

DRIVE CYCLE-BASED LOSS EVALUATION OF TWO-LEVEL AND THREE-LEVEL INVERTERS IN 400 V AND 800 V ELECTRIC VEHICLE APPLICATIONS

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Received: 9 May 2025; Revised: 4 June 2025; Accepted: 6 June 2025

ABSTRACT

In this paper, the driving cycle model tested by the Environmental Protection Agency (EPA) is utilized to analyze power losses in inverter components, aiming to assess the actual performance and energy consumption of electric vehicle drive systems. The primary losses considered include conduction and switching losses that occur under real-world operating conditions. The analyzed conditions cover urban environments, highways, and challenging terrains involving multiple phases of acceleration and deceleration. Two types of semiconductor devices are evaluated: Silicon Insulated Gate Bipolar Transistor (Si IGBT) and Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistor (SiC MOSFET), corresponding to battery system voltage levels of 400 V and 800 V, respectively. Three inverter configurations are considered in this study: two-level inverter, T-type three-level inverter, and ANPC three-level inverter. The efficiency and energy losses of each configuration are assessed based on simulation results.

Keywords: Electric vehicle, efficiency, loss calculation, traction inverter.

1. INTRODUCTION

The inevitable trend of the electric vehicle industry is driving the demand for optimizing the performance of the vehicle's drive system, as it is considered a mode of transport with advantages in high efficiency, energy savings, and environmental friendliness compared to internal combustion engines. In this context, the inverter plays a crucial role in converting Direct Current (DC) power from the battery into Alternating Current (AC) for the motor. However, this process is always accompanied by energy losses, which directly affect operational efficiency. During operation, the efficiency of the inverter varies significantly due to the nonlinear losses of the power components, which depend on the operating voltage and current, both of which are influenced by the motor's torque and speed [1].

Currently, the 400 V system is commonly applied in small and medium electric vehicles, while the 800 V system is prioritized in high-performance vehicles due to its fast-charging capability, reduced conduction losses, and minimized energy losses during power transmission through conductors [2]. With voltages reaching up to 870 V, double that of traditional 400 V battery systems [3], two-level inverter configurations are gradually revealing limitations regarding the rated voltage of components. Therefore, multilevel converters such as T-type and Active Neutral Point Clamped (ANPC) are being researched to reduce losses and enhance efficiency, with the configurations presented in Figure 1. The selection of inverter topologies and power components must be based on performance criteria, as they are influenced by voltage, current, torque, and motor speed.

Wide-bandgap semiconductor components can further enhance the efficiency of inverters [4]. Consequently, two semiconductor devices used in loss analysis are SiC MOSFET and Si IGBT. SiC MOSFET is gradually replacing Si IGBT in modern applications due to advantages such as low switching losses, high breakdown voltage [5, 6], and the ability to operate at junction temperatures of up to 250 °C [7]. These significant advantages help increase power density [8], reduce DC/DC losses [9], and improve integrated charging efficiency in electric vehicles [10, 11], making SiC an ideal choice in the optimal design of inverters for various applications [12].

SiC MOSFETs and Si IGBTs have both been investigated for automotive traction inverters and are used in commercial electric vehicles [13]. Their suitability depends on the operating requirements of the drive system, particularly the DC-link voltage, current rating, switching frequency, and thermal conditions [13]. From a cost perspective, SiC-based inverters generally have a higher initial device cost than conventional Si IGBT-based designs. However, the lower power losses achievable with SiC devices may reduce energy consumption during vehicle operation [14]. Whether these efficiency improvements compensate for the additional investment depends on the operating profile, annual mileage, and overall system cost [14]. Increasing the DC-link voltage from 400 V to 800 V can reduce the current required to deliver a given power level. This reduction may decrease resistive losses in the electrical conductors and allow smaller cable cross-sections. However, an 800 V architecture also requires appropriately rated power semiconductor devices and insulation systems, which can increase the initial system cost. Therefore, the overall benefit of adopting an 800 V architecture must be evaluated by considering both efficiency improvements and additional hardware requirements. Finally, the loss analysis of inverter configurations is based on standard EPA driving cycles, with driving cycles of Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET), thereby providing a comprehensive view of energy losses and the actual efficiency of the electric drive system.

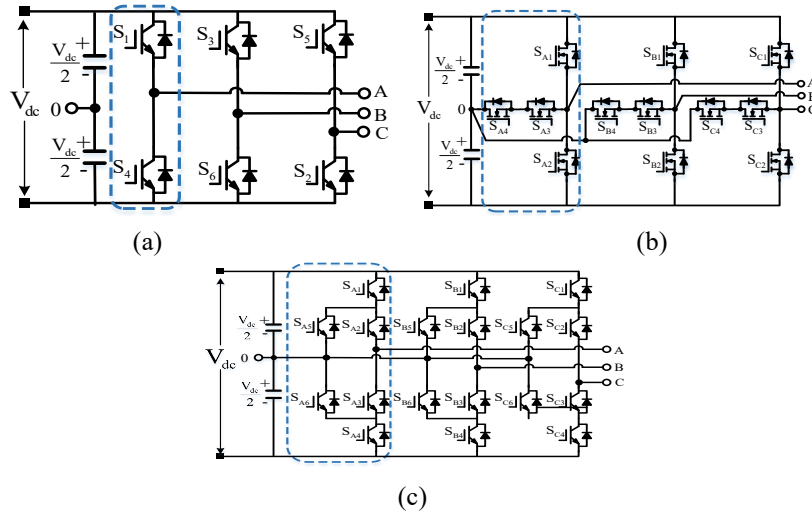


Figure 1. Inverter topologies are considered for comprehensive loss analysis. (a) Two-level (2L), (b) Three-level T-type (3L T-type), (c) Three-level active neutral point clamped (3L ANPC).

2. INVERTER SEMICONDUCTOR LOSS MODELING OVERVIEW

2.1. Loss analysis methods

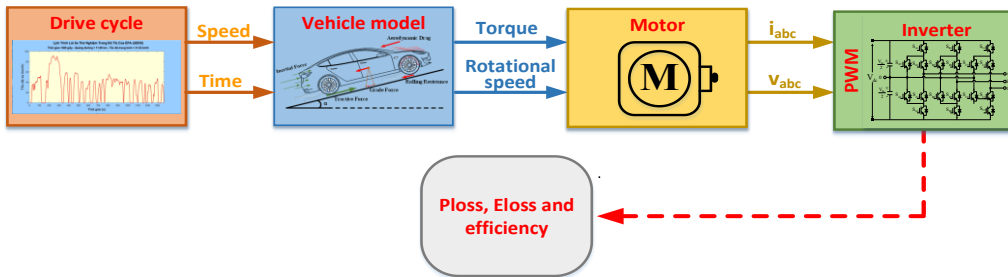


Figure 2. Inverter topologies considered for comprehensive loss analysis

The method for calculating inverter losses is based on four main factors: the standard driving cycle, the vehicle model, the motor model, and the inverter configuration, as illustrated in Figure 2. First, speed and time data are obtained from the EPA driving cycles and used as inputs for the electric vehicle model. This model includes parameters such as vehicle mass, rolling resistance, aerodynamic drag, inertia, road gradient, and gear ratio to compute the torque and rotational speed of the wheels,

from which the motor speed is inferred. The Interior Permanent Magnet Synchronous Motor (IPMSM) model then uses these values to calculate the phase voltages and currents (V_{abc} , I_{abc}), which serve as inputs to the inverter model. Based on V_{abc} and I_{abc} , inverter losses are computed by evaluating both conduction and switching losses in the semiconductor devices (SiC MOSFET and Si IGBT). Each switch contributes to both types of losses, and the total inverter loss is determined by summing up the losses of all switches over the entire driving cycle. From the simulation results, the study compares energy losses between two-level and three-level inverter topologies and analyzes the effect of two system voltage levels 400 V and 800 V, on overall operational efficiency.

2.2. Data parameters for loss analysis

The parameters of the three driving cycles proposed by the EPA are presented in Table 1 [15]. Specifically, the UDDS cycle represents urban driving conditions, characterized by frequent stop-and-go phases and slow acceleration. The HWFET cycle simulates highway conditions with relatively steady speeds and minimal stopping.

Table 1. Summary of EPA UDDS and EPA HWFET drive schedule

Parameter	UDDS	HWFET
Test drive time	1369 s	756 s
Average speed	19.59 mph	48.3 mph
Maximum speed	56.7 mph	59.9 mph
Test distance	7.45 mile	10.26 mile

The product codes and specifications of the inverter modules used in the loss analysis include five types of modules selected for two voltage levels: 400 V and 800 V. These modules incorporate two main types of semiconductor devices: Si IGBT and SiC MOSFET. All modules are manufactured by SEMIKRON and belong to the SKM, SEMiX, and SK product lines, as shown in Table 2 [16]. The selection of these modules aims to support energy loss analysis across different inverter topologies, including 2-level, T-type 3-level, and ANPC 3-level configurations. The engine specifications selected for the analysis are summarized in Table 3 [1].

Table 2. Technical specifications of selected inverter modules for 400 V and 800 V systems

Voltage	Component	Part Number	Rating	Inverter
400 V	Si IGBT	SKM300GB07E3	650 V/300 A	2L & 3L T-type
	SiC MOSFET	SK90MH65CR03TKE2	650 V/96 A	2L & 3L T-type
800 V	Si IGBT	SEMiX202GB066HDs	600 V/200 A	3L ANPC
	Si IGBT	SEMiX202GB12E4s	1200 V/200 A	2L & 3L T-type
	SiC MOSFET	SK90MH65CR03TKE2	650 V/96 A	3L ANPC
	SiC MOSFET	SK200MB120CR03TE2	1200 V/186 A	2L & 3L T-type

Table 3. The IPMSM parameters of 800 V and 400 V are selected to determine the operating point of the inverter.

Parameter	Value		Description
	800 V	400 V	
P_r	75 kW	32.7 kW	Rated power
V_{dc}	800 V	415 V	DC bus voltage
P	8	8	Number of poles
R_s	20 m Ω	6 m Ω	Stator resistance
L_d	491 mH	613 mH	d-axis inductance
L_q	678 mH	13.8 mH	q-axis inductance
λ_f	0.122 Wb	0.024 Wb	PM flux linkage
T_N	90 Nm	80 Nm	Rated torque

The simulation parameters outlined in Table 4 include vehicle mass, wheel dimensions, and road surface conditions. These parameters are essential for conducting a comprehensive analysis of the forces acting on the vehicle, including rolling resistance, grade resistance, inertial forces, and aerodynamic drag. This detailed force analysis enables a more accurate estimation of inverter losses under varying operating conditions, thereby improving the reliability and validity of the simulation results [17, 18].

Table 4. Vehicle Road model parameters

Parameter	Unit	Value	Description
m	kg	1500	Mass of the vehicle
r_w	m	0.27	Radius of wheel
ρ	kg/m ³	1.225	Density of air
C_d	-	0.35	Drag co-efficient
A_f	m ²	2.3	Vehicle frontal area
C_{rr}	-	0.03	Rolling resistance co-efficient
g	m/s ²	9.8	Acceleration due to gravity
α	degree	0.1	Grade of road
$gear$	-	14	Gear ratio

3. SIMULATION RESULT

3.1. Results of the simulation of velocity and reference torque in EPA driving cycles

Figure 3 illustrates the simulation results of vehicle velocity over time for the EPA driving cycles, each of which represents a distinct operational characteristic. Based on the data shown in Figures 3(a) and 3(b), a detailed loss analysis of the inverters can be performed for each specific operating condition.

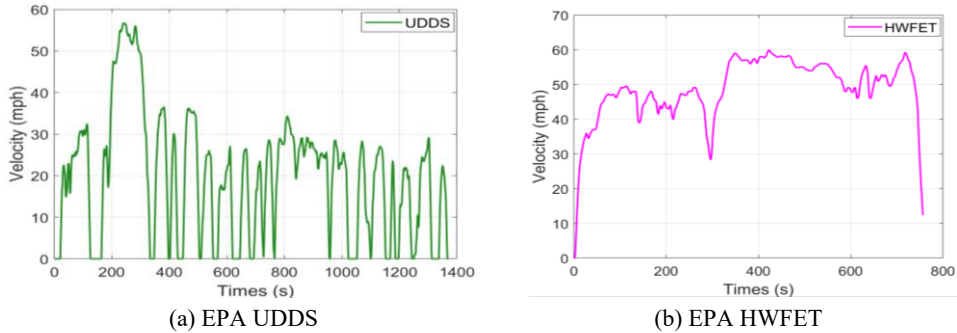


Figure 3. Driving schedule EPA UDDS, EPA HWFET, and EPA US06

Based on the velocity profiles shown in Figure 3 and the selected vehicle model, the corresponding reference torque for each driving cycle has been calculated and is illustrated in Figure 4. Specifically, Figure 4(a) shows that the torque in the UDDS cycle fluctuates continuously with small amplitude, reflecting urban driving conditions characterized by frequent stop-and-go behavior. Figure 4(b) depicts the torque profile of the HWFET cycle as relatively stable, with minor oscillations around the average value due to the vehicle operating at high speeds with minimal variation. These torque characteristics are critical for analyzing inverter losses and evaluating the system's performance under varying operating scenarios.

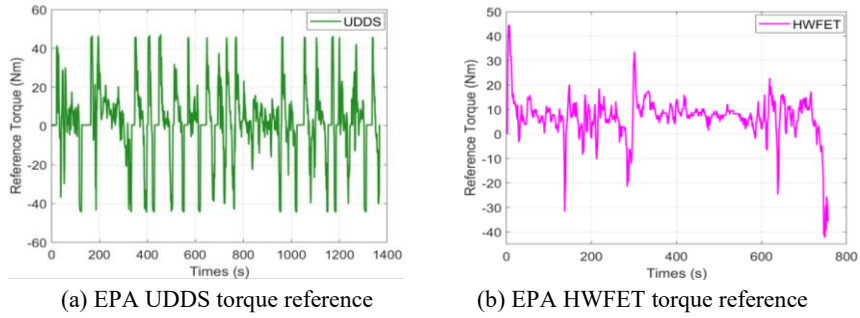


Figure 4. Reference torque moments from three driving cycles UDDS and HWFET.

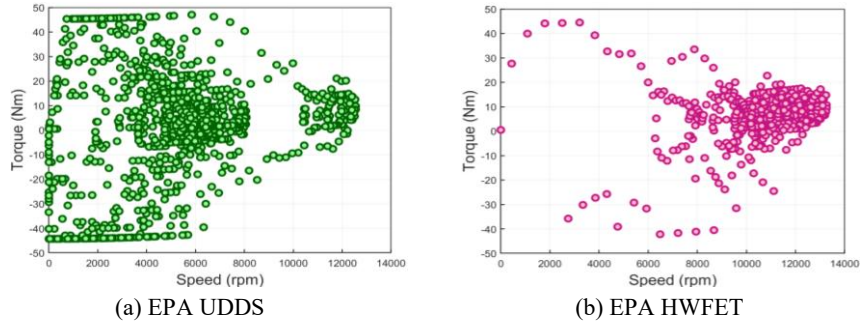


Figure 5. The operating point provides the traction motor for the drive cycle.

Figure 5 illustrates the operating points of the traction motor on the torque–speed plane for the three driving cycles. In the UDDS cycle, shown in Figure 5(a), the operating points are concentrated in the low-speed region with notable torque fluctuations, characteristic of urban driving with frequent stop-and-go behavior. In the HWFET cycle, depicted in Figure 5(b), the points are primarily distributed in the high-speed, low-torque region, reflecting steady driving conditions typical of highways.

3.2. Loss of inverter configurations over each driving cycle

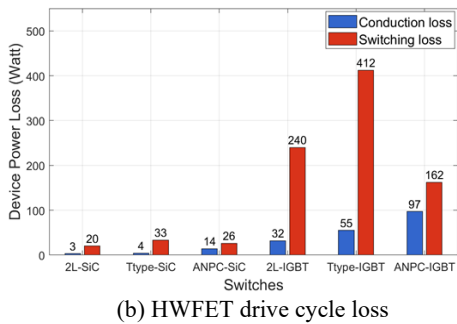
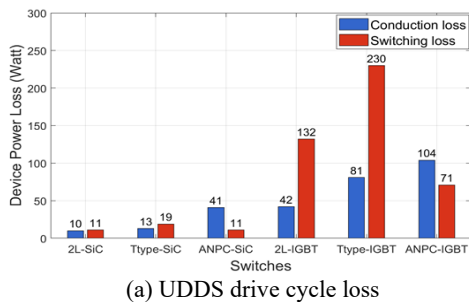


Figure 6. Inverter loss at a voltage level of 800 V over three driving cycles

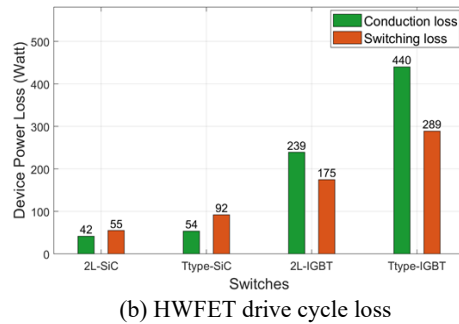
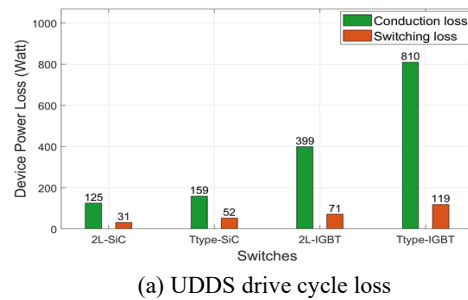
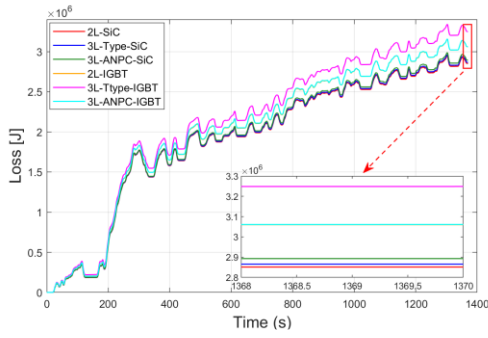


Figure 7. Inverter loss at a voltage level of 400 V over three driving cycles

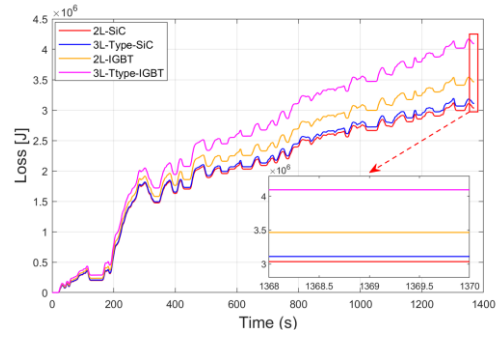
The simulation results in Figures 6 and 7 demonstrate that SiC MOSFETs exhibit a distinct advantage over Si IGBTs due to lower losses in the 2-level and 3-level T-type and ANPC inverter configurations across three cycles UDDS and HWFET. In the UDDS cycle, switching losses are predominant due to the urban operating characteristics involving multiple acceleration, deceleration, and stop phases. The HWFET cycle experiences higher conduction losses as it operates at high speeds and under stable load conditions. Furthermore, at the same cycle, a voltage level of 400 V results in higher losses compared to 800 V due to the larger current, which amplifies both conduction losses (current squared relationship) and switching losses. Consequently, operating at 800 V significantly enhances the inverter efficiency.

3.3. Energy consumption of inverters under real driving conditions

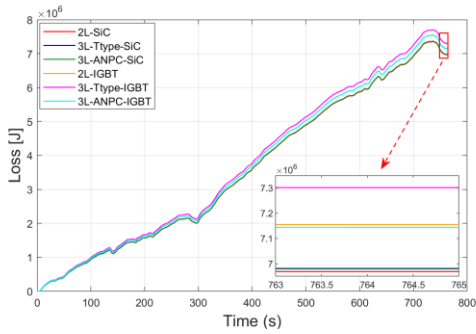
Figures 8 and 9 illustrate the energy consumption across various driving cycles at voltage levels of 400 V and 800 V, respectively. Analysis of the data reveals that the inverter utilizing SiC MOSFETs consistently delivers superior energy efficiency compared to the inverter employing Si IGBTs throughout the entire operation. Notably, the two-level inverter configuration based on SiC MOSFETs exhibits the lowest energy consumption among all evaluated configurations.



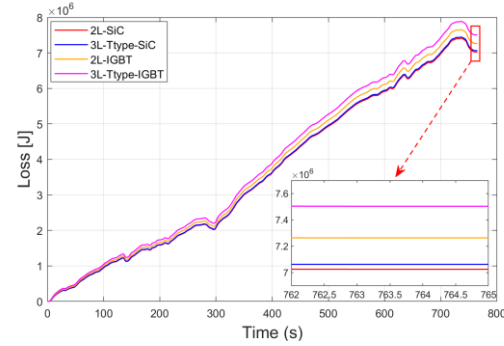
(a) Energy consumption of UDDS



(a) Energy consumption of UDDS



(b) Energy consumption of HWFET



(b) Energy consumption of HWFET

Figure 8. Energy consumption of driving cycles at a voltage level of 800 V

Figure 9. Energy consumption of driving cycles at a voltage level of 400 V

It can be seen that the HWFET cycle (765s) exhibits higher consumption than the UDDS cycle (1369s) despite having a low duration. These results indicate that energy consumption is not solely proportional to operating time; it is also significantly influenced by the load characteristics and driving conditions of each cycle. The deceleration has been performed frequently in the EPA UDDS.

Furthermore, the results show that the system operating at 400 V consistently consumes more energy than when operating at 800 V under the same driving conditions. This can be attributed to the fact that at lower voltage levels, a higher current is required to maintain the same power output. The increased current leads to greater conduction losses (I^2R) and elevated switching losses in the power devices. In contrast, higher voltage operation reduces the current demand, thereby minimizing losses and enhancing overall system efficiency.

4. CONCLUSION

In this paper, the standard driving cycles provided by the EPA are used to reflect the actual operational characteristics, including speed and duration of operation across various types of terrain. Through the analysis, SiC MOSFET components demonstrate significant advantages over Si IGBT, as validated by the evaluation results of conduction losses and switching losses across all three driving cycles examined. Notably, the two-level inverter configuration utilizing SiC MOSFET exhibits lowest losses compared to other inverter configurations, at both voltage levels of 800 V and 400 V. Furthermore, the system operating at the higher voltage of 800 V shows superior performance compared to the 400 V system, owing to its ability to reduce conduction and switching losses in the semiconductor components, while also decreasing the overall energy consumption of the system during the driving cycles. This contributes to the enhancement of the overall efficiency of the electric drive system.

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Additional information

Author contributions

All authors have contributed equally.

Conflict of interest

The authors declare that they have no conflict of interest and no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

Artificial Intelligence (AI) use

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No AI tools were used in the preparation of this manuscript. AI tools were used solely for grammar checking. The authors reviewed and approved all changes.

Funding statement

This research received no external funding.