Performance Evaluation of Two-Level and Three-Level NPC Inverters in Electric Vehicles under Various Drive Cycles and Switching Frequencies

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Received: 11 January 2025 | Revised: 31 January 2025, 11 February 2025, and 15 February 2025 | Accepted: 16 February 2025

 DOI: https://doi.org/10.48084/etasr.10194

ABSTRACT

Internal Combustion Engine (ICE) vehicles contribute significantly to environmental pollution, rendering Electric Vehicles (EVs) essential for sustainability. Inverters are an important component of the EV propulsion system, and their design has a big impact on the system's overall efficiency. This study compares the performance of two topologies of the inverters, which are the two-level and three-level Neutral Point Clamped (NPC) inverters. Furthermore, the impact of switching frequency on the inverter's efficiency and Total Harmonic Distortion (THD) was analyzed. The analyses were conducted using MATLAB/Simulink to model the EV propulsion system, including the vehicle body, and PLECS to calculate power losses and efficiency. The inverters were tested under two drive cycles, the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET), to cover torque-speed operating points and provide a comprehensive view of their performance. The results demonstrate that the three-level inverter outperforms the two-level inverter by reducing both power losses and THD, thereby improving the overall efficiency of EVs. These findings suggest that the three-level inverter is a more sustainable option for EVs.

Keywords-two-level NPC inverter; three-level NPC inverter; EV; PMSM; SVPWM; efficiency maps

I. INTRODUCTION

Internal Combustion Engine (ICE) vehicles greatly contribute to harmful gas emissions and environmental pollution. This makes the transition to Electric Vehicles (EVs) necessary to reduce the emissions [1]. EVs have many features that make them a viable alternative to ICE vehicles. For example, EVs use electrical energy instead of fossil fuels, meaning they do not produce carbon emissions during operation. In addition, EVs are highly energy efficient, more reliable, and require less maintenance due to their simpler mechanical components. However, there are some challenges that prevent EVs from being widely adopted. The biggest challenges are their limited range on a single charge and how long it takes to charge the batteries [2]. Although increasing the size and capacity of the battery seems like a logical way to increase range, it also increases cost, weight, and size, making it impractical. Instead, improving the efficiency of the electric propulsion system, which consists of the motor, inverter, and control system, is a more effective way to increase EV's range

[3, 4]. The inverter converts the electrical energy stored in the battery from Direct Current (DC) to the Alternating Current (AC) required to drive the electric motor [5].

Different inverter topologies can be used in EVs. One commonly used topology is the two-level inverter, which has six groups of switches. However, it has high power losses, especially during high switching, which requires reducing the size and weight of the filtering components in the circuit. This reduces the overall efficiency of the system. In addition, the two-level inverter produces high harmonic distortion in the output voltage due to the significant voltage change during the switching process [6].

Increasing the switching frequency can reduce harmonic distortion and increase the power density of the inverter, which in turn reduces the size of the LC filters [7]. However, increasing the switching frequency in a two-level inverter increases the switching losses and reduces system efficiency. In contrast, multi-level inverters can lower harmonic distortion in the output voltage without increasing the switching frequency or reducing the inverter's output power [8]. They have lower switching losses, even at high switching frequencies, as they use switches with low voltage ratings. Also, multi-level inverters produce lower voltage changes (dV/dt) across the switches. This reduces electrical stress and Electromagnetic Interference (EMI) [9]. These features allow for the use of higher voltage inverters, which increases the efficiency and performance of EVs. There are several multilevel inverter topologies and the most common are the Flying Capacitor (FC), the Cascaded H-Bridge (CHB), and the Neutral Point Clamped (NPC) topology [10].

The FC topology requires many capacitors, which increases the cost, size, and the complexity of the control system needed for voltage balancing. The CHB topology requires multiple isolated power sources, which increases cost and complexity. Therefore, the FC and CHB topologies are not suitable options for EV applications. The NPC topology, on the other hand, is a better option for EVs. It uses fewer components, which reduces the cost and complexity. Additionally, the NPC inverter provides better voltage balancing without requiring a complicated control system [11]. Nevertheless, implementing a three-level NPC inverter still involves additional components and design considerations that can impact the cost and long-term reliability of practical EV applications.

The three different states of current flow associated with the three voltage levels in the inverter are determined by the switching states [12]. Table I presents the relationship between the three switching states and the output voltage of the three-level NPC inverter. In the first state, the upper switches (SG1 and SG2) in leg 1 are on while the lower switches (SG3 and SG4) are off, allowing current to pass from the upper capacitor to the load and producing a positive voltage of $V_{dc}/2$. In the second state, SG1 is off, SG2 is on, SG3 is on, and SG4 is off, allowing current to bypass the capacitors, resulting in a neutral point voltage of 0 V. In the third state, the upper switches SG1 and SG2 are off and the lower switches SG3 and SG4 are on. This allows current to pass from the lower capacitor to the load, producing a negative voltage of $-V_{dc}/2$. Unlike a two-level inverter, a three-level NPC inverter has a lower voltage on each switch.

TABLE I. SWITCHING STATES FOR THREE-LEVEL NPC INVERTER

Switch group status				Output voltage	Switching states
SG1	SG2	SG3	SG4		
ON	ON	OFF	OFF	$V_{dc}/2$	P
OFF	ON	ON	OFF	0	O
OFF	OFF	ON	ON	$-V_{dc}/2$	N

Many studies have been conducted to improve the performance of the inverters in the EVs by improving the efficiency and reducing the power losses. In studies [13-15], it was demonstrated that the three-level NPC inverter provided superior performance compared to two-level inverters in reducing the torque ripple and the harmonic distortion at high switching frequencies. These studies emphasize that the three-level NPC inverters are more suitable for EV applications. Additionally, studies [16-18] have demonstrated that the switching losses in three-level NPC inverters were lower than those in two-level inverters. This increased their efficiency and performance. However, most of these studies have focused on analyzing inverter performance under steady-state conditions. In contrast, this study evaluates the performance under dynamic conditions using Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) drive cycles, offering a more realistic assessment of efficiency and losses. Additionally, this study examines the impact of switching frequency variations on inverter efficiency and power losses.

This paper extends the study to include more complex dynamics by modeling and simulating EVs in a MATLAB/Simulink environment. It also calculates inverter power losses and efficiency using PLECS. The inverters were tested under two different drive cycles, UDDS and HWFET, to simulate a wide range of operating conditions, including high and low torques and speeds. This dynamic analysis provides a more comprehensive view of the inverter's performance under varying conditions. It offers insights into the inverters' efficiency in EV applications. This goes beyond the steady-state focus of previous studies. In addition, the study investigates the effect of switching frequencies on inverter efficiency and Total Harmonic Distortion (THD). A Permanent Magnet Synchronous Machine (PMSM) motor was used due to its small size with high power density [19].

II. MODELLING AND SIMULATION

Unlike many studies that apply constant torque and speed to the EV's motor, this study includes the dynamic forces acting on the vehicle during operation [20]. Specifically, four primary forces affecting the vehicle are considered.

A. Aerodynamic Force

Aerodynamic force is the force that resists the vehicle's motion when it travels against the wind. It is calculated using (1).

$$F_{ad} = \frac{1}{2}\, p.v^2.C_d.A \tag{1}$$

where p is the air density, v is velocity, C_d is the aerodynamic coefficient, and A is the frontal area of the vehicle's body.

B. Rolling Resistance Force

Rolling resistance force is the force that resists the vehicle's motion due to the friction of tires with the road surface. It is calculated using (2).

$$F_{rr} = C_{rr}.m.g.\cos(\theta) \quad (2)$$

where C_{rr} is the rolling resistance coefficient, m is the mass of the vehicle, g is the gravitational acceleration, and θ is the angle of the road's incline.

C. Grade Force

Grade force is the force that resists the vehicle's motion when it climbs a slope or hill. It is calculated using (3).

$$F_{hc} = m.g.\sin(\theta) \quad (3)$$

D. Acceleration Force

Acceleration force is the force that the vehicle must exert to accelerate. This force depends on the mass of the vehicle and the required acceleration. It is calculated using (4).

$$F_A = m.a \quad (4)$$

The total tractive force (F_T) acting on the vehicle is determined by the sum of all forces that resist or assist the motion of the vehicle, as shown in the equation below:

$$F_T = F_{ad} + F_{rr} + F_{hc} + F_A \quad (5)$$

The wheel torque (T_w) required to produce the tractive force at the wheel is determined by (6). Then, the motor power (P_m) required to achieve the motion needed for the vehicle to move at a specific speed can be computed by (7).

$$T_w = \frac{F_T * r_w}{\eta_d} \quad (6)$$

$$P_m = \frac{T_w * \omega_w}{\eta_m} \quad (7)$$

where r_w is the radius of the wheel, η_d is the drivetrain efficiency, ω_w is the angular velocity, and η_m is the motor's efficiency.

To compare the performance of two-level and three-level NPC inverters, the electric propulsion system of an EV, including its body, was modeled, and simulated using MATLAB (Simscape and Simulink) and PLECS. Field-Oriented Control (FOC) and Space Vector Pulse Width Modulation (SVPWM) were employed for control, as shown in the block diagram in Figure 1.

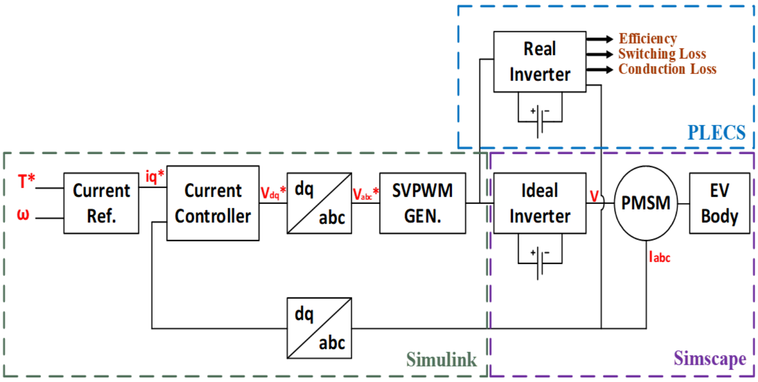


Fig. 1. EV propulsion system with FOC and SVPWM control.

In MATLAB/Simscape, an urban EV is modeled and simulated, with parameters listed in Table II. The total tractive force and the wheel torque were calculated to assess the power requirements for the vehicle to move under UDDS and HWFET drive cycles, respectively. These two drive cycles were selected to ensure that the vehicle operates within different operating regions of high and low speeds and torques, as shown in Figure 2. They are also commonly used as benchmarks for evaluating vehicle performance under urban and highway driving conditions.

TABLE II. EV PARAMETERS

Parameter	Value	Unit
Gross vehicle mass (GVM)	1300	kg
Wheel radius (r_w)	0.293	m
Frontal area (A)	2.459	m^2
Air density (p)	1.225	Kg/m^3
Drag coefficient (C_d)	0.250	-
Gear ratio (GR)	1.583	-

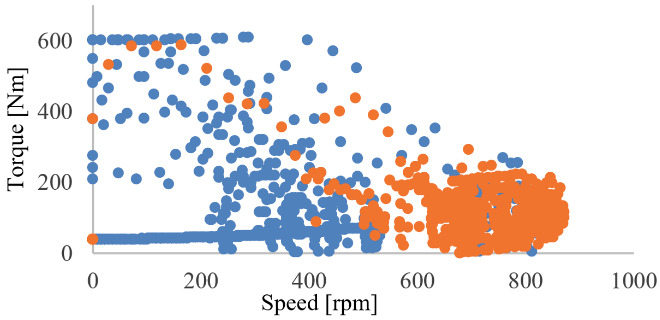


Fig. 2. EV operating points under UDDS and HWFET drive cycles.

A 52 kW PMSM motor with its parameters listed in Table III was modeled and simulated. The motor power was calculated to ensure that the vehicle operates smoothly within the required speed range of the drive cycles. To calculate and compare the power loss, two-level and three-level NPC inverters with a DC link voltage of 400 V were built and simulated in PLECS to calculate the efficiency and the power loss. The two-level inverter was constructed using two IKQ100N120CH7 Insulated Gate Bipolar Transistors (IGBTs) from Infineon in parallel in each switch group. Each IGBT has a blocking voltage of 1200 V and a rated current of 166 A to meet the motor's high current needs. Similarly, the three-level NPC inverter was constructed using two IKQ120N65EH7 IGBTs from Infineon in parallel in each switch group. Each IGBT has a blocking voltage of 650 V and a rated current of 160 A.

SVPWM modulation was used to generate the pulses required to control the inverter switches for both two-level and three-level NPC inverters, as shown in Figure 3. Two drive cycles, UDDS and HWFET, were used with switching frequencies of 10 kHz and 20 kHz. The purpose was to analyze the impact of two-level and three-level NPC inverters on power loss and efficiency across the full speed-torque range. Efficiency and power loss maps were created for the vehicle's speed-torque range, and the effect of increasing the switching frequency on the THD and power loss for both inverters was examined.

TABLE III. PMSM MOTOR PARAMETERS

Parameter	Value	Unit
Output power (P_{out})	52.36	kW
Number of pole pairs (P)	3	-
Stator resistance (R_s)	54	mΩ
L_q and L_q inductances	0.00285	H
Permanent magnet flux linkage (λ_m)	0.86026	Wb

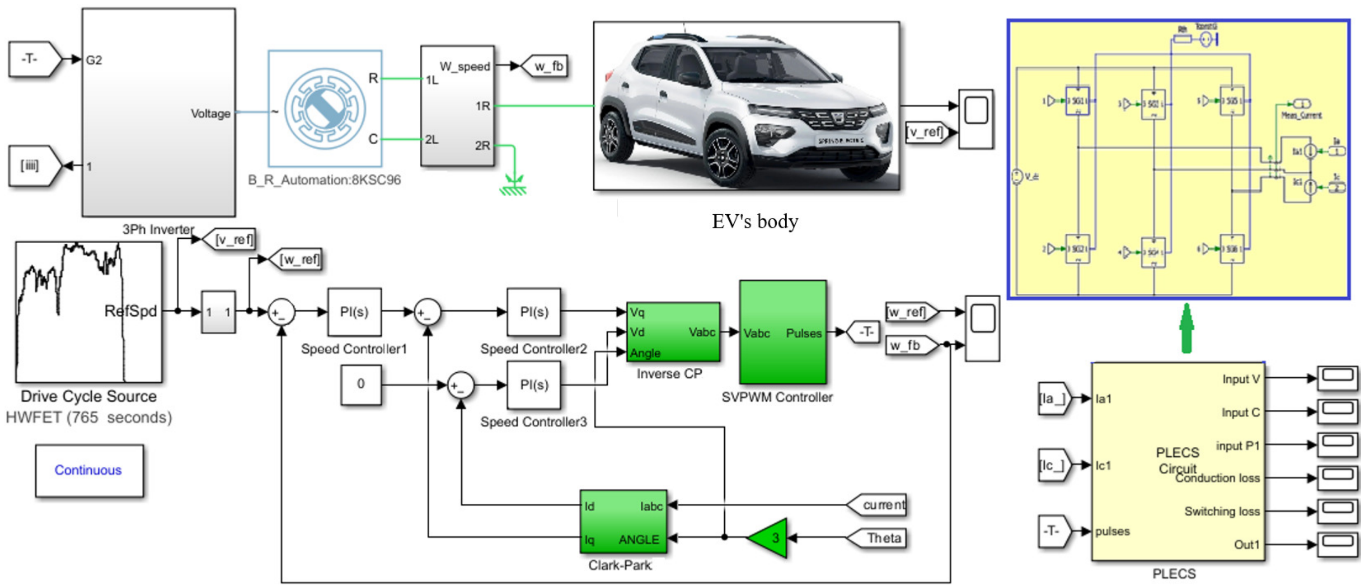


Fig. 3. EV powertrain simulation in MATLAB/Simulink and PLECS.

III. RESULTS AND ANALYSIS

At an operating speed of 450 rpm, a torque of 100 Nm, and a switching frequency of 10 kHz, the switching loss of the two-level inverter was significantly higher than that of the three-level NPC inverter, as illustrated in Figure 4. The switching loss of the two-level inverter was 42 W, whereas for the three-level NPC inverter, it was 11.6 W. However, the conduction loss in the three-level NPC inverter was 58.1 W, higher than that of the two-level inverter which was 51 W. This reflects the trade-off: while three-level inverters reduce switching losses due to lower voltage steps, they introduce higher conduction losses because of the additional switches. The overall efficiency depends on the operating region, where switching losses dominate at high speeds, whereas conduction losses have a more significant impact at low speeds.

However, when the switching frequency increased to 20 kHz, the switching losses in both inverters doubled. Meanwhile, the conduction losses remained constant for both inverters. This confirms the direct relationship between switching frequency and switching losses, emphasizing its impact on overall inverter efficiency. From the results obtained, it can be deduced that the total losses (switching and conduction) are lower for the three-level NPC inverter. This, in turn, renders the three-level inverter more efficient in comparison to the two-level inverter.

Moreover, the FFT analysis showed that the THD in the output voltage at the switching frequency of 10 kHz was 34.89% for the three-level NPC inverter, which is significantly lower than the 79.38% observed in the two-level inverter. This reduction in THD decreases the iron losses in the motor, which in turn increases its efficiency. When the switching frequency was increased to 20 kHz, the three-level NPC inverter achieved a THD of 34.70%, still lower than the 78.27% observed in the two-level inverter. These results demonstrate that increasing the switching frequency reduces THD in both inverters.

Figure 5 illustrates the efficiency maps at a switching frequency of 10 kHz. Figure 5(a) presents the efficiency map for the two-level inverter with efficiencies ranging from 82.4%

to 98.6%, whereas Figure 5(b) presents the efficiency map for the three-level NPC inverter, with efficiencies ranging from 91.1% to 98.7%. The three-level inverter demonstrated higher efficiencies compared to the two-level inverter, especially in the low-speed regions. However, when the switching frequency increased to 20 kHz, a slight reduction in the efficiency was observed in both inverters.

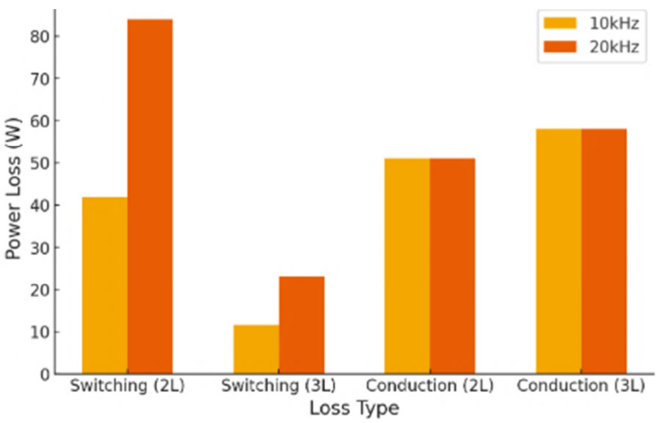
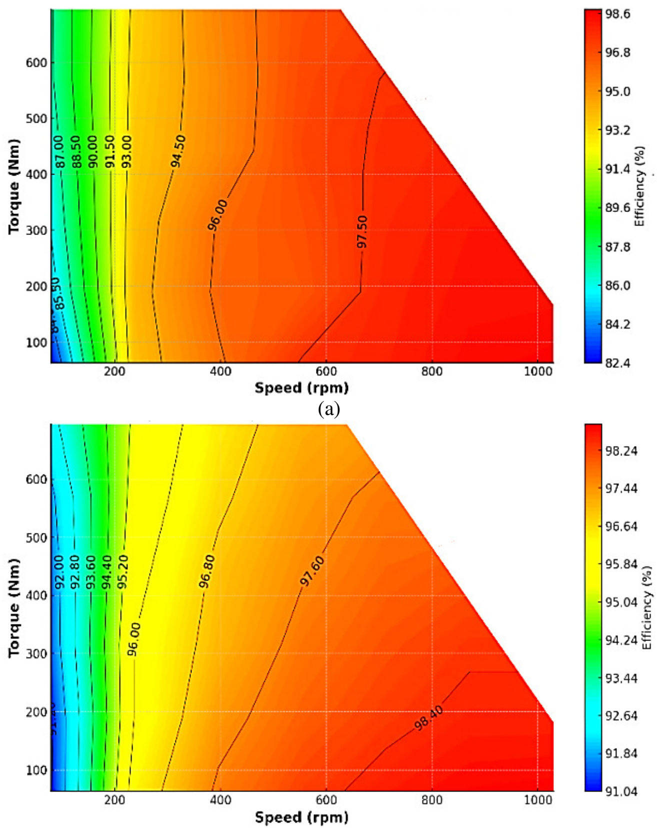


Fig. 4. Power losses in two-level and the three-level inverters at 10 kHz and 20 kHz.

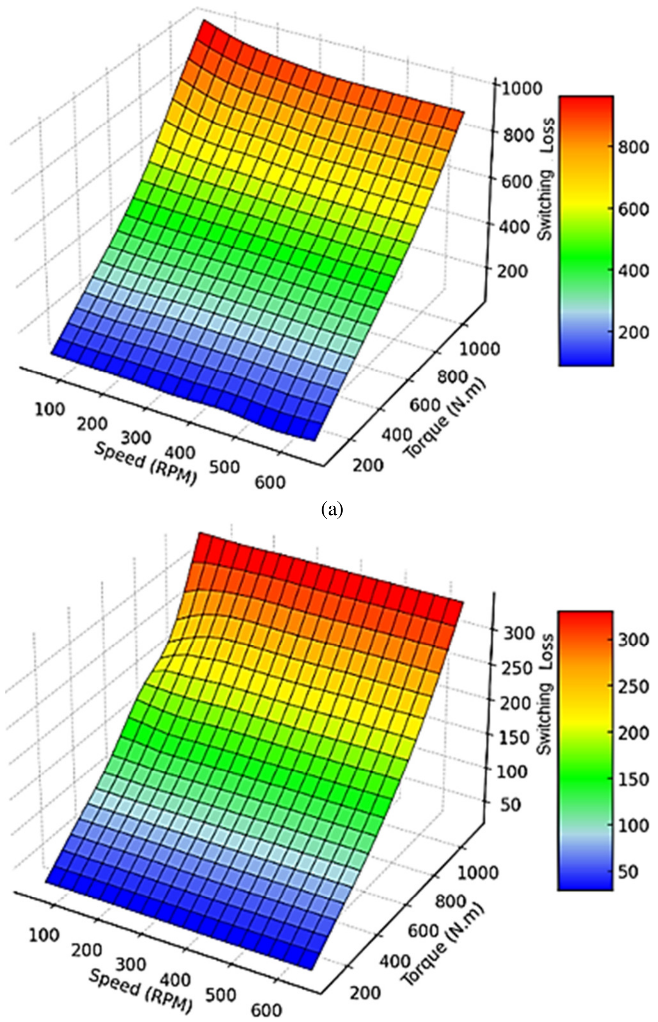


(a)

(b)

Fig. 5. Efficiency maps at 10 kHz switching frequency: (a) two-level NPC inverter, (b) three-level NPC inverter.

Figures 6(a) and 6(b) illustrate the switching losses at a switching frequency of 20 kHz for the two-level and the three-level NPC inverter, respectively. It can be observed that at high speeds, the switching losses of the three-level inverter were lower than those of the two-level inverter. For example, at the operating point with a speed of 600 rpm and torque of 1000 Nm, the switching losses of the three-level NPC inverter were approximately 300 W, whereas the losses for the two-level inverter were higher, approximately 800 W. This confirms that the three-level NPC inverter has considerably lower switching losses compared to the two-level inverter. This reduction is due to the reduced switching stress on the switching devices in the three-level inverter, which produces lower voltage changes dV/dt across the switches.

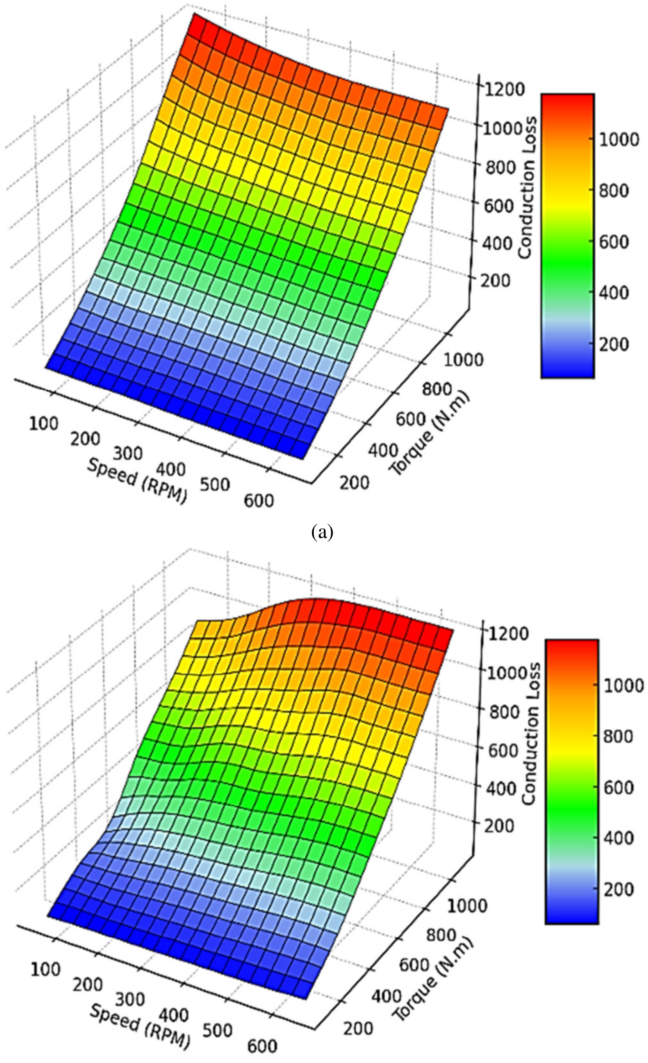


(a)

(b)

Fig. 6. Switching losses at 20 kHz switching frequency: (a) two-level NPC inverter, (b) three-level NPC inverter.

Figures 7(a) and 7(b) illustrate the conduction losses at a switching frequency of 20 kHz for the two-level inverter and the three-level NPC inverter, respectively. It can be observed that at high speeds, especially higher than 400 rpm, the conduction losses of the three-level inverter were higher than those of the two-level inverter. For example, at the operating point with a speed of 600 rpm and torque of 1000 Nm, the conduction losses of the three-level NPC inverter were approximately 1200 W, whereas the losses for the two-level inverter were lower, approximately 1000 W. This finding confirms that the three-level NPC inverter has significantly higher conduction losses compared to the two-level inverter. This is due to the higher number of switching devices in the three-level inverter. Conversely, at lower speeds, the three-level inverter demonstrated lower conduction losses than the two-level inverter. This was due to the three-level inverter's operation as a two-level inverter in this region, but with half of the voltage. This resulted in a substantial decrease in the current passing through the switches, which, in turn, led to a reduction in the conduction losses.



(a)

(b)

Fig. 7. Conduction losses at 20 kHz switching frequency: (a) two-level NPC inverter, (b) three-level NPC inverter.

IV. CONCLUSION

The present study demonstrated that the three-level Neutral Point Clamped (NPC) inverter provides significant improvements in the efficiency of electric drive systems compared to the two-level inverter, making it a suitable option for Electric Vehicle (EV) applications. The results demonstrated that, within the low-speed region and at a constant switching frequency, the three-level inverter achieves efficiencies ranging from 91.1% to 96.8%, whereas the two-level inverter ranges from 82.4% to 96% under the same conditions. Furthermore, at a specific operating point, the three-level inverter reduced switching losses by 72.4%, from 84 W for the two-level inverter to 23.2 W. Additionally, it decreased Total Harmonic Distortion (THD) by 56%, from 78.27 to 34.7%. Unlike previous studies that focused on steady-state analysis, this work examines inverter performance under dynamic conditions, using the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) drive cycles. This provides practical insights into the advantages of three-level inverters in real-world scenarios. While this study is based on simulations, the results provide a solid foundation for future experimental validation to assess real-world applicability. The findings of this study indicate that the three-level inverter is considered an effective option for enhancing the efficiency of EVs and reducing losses, especially at specific operating points, thereby supporting overall system performance and promoting environmental sustainability in EV applications.

ACKNOWLEDGEMENT

The authors would like to thank CSRIEM and CGS, Universiti Teknologi PETRONAS, for their support and guidance.

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