The Potential Impact of Using Traction Inverters With SiC MOSFETs for Electric Buses

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This work was supported in part by the Key-Area Research and Development Program of Guangdong Province under Grant 2020B010173001, in part by the Power Electronics Science and Education Development Program of Delta Group under Grant W2019JSKF0363, in part by the Institute of Energy at Hefei Comprehensive National Science Center under Grant 19KZS207, and in part by the 111 Project.

ABSTRACT The efficiency improvements offered by adopting Silicon Carbide (SiC) devices in Electric Vehicle (EV) inverters has been widely reported in various studies. However, it has still not been established whether or when the efficiency benefits can counteract the high price of SiC devices, especially for the scenario of urban electric buses. In this paper, the potential impact of installing SiC devices on electric buses is analyzed from the perspective of economic benefits. The SiC inverter used in the drive system is based on a discrete MOSFET in parallel. For comparison, an Si inverter based on a sixth-generation IGBT produced by Infineon is also evaluated. A vehicle simulation platform is established in Simulink for an evaluation of energy consumption for different scenarios. It is shown that significant energy savings can be gained when the vehicle operates mostly in the partial load area. While in the nominal load area, energy savings are very limited. Based on the analysis, the conditions for offsetting the cost premium of SiC devices to realize system-level advantages are discussed using a multi-dimensional analysis considering the change in battery and device prices, driving range, vehicle mass, and driving cycles.

INDEX TERMS SiC devices, electric bus, energy consumption, system-level advantages, driving cycles.

I. INTRODUCTION silicon Carbide (SiC) is regarded as the next-generation power semiconductor for automotive applications due to its superior properties such as high switching frequency, low switching loss, and better thermal capability [1]–[4]. The implementation of SiC power devices in electric vehicle (EV) powertrains can reduce the power loss and further improve the energy conversion efficiency, and this has been widely proven [5]–[13]. In [8], 1 kW permanent magnet synchronous machine (PMSM) drive prototypes based on the Si Insulated Gate Bipolar Transistor (IGBT) and SiC Metal Oxide Semiconductor Field Effect Transistor (MOSFET) were fabricated, and a comparison of the results showed that the efficiency of the SiC-based inverter was 1% higher than that of the Si inverter. In [9], a 3.3 kV full-SiC MOSFET module has compared with a 3.3 kV Si IGBT power module with similar current rating. It showed that the loss of the traction inverter can be reduced by 59% by the SiC based inverter. Paper [10] presents a 500 kW DC/AC inverter based on SiC devices. It can achieve an efficiency of 98.74% in experiment, which is higher than Si IGBT at the same power level. In [11], a peak efficiency of 99.5% was achieved on a 30kW traction inverter using 1200 V SiC MOSFET devices. The above papers focused on efficiency improvements by using the SiC device in nominal or peak power operation. In partial load operation, e.g., 10% of the nominal power, the efficiency improvements offered by the SiC device are much more significant. Paper [12] pointed out that SiC devices could lead to a reduction in power loss by more than 50% in partial load operation, while paper [13] showed that efficiency could be improved by 5% – 10% in partial load operation.

The efficiency benefits offered by SiC inverters can be translated into a higher driving range or a lower requirement...
on the installed battery energy storage [14]. In contrast to private electric vehicles, high driving range is not a priority for electric buses because a 100 km-300 km range can easily meet the operating needs in most cities with a relatively regular charging time. Besides, the volume of the motor for electric buses is much larger than the inverter, hence it is not necessary to pursue the high-power density of the inverter in the drive system. Therefore, the main advantage of the SiC inverter for electric buses is the reduction of the overall energy consumption, which can be further converted into savings on battery costs. In automotive applications, the cost is always a key factor in the design [15]. At present, the price of SiC devices is much higher than for Si devices, which can be a major disincentive for commercial applications [16]. Thus, for the application of SiC inverters in electric buses, the battery cost savings and the additional device cost are a pair of opposite factors that affect the system-level advantage.

In [17], it was found that lower energy consumption could be achieved by changing the number of paralleled SiC MOSFETs in hybrid vehicles over various driving cycles. However, the relationship between variable device costs and the change in energy efficiency was not considered. Paper [18] introduced the challenges of applying SiC devices to EVs, but how the battery and device costs affected the system were not analyzed in detail. Thus, it is still not clear whether or when the system-level advantage brought by SiC inverters will outweigh its high price in automotive applications [19], [20].

The aim of this paper is to investigate the potential impact of SiC devices on electric buses from the perspective of economic benefits. A SiC inverter for electric buses is constructed and compared to an advanced Si IGBT inverter. A full vehicle simulation platform is established for evaluating the energy consumption of electric buses under different scenarios. The system-level advantage is analyzed by comparing the battery cost savings with the additional device cost. Using a multi-dimensional analysis considering the changed battery and device prices, driving range, vehicle mass, and driving cycles, the applicability of the SiC inverter in electric buses is also discussed. The following sections are organized as follows: Section II gives a brief introduction of the traction inverter in the electric bus, and a cost comparison of SiC and Si inverters is also presented. Section III evaluates and compares the energy consumption of the SiC and Si inverter based on a full EV simulation model. A system-level advantage of the SiC inverter applied to electric bus is systematically conducted with the Si inverter as a benchmark. in Section IV. Section V provides a conclusion of this paper.

II. TRACTION INVERTERS IN DRIVE SYSTEMS

A. SYSTEM SPECIFICATIONS

A typical electric bus drive system consists of a Lithium-ion based battery, a traction inverter, a three-phase AC permanent magnet synchronous machine (PMSM), and a fixed-gear transmission [21]. Thus, the drive system used in this study is comprised of these components, as shown in Fig. 1. The specific parameters of the traction system are provided in Table 1. Fig. 2 shows the prototype of the SiC inverter used for the drive system. The maximum current in each phase of the inverter is 350 A.

| Table 1. Specifications of the PMSM drive. |
|-------------------------------------------|
| **Bus Voltage** | 620 V |
| **Power Rating** | 120 kW |
| **Peak Power** | 200 kW |
| **Max. Torque** | 750 Nm |
| **Switching Frequency** | 8 kHz |
| **Modulation Method** | SVPWM |
| **Inverter Topology** | Two-level Three-phase |

Due to the limited current-carrying capability of a single SiC die, SiC MOSFETs that are either in the form of dies or discrete devices are required to be used in parallel on each leg of the inverter for a large current capacity. Thus, two forms of devices are usually available, which are the power module or the discrete device with TO-247 package. For high-power applications, the power module seems to be a better choice. However, the market for commercial use of SiC power modules is not yet mature in many regions due to some reasons such as the reliability, the cost, etc. Hence, the solution based on discrete devices in parallel is more likely attractive to the industry due to its relatively lower cost at this stage. As the most successful manufacture
of commercially using SiC devices, Tesla has equipped its product model 3 with SiC inverters, which is based on the solution of discrete devices in parallel. In addition to the advantage of the lower cost compared to the power module, the solution of discrete devices in parallel has other benefits, which is summarized by paper [22].

Therefore, the SiC inverter designed in this EV drive system for analysis is based on the solution of discrete devices in parallel. A commercial Gen3 SiC MOSFET C3M0016120K from Wolfspeed which has the lowest on-state resistance among the current discrete SiC MOSFETs is used for the SiC inverter. It can handle 85 A at $T_c = 100^\circ$C with a TO247 package, hence six of them are required in parallel to handle the current. For performance comparison, an Si inverter is also designed. The sixth-generation IGBT IKQ75N120CS6 from Infineon with high switching speed is chosen, as it can demonstrate the most advanced performance of current Si inverters. This device can handle 75 A at $T_c = 100^\circ$C. Similarly, six of them are required in parallel to handle the current. Some main parameters of the selected devices are presented in Table 2.

### TABLE 2. Device data for comparison.

|                | SiC                  | Si                  |
|----------------|----------------------|---------------------|
| Manufacturer   | Cree                 | Infineon            |
| Selected Device| C3M0016120K          | IKQ75N120CS6        |
| Rated Voltage  | 1200 V               | 1200 V              |
| Rated Current  | 85 A @ $T_c = 100^\circ$C | 75 A @ $T_c = 100^\circ$C |
| On-resistance  | 16 m$\Omega$         | /                   |
| Turn on time   | 67 ns                | 78 ns               |
| Turn-off time  | 78 ns                | 331 ns              |
| Number of parallels | 6                     | 6                   |

#### B. THE COST OF THE INVERTERS

The cost of the main subparts of the inverters based on the SiC and Si solutions is roughly estimated and compared. The total cost of the inverter is divided in the following main subparts, which are the power switches, the heatsink, the dc-link capacitor, the busbar, the driver and controller boards, and others (housing or assembly, etc.). The cost model of the semiconductor was proposed in [23], and was defined as:

$$\sum_{SC} = \sum_{chip} + \sum_{pack,x} = \left( \sum_n \sigma_{chip,x(n)} A_{chip,n} \right) + \sum_{pack,x}$$

where $\sigma_{chip,x}$ is the specific price per unit area of the chip and can be interpreted as the sum of all processing and development costs for a given chip technology. $A_{chip}$ is the area of the chip which depends on the chip technology [24], and the area can be considered as a function of the nominal current [25]. $\Sigma_{pack,x}$ is the package price, including chip integration and bonding.

Equation (1) indicates that the switch prices are related to the switch type, die size, and packing type. In [23], the price of $\sigma_{chip,x}$ for a SiC Schottky diode was estimated to be about 18 times higher than a Si PiN diode. At present, the price of SiC switches has decreased and has been recalibrated according to the current market price. A price comparison of Gen3 SiC MOSFETs and Gen6 Si IGBTs at 1200 V is shown in Fig. 3. These data are available on the manufacturer websites [26], [27]. It can be observed that the SiC price at high current levels is much higher than for Si devices.

The heatsink cost in [25] depended linearly on volume, with an additional fixed cost. The two kinds of inverters used in the drive system are developed on the same platform. In addition, the parallel devices of a single phase are laid closely and flat on the heatsink surface in sequence. Thus, the size of the heatsink depends mainly on the total length of the six parallel devices. Since the size of the used SiC MOSFETs and Si IGBT based on the TO247 package is very close, the heatsinks of the two inverters have the same specifications. Besides, other components, such as the capacitor module, control and driver circuit boards, busbars, etc., are almost the same for the two inverters. Moreover, the structure and volume of the two inverters are roughly equal, leading to a very similar housing cost. Therefore, the cost of these two inverters is almost the same, except for the switching devices. The specific cost of the two types of inverters is shown in Table 3. And the cost breakdown of the inverters in this paper is shown in Fig. 4. It can be seen that the cost of power switches is most significant in the inverter. The SiC MOSFETs account for 74.6% of the total cost of the inverter. For the Si inverter, the cost of the IGBTs accounts for 54.1%, based on the premise that the other components are similar to the SiC inverter. It can be noted that the cost of the SiC inverter is much higher than that of the Si inverter due to the high price of the SiC device. In fact, the cost breakdown in Fig. 4 is based on the production cost of a very small batch of prototypes. As the large-scale application of SiC devices,
its prices will gradually decrease. Thus, the impacts of the changed cost of SiC devices on the EV system should also be investigated.

### III. EVALUATION OF ENERGY CONSUMPTION

In addition to the inverter, the cost of the battery also accounts for a significant portion in the drive system [28]. The vehicle adopting the SiC inverter can save the energy consumption within the same driving range, which in turn reduces the installed battery capacity. Thus, the cost of the battery can be further reduced. While, the extent of the energy saving by the SiC inverter depends on the specific scenarios. This section gives a further insight into the influence of the SiC inverter on the energy consumption of electric buses in different conditions.

### TABLE 3. The cost of the SiC and Si based inverters in US$. 

| Subparts                | SiC inverter | IGBT inverter |
|------------------------|--------------|---------------|
|                        | U/P | Qty | Sum | U/P | Qty | Sum |
| Power devices          | 52  | 36  | 1875 | 21  | 36  | 756 |
| Capacitor module       | 56  | 1   | 56   | 56  | 1   | 56  |
| Control and drive board| 225 | 1   | 225  | 225 | 1   | 225 |
| Heatsink               | 150 | 1   | 150  | 150 | 1   | 150 |
| Busbar                 | 37  | 1   | 37   | 37  | 1   | 37  |
| Housing                | 169 |     | 169  |     |     |     |

### FIGURE 4. The cost breakdown of the used two kinds of inverters. (a) SiC-based inverter. (b) Si-based inverter.

A drive system model is developed to simulate the energy consumption of the EV drive system, as illustrated in Fig. 5. It is compiled in MATLAB/Simulink and comprised of seven parts. The driving cycle that can be chosen for each individual scenario contains velocity information with time as a variable. It provides the desired velocity \(v^*\) at which the vehicle drives in this scenario. The driver model reaches this velocity by controlling the virtual driving pedal \(p\) and comparing the desired velocity with the actual one \(v\) [28]. The vehicle control unit (VCU) is the central control entity in this model, which performs a related analysis of the signals given by the driver model as well as the information gained from the vehicle, the inverter (including the motor), and the battery, etc. The VCU afterward sets the required torque \(T^*\) and sends to the inverter model based on the analysis. The inverter controls the desired torque by regulating the current in the motor. This requires electrical power \(P\) from the battery. Finally, the vehicle transmission system transmits the output torque \(T_e\) from the motor to drive the vehicle.

The energy consumption of the EV drive system adopting the SiC inverter or Si inverter can be simulated separately by this model under different conditions. In turn, the energy saving by SiC inverter can be further evaluated. In this simulated platform, the operating points covering the torque-speed range of the motor are converted into output power from the battery. Denoting the demand power consumed at the wheel as \(P_{\text{tra}}\), and the power from the battery as \(P_{\text{bat}}\), the following relationship can be determined:

\[
P_{\text{bat}}(t) = \frac{1}{\eta_{\text{bat}}} \frac{1}{\eta_{\text{pt}}} P_{\text{tra}}(t) \tag{2}
\]

where \(\eta_{\text{bat}}\) is the battery efficiency, and \(\eta_{\text{pt}}\) is the drive system efficiency, which includes the efficiency of the inverter, electric motor, transmission system, etc. The total energy consumed during driving can be further calculated by a time integral of the battery power. Thus, comprehensive efficiency maps for different operating points need to be provided in the simulator to obtain energy consumption. In fact, the battery
efficiency is a weak function of different operating conditions and it can be considered a constant value [29], while the transmission efficiency can also be considered constant. The system efficiency including the inverter and motor should be generated over the range of the torque-speed plane. In [11] and [17], the vehicle simulation model used mathematical models based on datasheet parameters to calculate efficiency. However, in this paper the inverter and motor efficiency map applied to the model in the simulator uses measured results based on the test platform shown in Fig. 6, which presents a more accurate estimation of energy consumption for a specific EV.

The SiC inverter and the Si inverter are installed into the experimental platform separately for testing. The obtained system efficiency including the motor and inverter as a function of motor speed and torque is shown in Fig. 7. For clarity, the efficiency in regenerative mode is not shown. It can be observed in general that higher efficiency is achieved at intermediate speed/torque combinations but deteriorates significantly at a lower power level. In comparison, the system efficiency of the SiC inverter is higher than the Si inverter in all operating conditions, especially in the low-speed range. Moreover, the high-efficiency zone is much more extensive than for the Si-based drive system. It is evident that the SiC inverter has a great advantage in improving the efficiency of the traction system.

### B. ENERGY CONSUMPTION EVALUATION FOR ELECTRIC BUSES

#### 1) UNDER DIFFERENT DRIVING CYCLES

A common way to estimate the energy consumption of EVs is through driving cycles [30], [31]. In this paper, three types of driving cycles - urban congested driving cycle, urban smooth driving cycle, and suburban unimpeded driving cycle - are investigated for an evaluation of energy consumption. Fig. 8 shows the speed profile of the driving cycles. The Manhattan cycle is used to model the driving conditions for electric buses with lower average velocities and frequent starting and stopping. The WVUSUB cycle is one with smoother traffic conditions and has a higher speed level than the Manhattan cycle. The final driving cycle, INDIAHW, is used to model the electric bus driving in suburban areas, maintaining a higher speed throughout.

The reference bus that is meant for urban and suburban driving with a moderate speed level is shown in Table 4. Based on the full-vehicle simulation model, the energy consumption of the reference vehicle using the two inverters is simulated separately. The state of charge (SOC) is used to reflect the capacity of the battery. All simulations start at 95% SOC and end at 15% SOC, as a margin of a few percent is typically used in EVs to prolong the battery life. The results are listed in Table 5. All of the energy values are converted to kWh/100 km to form a comparison basis. In general, it is seen that energy consumption can be saved with the adoption of a SiC inverter. Compared with the urban smooth cycle, the reduction is more significant in the urban congested cycle. However, the reduction is very limited in the suburban unimpeded cycle.

Each driving cycle consists of different running modes, such as acceleration, cruising, braking, and deceleration. Therefore, the operating points of the motor in each driving cycle has a great difference. The graphs in Fig. 9 characterize the efficiency improvement ($\eta_{\text{SiC}} - \eta_{\text{Si}}$) provided by the SiC inverter in the speed/torque plane, and the converted operating points of each driving cycle are distributed on it. It is observed that different driving cycles have significant differences in the distribution of their operating points. The efficiency improvement offered by the SiC inverter depends on the distribution of the operating points.
Taking the urban congested cycle in Fig. 9(a) as an example, due to the lower average speed of this driving cycle, more than 70% of the operating points appear in the low-speed area of 0 - 1000 r/min. In this area, it is observed that the efficiency improvement of the SiC inverter is significant, being in the range of 5 - 14%. For the urban smooth cycle in Fig. 9(b), it is noted that some of the operating points have moved to the higher speed area of 1500 - 3500 r/min, which corresponds to the high-efficiency area. Hence it results in a relatively small improvement in efficiency. For the suburban cycle in Fig. 9(c), as the vehicle speed is high, more than 90% of operating points reach the high-efficiency area where the advantage of the SiC inverter in improving efficiency is very limited.

To evaluate the effect of efficiency improvements on energy consumption, the average efficiency improvement of each driving cycle by the SiC inverter is defined as:

$$\eta_{\Delta} = \frac{\sum_{i=1}^{N} [\eta_{\text{SiC}}(i) - \eta_{\text{Si}}(i)]}{N} \quad (3)$$

where $\eta_{\text{SiC}}(i)$ and $\eta_{\text{Si}}(i)$ represent the efficiency of a specific operating point applied to the SiC and Si inverter, respectively.
respectively. $N$ is the total number of operating points in the specific driving cycle. The calculated average efficiency improvements for each of the three driving cycles are 7.6%, 4.0%, and 2.2%, which can be manifested correspondingly in the reduction of energy consumption. It can be concluded that the higher the average efficiency improvement, the more significant the reduction in energy consumption.

2) UNDER DIFFERENT VEHICLE TYPES

The simulation platform can be used to analyze a wide range of vehicle types. In the vehicle system, the transmission ratio and vehicle mass are the key factors that affect energy consumption [32], [33]. Thus, the three cases listed in Fig. 10 are studied for evaluating the energy consumption of electric buses in the urban congested driving cycle. Case A is the reference vehicle shown in Table 4. The energy saved using the SiC inverter is 3.9 kWh/100 km. In comparison to the reference, Case B has the same vehicle mass but a higher transmission ratio. It is observed that the energy consumption is reduced, but at the same time, the energy saved by using the SiC inverter also decreases. In Case C, the vehicle is heavier but with the same transmission ratio as the reference vehicle. Meanwhile, other vehicle parameters such as the cross-section and the radius of the tires become larger, considering the larger size. The energy consumption raises dramatically due to the increased weight, but the energy saved by the SiC inverter also grows to 4.9 kWh/100 km.

![FIGURE 10. Comparison of energy consumption with different vehicle types.](image)

It can be observed that the level of energy savings brought by the SiC inverter is also related to the specific vehicle. Fig. 11(a) shows the distribution of the operating points for Case B. Compared with the reference vehicle in Fig. 9(a), it can be seen that the operating points move towards the higher rotation speed range, which corresponds to the high-efficiency area of the traction system. Thus, energy consumption is reduced due to the higher energy conversion efficiency. Moreover, since the level of efficiency improvement by the SiC inverter in this region is very significant, leading to more savings in energy consumption. Based on (3), the average efficiency improvement in Case B and Case C is 6.1% and 9.1%, which shows agreement with the conclusion in the previous section.

3) SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to demonstrate the advantages of the SiC inverter with different driving cycles and vehicle parameters. In the simulation model, the vehicle transmission system is equivalent to a rigid body with a fixed transmission ratio. According to automotive theory, the design principles of the transmission ratio should meet the requirements of the maximum speed and maximum gradeability, which are determined by the following formula [34].

$$\frac{mg(f \cos \alpha_{\text{max}} + \sin \alpha_{\text{max}})r}{T_{\text{max} \eta_{t}}} \leq \frac{0.377 n_{\text{max}} r}{v_{\text{max}}} \leq 0$$ (4)

where $\alpha_{\text{max}}$ is the maximum grade angle, $f$ is the rolling resistance, $r$ is the radius of the tire, $\eta_{t}$ is the transmission efficiency, $n_{\text{max}}$ is the maximum rotation speed in rpm, $v_{\text{max}}$ is the maximum vehicle speed (km/h), and $T_{\text{max}}$ is the maximum torque (N-m). Thus, the relationship of the vehicle mass and the transmission ratio can be constrained to within a certain range. Following that, the corresponding energy consumption can be further predicted by the simulation platform.

![FIGURE 11. Distribution of the operating points for Case B and Case C in the Manhattan driving cycle. (a) Case B. (b) Case C.](image)
Fig. 12 displays the simulation results. It can be seen that the electric bus utilizing the SiC inverter has a great advantage in energy-saving when it is driven in congested road conditions, as shown in Fig. 12(a). Moreover, the effects are more significant in the vehicle with a lower transmission ratio or heavier weight. However, a lower transmission ratio will make the EV operate at a sub-optimal level, which can result in increased overall energy consumption. In relatively smooth traffic conditions, as shown in Fig. 12(b), the level of energy savings is smaller for most vehicle types. As Fig. 12(c) shows, when in suburban road conditions, the energy savings provided by the SiC inverter are very limited.

Based on the analysis, it can be concluded that the benefits of the SiC solution depend on the driving scenarios. If the vehicle operates frequently in the partial load area, the advantage of the SiC inverter in saving energy is more significant. Conversely, if the vehicle operates mostly in the nominal area, the energy savings offered by the SiC solution are not obvious.

IV. APPLICABILITY OF SiC INVERTERS

So far, the SiC inverter has proven to be a better choice than the Si inverter in terms of reducing energy consumption. However, the price of the SiC device is significantly higher than the Si device, and it is the major roadblock for its adoption in automotive systems. Although the saved energy consumption can be translated into battery cost savings to offset the premium of the SiC device, the level of savings is not clear due to the saved battery capacity depending on different scenarios. Therefore, in terms of the system-level cost, the potential impact of the SiC inverter on electric buses needs to be investigated, according to different applications.

In [28], the distribution of the cost for drivetrain components was described, as shown in Fig. 13. It can be seen that the battery and the inverter account for most of the cost. Moreover, in the drive system, all of the components are identical except for the two types of inverter tested in this paper. Therefore, the system-level cost comparison is limited to the cost difference between the inverter and the battery. The reliability or lifetime of the inverter can also affect the total cost. The SiC inverter is designed based on actual engineering products with a relatively high reliability. Moreover, it applies a relatively mature SiC devices in the form of TO247 package. Although the SiC devices are the emerging power devices, the SiC technology has substantially matured after years of development. The reliability of the SiC device can meet commercial needs at this stage [35]. In fact, the high cost of SiC devices is still the major roadblock for the technology adoption in automotive systems. The main cost difference between the SiC and Si inverter is the semiconductor power devices. Hence, this paper mainly focuses on two perspectives, that is, the high cost of SiC devices and the saved battery cost, thereby predicting the system-level cost advantages of SiC devices for electric bus.

For an evaluation of the system level advantage of the SiC inverter, the parameter $CV$ is used and defined as:

$$CV = \Delta C_{\text{device}} - \Delta C_{\text{battery}} = \Delta C_{\text{device}} - \left(\frac{E \cdot \beta \cdot l}{100}\right)$$

where $\Delta C_{\text{device}}$ ($) is the total cost variance of the SiC MOSFET and the Si IGBT, and $\Delta C_{\text{battery}}$($) represents the

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![FIGURE 12. Sensitivity analysis of energy consumption over different driving cycles. (a) Manhattan driving cycle. (b) WVUSUB driving cycle. (c) INIDAHS driving cycle.](image-url)
total saved battery cost resulting from the SiC solution. This, in turn, depends on the saved battery capacity $\Delta E$ (kWh/100 km), the battery price $\beta$ ($/kWh$), and the nominal range $l$ (km) rated by the driving cycle. If the value of $CV$ is less than zero, it means that the saved battery cost can completely counterbalance the additional cost of the SiC device, thus the SiC inverter solution has the advantage in system-level cost. Conversely, if the $CV$ value is greater than zero, the Si inverter solution is preferred.

To demonstrate the general applicability of the SiC inverter, a multi-dimensional cost analysis is conducted. Five parameters are varied to define a range of vehicle concepts in which the SiC inverter solution will bring benefits. These parameters are the driving cycles, the vehicle weight, the driving range, the cost difference between the semiconductor devices, and the battery price.

Firstly, a multi-dimensional cost analysis is performed on EVs with different mass, driving cycles, and driving ranges. For electric buses, a higher driving range will not be the priority, and a nominal driving range of 100 km to 300 km can meet operational needs in most cities. The price of the battery is determined to be US$ 150 per kWh [36], and the cost variance of the device is US$ 1200. Fig. 14 shows the calculation results. For clarity, the circular markers indicate where the SiC solution is advantageous. Conversely, triangular markers are used to show where the Si Inverter is a better option. In general, as the nominal range increases, the extent in offsetting the premium of the SiC device becomes more significant, because more battery capacity can be saved. Moreover, as the weight of the vehicle increases, the SiC solution slightly narrow the cost gap with the Si solution. However, there is no obvious difference for suburban cycles as the energy savings are roughly the same for different vehicle types. Furthermore, it is observed that when the Manhattan cycle is used to rate the range at 200 km and 300 km, the extra cost of the SiC devices can be fully covered by the saved battery costs. However, in the urban smooth cycle and the suburban cycle, the SiC solution is not competitive for the system-level cost.

In the foreseeable future, the cost of manufacturing SiC devices will gradually fall with high-volume commercial production. The price of lithium-ion batteries in the pack-level was forecasted in [37], and [38], and is illustrated in Fig. 15. A steady falling trend in battery prices has been observed in recent years. Thus, it will also be necessary to discuss the situation when both batteries and SiC devices are cheaper. Here, the vehicle mass is set to 6000 kg, and the calculations of the total saved battery capacity uses 200 km as the rated range. The battery price ranges from US$ 150/kWh to US$ 50/kWh, the device cost difference ranges from US$1200 to zero, and the calculated results are illustrated in Fig. 16. The solid black line represents the curve with a $CV$ of zero and indicates where the saved battery cost of the SiC solution is equal to the added cost of the SiC inverter.

Fig. 16(a) displays the results based on the urban congested cycle. It can be seen that the SiC solution can achieve a cost advantage for a wide range of battery price changes without a substantial reduction in the SiC price. For instance, the battery price in 2024 is forecast to be US$ 94/kWh, which is 37% lower than the current price. The SiC prices should fall by about 39%, and that can realize a balance between the saved battery cost and the added cost of the SiC switches. However, for the urban smooth cycle and the suburban cycles in Fig. 16(b) and (c), the SiC prices will need to fall by 74% and 84% respectively to achieve a cost balance. This shows that the SiC solution will realize the advantage of the system-level cost more easily when the powertrain operates mostly in the partial load area. However, in the nominal load area, the SiC solution will have a higher cost than the Si solution unless the SiC prices drop significantly.

At this stage, the advanced Si inverter can be applied to more vehicles and in more scenarios due to the large device
cost gap. However, when the route of an electric bus requires it to operate more in the partial load area, the SiC inverter may be preferable. In the future, to make the SiC inverter suitable for more scenarios, a significant cost reduction of the SiC device is required.

V. CONCLUSION

The high cost of SiC devices is considered a major obstacle to their use in automotive applications. However, the savings in battery costs resulting from its higher efficiency can help offset part of the price difference. In order to investigate the potential impact of the SiC inverter on electric vehicles from the perspective of economic benefits, this paper provides a comprehensive analysis of the system-level advantages offered by the SiC solution over various conditions.

For performance comparison, SiC MOSFET and Si IGBT inverters are constructed separately. Then, the energy consumption of electric buses adopting these two types of inverters is evaluated by an established vehicle-level simulation platform over various scenario. Unlike other simulation models that use a calculated efficiency map based on the power loss model, this simulation applies a tested efficiency map based on the PMSM drive system to the model for a more accurate prediction of the energy consumption. The results show that the energy savings offered by the SiC inverter in electric buses are significant in the urban congested cycle, noticeable in the urban smooth cycle, yet very limited in the suburban unimpeded cycle. Furthermore, the reduction in energy consumption with the SiC solution, which results in saved battery costs, is compared with the additional cost of the device. Finally, a multi-dimensional cost analysis is conducted to demonstrate the general applicability of the SiC solution. The analysis evaluates variations in the changed battery and device price, driving range, vehicle mass, and driving cycles. Based on the analysis, it is concluded that the SiC solution has a positive effect on electric buses when they operate mostly in the partial load area. However, when buses operate mostly in the nominal load area, the Si solution is preferred. If the SiC price falls far faster than the price of batteries, or the nominal driving range is high enough, the SiC solution will be superior. However, this scenario is hard to realize at this stage.

This paper is primarily about the impact of the SiC inverter on electric buses from the perspective of economic benefits. To fully exploit the benefits, more detailed studies regarding the reliability, complexity of control, and drive system design should still be conducted.

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