of resources and climate change [1]. Contributing to both these challenges is the use of energy for transportation. Electric traction is superior when comparing to transportation based on internal combustion engines. The energy used to supply the electric train is, however, often generated using fossil fuels. For the whole railway system to achieve good energy efficiency it is, therefore, important that the efficiency of the drive system is very high [2,3]. Also, in the case where the electric energy is generated using renewable energy sources it makes sense to reduce the energy consumption, because this makes energy available for other uses and thus reduces the demand for energy generation using sources that emit carbon dioxide.

The introduction of silicon carbide (SiC) power devices is from this perspective very attractive. Recently, SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) have become available in ratings and housings suitable for electric traction [4]. The most obvious benefit of SiC MOSFETs compared to silicon (Si) insulated-gate bipolar transistors (IGBTs) is a significant reduction in power losses [5,6]. A reduction of 55% in switching losses is reported in [7] for a 3.3 kV module prepared for traction use. In [4,8] reductions in total power losses of 70%–80% have been reported. Another advantage when changing from Si IGBT to SiC MOSFET is that the conduction losses can be chosen through the choice of total chip area [9, 10]. One characteristic of the MOSFET is that it does not have the built-in potential (knee voltage) of the IGBT, which can be utilized to substantially reduce the conduction losses at low and moderate inverter output load [6,11]. This results in significant reductions in conduction losses if an investment is made to increase the total number of semiconductor chips.

Apart from the energy savings, several additional benefits can be obtained on the system level using SiC MOSFETs. The lower power losses lead to a lower performance requirement on the cooling system, which can then be designed with reduced volume, weight and cost [12,13]. The cooling principle can be changed from liquid to air cooled, or from air cooled to natural convection with the fans removed [11,12]. In a traction application, the motion of the air surrounding the vehicle can be utilized for cooling, as is the case in the here presented solution. This is called car motion cooling. The use of car motion cooling gives the benefits of higher reliability and lower...
maintenance costs due to fewer moving parts, and a reduced acoustic noise when the fan is removed.

The lower power losses when using SiC technology also opens the possibility to increase the inverter switching frequency. With an increased switching frequency, the harmonic losses in the motor may be reduced [14]. The reduction in harmonic motor losses is even greater than the reduction in inverter losses when the Si IGBT is replaced by SiC MOSFET. In addition, the higher possible switching frequency makes it possible to tune the system to avoid mechanical resonance frequencies of the motor. In this way, electromagnetically generated acoustic noise within the spectrum humans can hear is reduced. Furthermore, the harmonic pollution to the supply grid may be reduced, which in the railway supply system has the benefit of decreasing the requirement on power quality conditioners [15].

Despite these benefits, the SiC technology has still not reached widespread use. The main reason, besides the higher cost of an emerging technology [16], is the uncertainty of the reliability [17–21], mostly in terms of leakage currents [22,23] and short-circuit performance [5]. Furthermore, issues on the system level such as electromagnetic interference and voltage stress on the traction motor winding have been reported [24,25]. However, studies of the reliability on semiconductor module level have now started to bring more promising results [22, 23, 26], and it seems like the emerging SiC technology has matured sufficiently to be tested in real-world operation on a metro train.

Previous publications have investigated the capability of SiC-hybrid power semiconductors (Si IGBT and SiC Schottky diode) in railway field tests [27–29], and it has been reported that a traction inverter with full-SiC power semiconductors (SiC MOSFET and SiC Schottky diode) has been built [4,7]. However, a field test with results demonstrating the capability of a traction inverter equipped with full-SiC power semiconductors in a real-world environment is lacking. The hypothesis of the authors is that the full-SiC technology now has matured so that such a field test would be successful. Therefore, the present study is the first published field test, which investigates if full-SiC power semiconductors can be operated successfully on a real metro train with a propulsion system suitable for metro trains in the power range 50–250 kW per inverter.

Novel contributions are also reported regarding acoustic noise evaluated both in the laboratory and in the field, as well as energy efficiency improvements on the propulsion system level. Semiconductor performance in the traction inverter for varying switching frequencies is also evaluated, where state-of-the-art Si IGBT power modules are compared to SiC MOSFET power modules, both mounted in the same inverter and both in the new generation railway traction housing. A broad perspective of the benefits of SiC power semiconductor devices in the railway traction application is shown.

The study is structured as follows. In Section 2, the field test application and the SiC inverter demonstrator box is described. In Section 3, tests performed in the laboratory are reported. Results from the field test are presented in Section 4. Finally, the conclusions are drawn in Section 5.

2 | SiC TRACTION INVERTER DEMONSTRATOR

In the following study, the overwhelming possibilities offered by replacing a Si IGBT inverter with a SiC MOSFET inverter in a metro propulsion system have been evaluated. The SiC traction inverter was designed and tested in the field to demonstrate the customer values of full-SiC power semiconductors and to increase the confidence in the technology by proving a successful field demonstration (Figure 1).

A demonstrator railway traction inverter using full-SiC power semiconductor modules and car motion cooling was built to perform the evaluation [30]. The SiC traction inverter is a two-level voltage source inverter, using a full-SiC phase-leg power semiconductor module in the new generation housing next High Power Density Dual (nHPD2) [31,32] optimized for high switching speeds with low commutation inductance. The new generation housing is a 100 × 140 mm dual package developed for railway traction applications. nHPD2 is a brand name from Hitachi for this housing. Other suppliers use other names for traction housings with the same footprint and similar external interfaces.

The original Si IGBT inverter on the train was designed and delivered in the mid-1990s. It is rated for a nominal line voltage of 650 VDC and designed to feed two motors connected in parallel with a rated continuous phase current of 400 Arms. In railway traction applications, the tractive effort is highly dependent on slip [33]. If the motors instead would be fed individually, it would be possible to overcome slip problems. The induction motors could then also be designed with a lower rotor resistance and thus improve efficiency. The demonstrator box, therefore, contains two inverters which supply power to one motor each. The corresponding rated continuous phase current demanded in the application is, consequently, 200 Arms per inverter.

With the new SiC inverter demonstrator box, increased power density is achieved. The lengths of the inverters in the direction of the train are 2005 and 1150 mm for the original inverter box and the new inverter box, respectively. In total, a volume reduction of 51% is achieved. The main reason for the volume reduction is that the air-cooling fan can be removed due to the lower power losses. Instead, car motion cooling can be used. The weights of the original inverter and the new inverter are 315 and 236 kg, respectively. The weight reduction is therefore 25%. The reduction in weight is relatively smaller than the reduction in volume, as the car motion cooling requires a larger and heavier heat sink. The achieved volume reduction is visualized in Figure 2, where the SiC demonstrator box is compared to the replaced original Si IGBT inverter box.

All power devices in this study are rated 1.7 kV and use the same footprint. The Si IGBT semiconductor modules are of type Hitachi MBM1000FS17 G and the SiC MOSFET semiconductor modules are of type Hitachi MSM900FS17 A. The used gate drive voltage levels are +15 V and −10 V, which are the recommended driver voltage levels by the supplier. Two representative switching waveforms from the SiC module are shown in Figure 3.
3 | MEASUREMENTS IN THE LABORATORY

To complement the field test, additional investigations have been performed in the laboratory. This is done to perform tests under the controlled and repeatable conditions in the laboratory, and to be able to vary the switching frequency which is not possible in the field.

The SiC demonstrator box was set up to supply two 3-phase induction motors, the same type of motor which is used on the train. An overview circuit diagram of the test set-up is shown in Figure 4, where the motors are seen to be fed by one inverter each. The motor speed is determined by the load machine speed controller and the torque is determined by the inverter under test’s torque controller. Also shown in Figure 4 are the laboratory DC supply and the line filter consisting of a line inductor and two DC-link capacitors (of type metallized film).

3.1 | Semiconductor power losses

A comparison is made with Si and SiC power semiconductors in the same type of housing (nHPD ²). They are interchangeably mounted in the same inverter box. Two different types of heat sinks were used during these tests: a heat sink with heat pipes for the SiC case and a heat sink without heat pipes for the Si case. The cooling performances of the two heat sinks have been determined in a separate test, and the measured temperatures of the Si case reported here have been scaled to correspond to a heat sink with heat pipes to be able to compare the results.

The tests were set up under the following steady-state conditions:

- Carrier-based pulse width modulation (PWM)
- Train speed 45 km/h
- DC-link voltage 640 V
- Phase current 210 Arms
- Varying switching frequency in steps of 1 kHz
- Cooling air flow to simulate car motion cooling at the stated train speed

Measurements of the voltage and current harmonic spectrum for the SiC MOSFET case with 6 kHz switching frequency is shown in Figure 5.

Calculations of inverter power losses for the tested cases have been performed based on conduction losses as stated in the semiconductor datasheets and measured switching losses from the commonly used double-pulse test method described in [34]. Temperature dependence of the losses has been taken into account.

In general, for inverters realized with either MOSFETs or IGBTs, the total power losses $P_{\text{tot}}$ are modelled as described by:

$$P_{\text{tot}} = P_{\text{t,cond}} + P_{\text{d,tot}}$$  \hspace{0.5cm} (1)

where, $P_{\text{t,cond}}$ and $P_{\text{d,tot}}$ are the power loss contributions from the transistor and the diode, respectively. The transistor and diode losses in turn consist of conduction losses and switching losses given by:

$$P_{\text{cond}} = \frac{1}{T} \int_0^T v(t) \times i(t) \, dt$$  \hspace{0.5cm} (3)

$$E_{\text{on,off},rr} = \int_0^{T_{\text{sw}}} v(t) \times i(t) \, dt$$  \hspace{0.5cm} (4)

with the switching event time $T_{\text{sw}}$. The switching events correspond to turn-on and turn-off for the transistor, and reverse recovery for the diode. In both Equations (3) and (4), the voltage across the device is $v(t)$ and the current through it is $i(t)$.

As modelled by the above expressions, conduction losses are assumed to be independent of switching frequency and the total switching losses are assumed to depend proportionally on switching frequency. The results of the calculations are shown in Table 1 and Table 2. To exemplify, the switching losses for the 6 kHz case in Table 1 is calculated as follows: With average on, off and reverse recovery switching energy losses of $E_{\text{on}} = 22 \text{ mJ}$, $E_{\text{off}} = 7 \text{ mJ}$ and $E_{\text{rr}} = 3 \text{ mJ}$, respectively, the total switching losses are calculated as $P_{\text{sw}} = f_{\text{sw}} (E_{\text{on}} + E_{\text{off}} + E_{\text{rr}}) = 189 \text{ W}$.

Measured temperatures are shown in Figure 6 for Si and SiC power semiconductors with varying switching frequencies. The reported values are for steady-state operation taken when thermal equilibrium has been reached for each operation point. The reported case temperatures have been measured under the
dies of the semiconductors in the power modules. Based on the measured case temperatures and the power losses, the junction temperatures have been calculated.

The large reduction of power losses when changing from Si IGBT to SiC MOSFET can be seen in the results presented in Figure 6. As an example, the transistor junction temperature

| Switching frequency (kHz) | Conduction losses (W) | Switching losses (W) | Total losses (W) |
|---------------------------|------------------------|----------------------|------------------|
| 1                         | 39                     | 31                   | 70               |
| 2                         | 39                     | 63                   | 102              |
| 3                         | 39                     | 94                   | 133              |
| 4                         | 39                     | 126                  | 165              |
| 5                         | 39                     | 157                  | 196              |
| 6                         | 39                     | 189                  | 228              |
In the laboratory test, the switching frequency is varied to investigate the energy losses on the propulsion system level. Figure 7 shows the measured total average power losses on the propulsion system level for Si and SiC, as well as the calculated average motor losses. For the Si case, six-step modulation has been used for high train speeds, while carrier-based PWM has been used for all train speeds for the SiC case. The resulting voltage is sufficient for carrier-based PWM, but not for the Si case, where higher switching losses would have been generated. Six-step modulation has been used for the Si case instead.

The minimum of the total average propulsion system losses is 4.8 kW for Si and 3.9 kW for SiC. This corresponds to an improvement from 87.0% to 88.7%. As the switching frequency increases from around 2 kHz to 3–6 kHz, the total power losses also increase. However, if constraints regarding steep voltage slopes can be relaxed, the switching frequency for minimized propulsion system losses is probably increased significantly. The voltage experienced by the motor insulation is dependent on the specific system design, and varies with cable length and motor impedance. This is a topic of ongoing research.

In Figure 7, it can be seen that the switching frequency which minimizes the total power losses is increasing from around 2 kHz for Si to the range 3–6 kHz for SiC.
Motor acoustic noise

The dominating noise source of a train at low speeds, for example, in the proximity of passenger platforms, is generated by electromagnetic vibrations of the traction motor frame stemming from the switching of the inverter. The topic has been studied in, for example, [38–40]. If the switching frequency of the inverter is increased so that the main voltage harmonics are shifted above the resonance frequency peaks of the motor frame, then the resulting acoustic noise generated by the motor is reduced. At these higher switching frequencies, typical mechanical resonance frequencies of the traction motor may be avoided.

The lower switching losses of the SiC inverter discussed above can again be utilized to generate benefits. To demonstrate the benefits of the reduced acoustic noise, a test was set-up in the laboratory with the same type of motor as was used on the train. The switching frequency of the SiC inverter was gradually increased at no-load conditions and maximum flux with a motor speed corresponding to 10 km/h. The set-up of the motor and the microphones used to measure the sound pressure level can be seen in Figure 9. The measured sound pressure level is shown in Figure 10, and it can be seen that the sound pressure level is reduced by approximately 20 dB(A) while the switching frequency increases. Although acoustic noise still is generated for frequencies in the human audible range, the amplitudes are very low leading to the low sound pressure level.

Overall results for varying switching frequency

To summarize the results presented in the previous sections and to make the message very clear, the main results of the laboratory tests have been compiled in Figure 11. It is visualized in the figure that for a typical car motion cooling system for a railway traction application, a Si inverter is unable to operate at switching frequencies which give large system benefits from both energy loss perspective on a propulsion system level and from acoustic noise perspective. With SiC, the beneficial frequency range of 3–6 kHz is feasible.

RESULTS FROM THE FIELD TEST

The field test was performed during a 3-month period from 4 December 2017 until 9 March 2018. The duration of the test had been decided before the test started. One original Si IGBT inverter on the train was replaced with the SiC MOSFET inverter demonstrator. The train was then used in normal passenger service (revenue service) on the Green Line in the Stockholm metro system. Blinding was used in the sense that the train drivers were not informed that their vehicle was part of a test, so it can be assumed that the driving pattern is as usual. It was decided to keep the original switching frequency for the carrier-based PWM of 1 kHz to avoid time-consuming homologation of line interference requirements. The test was led by Bombardier Transportation.

During commissioning, measurements of the sound pressure level generated by the passing train were performed in the depot area with the results shown in Figure 12. The train was started from standstill with constant acceleration of approximately 0.15 m/s². The microphone was located 5 m from the track. Only the two SiC inverters were activated during the test, and the two active motors passed the microphone at approximately 6 s in the figure. The accelerating train was then approximately at speed 10 km/h. The test was repeated for different switching frequencies. It can be read from Figure 12 that the sound pressure level was reduced by approximately 9 dB(A) when the switching frequency was increased from 1 to 6 kHz.

After successful commissioning, the train was used in normal passenger service. The train covered approximately 30,000 km during the test period. In Figure 13, data collected during a typical day (specifically 7 March 2018) is presented. It can be seen that the train was operated in speeds between 0 and 70 km/h, produced by phase currents varying from 0 to 300Arms with a 10 min RMS value of approximately 100Arms. The initial temperature in the morning is approximately 20°C since the train was parked in a depot overnight.
On this day, the outdoor temperature was approximately −1°C and the highest measured heat sink temperature during the day was 16°C.

4.1 Discussion on results from the field test

The field test was completed successfully with the full-SiC inverter working flawlessly during the test. The train could successfully be operated following the planned schedule, in accordance with the hypothesis of sufficient reliability of the full-SiC power modules.

The large achieved reduction of 9 dB(A) in sound pressure level as measured on the train is demonstrating the value of introducing full-SiC in railway traction. Even if the reduction measured in the field is not as large as the reduction measured in the laboratory, it is still substantial. Reasons for the difference in measured sound pressure level in the laboratory and in the field may be that on the train other noise sources are also present, such as, for example, the gearbox and wheel-rail interaction, and that two motors were active in the field compared to one in the laboratory.

The test was performed in a season of the year and in a geographic area with low ambient temperature. For environments with higher ambient temperatures, care must be taken to design the inverter for the temperature dependence of the SiC MOSFET power losses, which is stronger compared to the Si IGBT. Future work will need to address the long-term reliability questions.

The main result of the field test is that the full-SiC MOSFET power modules successfully could be operated under real-world environmental conditions in a metro traction application. This result increases the confidence in the SiC technology and brings the technology one step closer to widespread use.

5 | CONCLUSION

Results have been reported from a 3-month field test using a full-SiC traction inverter operated in passenger service on the Green Line in the Stockholm metro system. To the authors’ best knowledge, this is the first time successful results with full-SiC on a real metro train are reported in literature. Power density improvements can be reported with volume and weight reductions of 51% and 25%, respectively, when comparing the replaced original Si IGBT inverter on the train with the SiC MOSFET inverter demonstrator. The lower power losses permit the use of car motion cooling compared with forced air-cooling for the original inverter.

The lower switching losses of the SiC MOSFET inverter permits operation at a higher switching frequency compared to the original Si IGBT inverter. On the propulsion system level, the higher switching frequency could be utilized to lower the
system energy losses and to reduce the acoustic noise from the motors.

On a day with the SiC demonstrator operated in normal passenger service, with a switching frequency of 1 kHz and an outdoor temperature of approximately \(-1^\circ\text{C}\) during the day, a heat sink temperature of maximum 16\(^\circ\text{C}\) was measured. To complement the field test, the Si IGBT and SiC MOSFET power semiconductors in the same nHPD\(^2\) housing were compared in the laboratory. A reduction of 63\% in transistor junction temperature increase over ambient was achieved for the test case with 2 kHz carrier-based PWM.

The reduction by 9 dB(A) in sound pressure level when measured outside of the running train in the field with the SiC inverter operated at 6 kHz switching frequency is an interesting novel result. When measured in the laboratory the sound pressure level was reduced by 20 dB(A). During the frequency sweep in the laboratory depicted in Figure 10 an observer experiences the noise emitted from the motor as developing from quite high noise, at times even irritating at mechanical resonances during the sweep, to gradually becoming virtually silent. This is a remarkable benefit made possible by the introduction of SiC. In general, increased switching frequency creates potential for reducing sound pressure level for traction motors during acceleration. The achievement in any particular case depends on the exact mechanical solution. However, we believe that most induction motors designed for traction follow similar principles with regards to mechanical design in this respect, and therefore that this conclusion holds in general. If a certain resonance frequency is hit, small adjustments of the switching frequency can solve the problem.

The main results of the laboratory tests were summarized in Figure 11 with sound pressure level, total propulsion system power losses, and semiconductor losses shown as a function of switching frequency. An interpretation of the figure is that large system benefits can be achieved in the switching frequency range of 3–6 kHz in terms of energy efficiency and acoustic noise. It is also visualized in the figure that such high switching frequencies are hard to realize with Si IGBT power semiconductors when a typical car motion cooling system for railway traction is used. With the SiC MOSFET power semiconductors used in an housing with the same footprint, the switching frequencies beneficial from the system perspective are feasible. The losses from the inverter and motor were reduced by 19\% in the laboratory.

All of this sounds very promising for the emerging SiC technology. One may ask what is hindering wide adoption at a faster pace? When comparing the prices of Si and SiC power semiconductors with similar rating, it becomes clear that SiC still is a lot more expensive, although the price difference is decreasing. This may today be the main reason for the slow adoption: the cost of the power converter itself increases when using SiC instead of Si. However, semiconductor manufacturers are now communicating very large ramp ups in SiC production capacity, for example at the industrial forum of the conference EPE 2019 (European Conference on Power Electronics and Applications). The high volume production is expected to bring down the prices due to economies of scale. We predict the price of SiC to be a factor of 2–3 times the price of Si in the foreseeable future for devices of similar ratings.

However, if the comparison instead is made of the life-cycle cost on a propulsion system level, SiC solutions already today are competitive and often the winning solution. The reason for this is its superior energy efficiency, which brings
down the operation electricity cost over the lifespan of the product.

Solutions utilizing the benefits of SiC may still be optimized along a number of dimensions, so trade-offs for specific applications need to be made. For example, an increased investment in chip area will increase the energy efficiency and thus bring down life-cycle cost. Increased chip area could also be utilized to reduce the required cooling performance, which may permit the use of passive cooling. If fans can be removed, savings on maintenance costs are achieved. The possibility to operate with a high switching frequency can be utilized to design a very quiet solution, as demonstrated here. Moreover, optimizations can be made to achieve further improvements in power density, although trade-offs then need to be made with the previously discussed benefits. How the balancing among these, sometimes conflicting dimensions are made, will depend on the specific application and wishes of the customer.

To conclude, it is the opinion of the authors that the SiC technology now is feasible for long-term commercial use in traction applications where life-cycle cost is highly valued, with switching frequencies in the range 3–6 kHz. The successful completion of the here presented 3-month field test increases the confidence in the full-SiC inverter technology, bringing the customer values of compact solutions with higher energy efficiency, lower acoustic noise and lower maintenance costs closer to reality.

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