Inverter Loss Calculation and Efficiency Analysis of a PMSM Drive Using PSIM Thermal Modeling

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Abstract: Accurate prediction of inverter losses in Permanent Magnet Synchronous Motor (PMSM) drives is difficult because conduction, switching, and diode recovery behaviors vary significantly with instantaneous current, voltage, and device temperature. Existing analytical methods often rely on fixed semiconductor parameters and averaged current assumptions, which limit their ability to represent dynamic operating conditions in practical electric-drive systems. This work develops a detailed inverter loss and thermal evaluation framework in PSIM 2025.1, combining thermally enabled MOSFET and diode models with nonlinear PMSM characteristics. The approach captures temperature-dependent on-state resistance, voltage–current overlap during switching transitions, and diode reverse-recovery effects while operating under Field-Oriented Control (FOC). The overall inverter losses and efficiency are evaluated across a wide range of torque–speed operating points. Simulation results demonstrate PSIM's capability for practical and accurate inverter loss prediction, offering valuable insights for the design and optimization of PMSM drive systems in electric vehicle and industrial applications.

Keywords: *Inverter Loss, PMSM, Field-Oriented Control (FOC), Thermal Modeling, Switching and Conduction Loss, Inverter Efficiency Analysis, PSIM.*

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I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) are widely used in traction and industrial drives due to their high torque density and efficiency. The inverter driving the PMSM experiences conduction, switching, and reverse-recovery losses, which directly affect thermal stress, reliability and overall drive performance. Analytical loss estimation often relies on fixed device parameters and averaged current assumptions, which limit accuracy under dynamic operating conditions.

Modern simulation tools such as PSIM incorporate temperature-dependent device characteristics and detailed switching behavior, enabling realistic transistor and diode loss estimation. This work investigates inverter losses in a delta-connected PMSM drive by combining PSIM's nonlinear machine model with thermally enabled MOSFET and diode components for accurate device-level loss extraction. The Machine Controller Interface Specification (MCIS), which contains the complete electrical and mechanical parameter set for the PMSM, is used to generate the lookup tables required for realistic electromagnetic torque and nonlinear parameter mapping within the PSIM environment.

The objective is to quantify conduction, switching, diode-recovery, and DC-link losses, track junction temperature over a torque–speed map and compute inverter efficiency. The methodology targets pre-hardware evaluation of component ratings and thermal margins in high-power EV drives.

II. PLANT MODEL DEVELOPMENT IN PSIM

➤ *Software Environment Setup*

The PMSM drive is modelled in PSIM 2025.1. A fixed simulation timestep of 2 μs ensures stable switching behavior at 10 kHz PWM frequency.

➤ *Parameter Identification and Data Import*

PMSM parameters—rated voltage, rated power, maximum current, stator resistance R_s, pole pairs, and rotor inertia J were obtained from MCIS. These values summarized in Table I, initialize the nonlinear PMSM block and ensure that the simulated machine accurately reflects physical characteristics.

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Table 1 Primary Motor Parameters

Parameter	Symbol	Value	Unit
DC bus operating voltage	Vdc	380	V
Switching frequency	Fsw	10000	Hz
Maximum inverter current (Peak)	Is_max	220	A
Pole Pairs	P	3	—
Stator Resistance	*Rs*	0.139875	Ω
Moment of Inertia	*J*	0.00277	kg·m²
Maximum Motor Power	P_max	40000	W
Maximum Motor Speed	nm_max	12000	Rpm
Modulation Index	Vtri	0.95	—

➢ *Non-Linear Delta-Connected PMSM Modeling and Its Limitation with Applied correction*

A nonlinear PMSM model with delta-connected stator windings is implemented to mimic the actual plant under both torque and speed control. The overall nonlinear PMSM model used in this study is shown in Fig. 1.

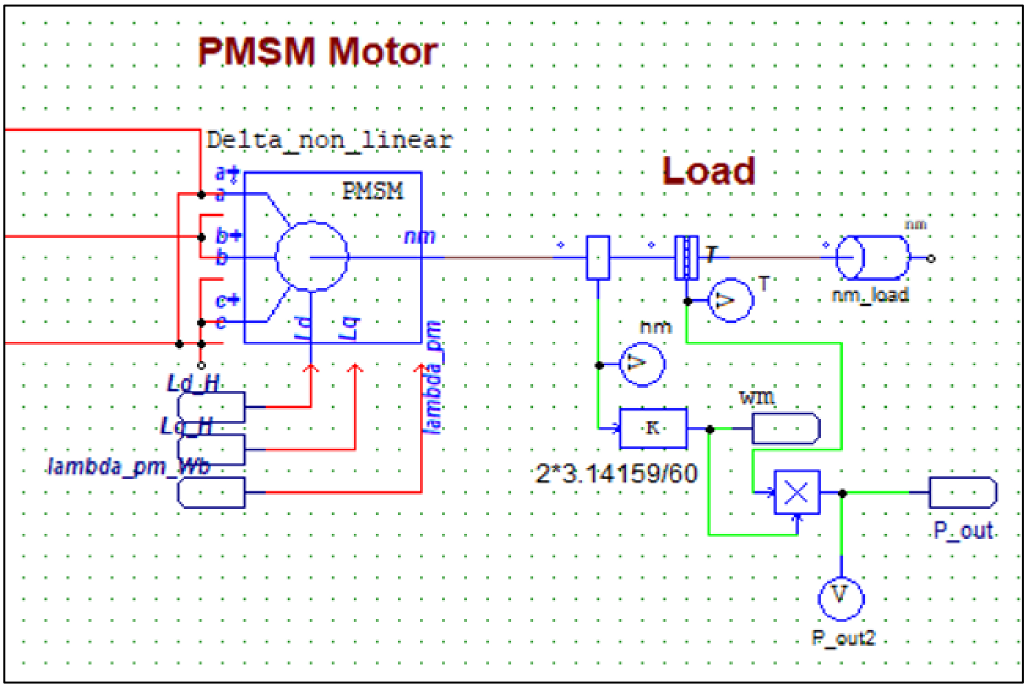

Fig 1 Nonlinear PMSM Model.

PSIM's PMSM block outputs torque without iron losses. To address this limitation, loss-inclusive torque maps generated using an electromagnetic simulation tool were imported into PSIM as a lookup table, as shown in Fig. 2. This corrected torque reference was then used to derive the machine parameter lookup tables.

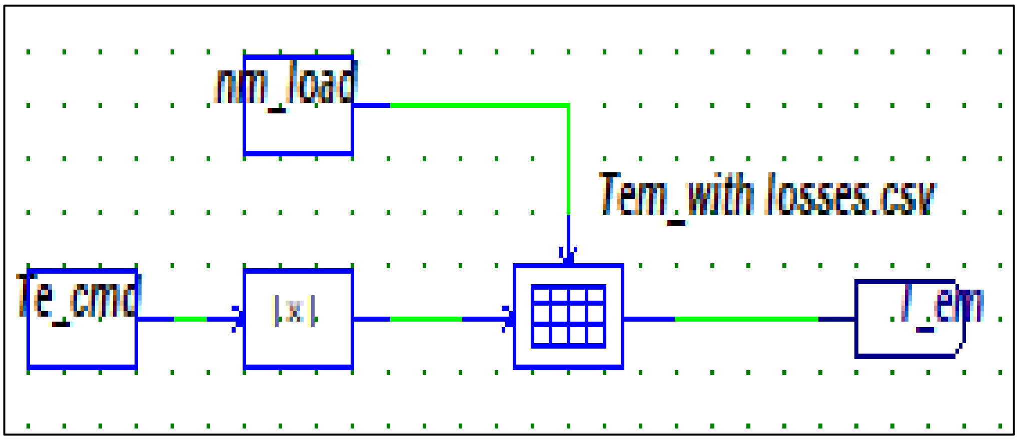

Fig 2 Loss-Adjusted Torque Lookup Table.

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The machine parameters are provided through a nonlinear lookup table to drive the PMSM using loss-adjusted data, as shown in Fig. 3.

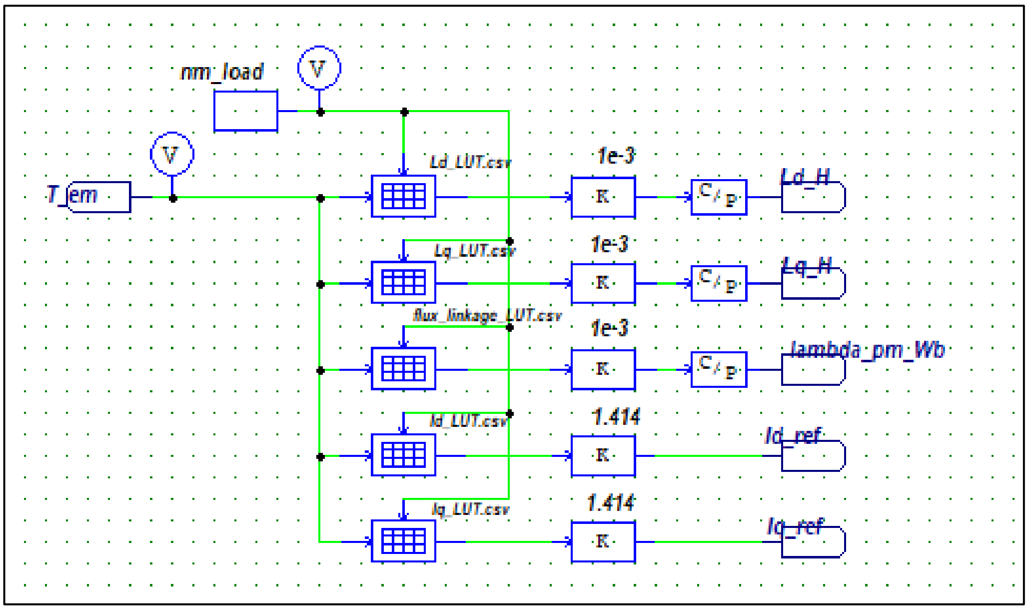

Fig 3 Nonlinear Lookup Tables Used for Loss-Adjusted PMSM Parameter Mapping.

A reduced set of representative operating points is selected to evaluate inverter loss and thermal behavior efficiently. These points, listed in Table II, capture low, medium, and high-speed operating regions. The corresponding PMSM electrical input parameters—Id, Iq, Ld, Lq, and flux linkage—used in the loss model are shown in Fig. 4.

➢ *FOC-Based Control and Modulation*

Field-Oriented Control is used to decouple torque and flux in the PMSM. Line currents from the delta-connected machine are first converted to phase currents, after which Clarke and Park transformations are applied to obtain i_d and i_q. Independent PI regulators control the d- and q-axis currents and generate the dq-voltage references, which are transformed back to three-phase commands using inverse Park and Clarke operations. The implementation of the Park transformation used in the FOC scheme for delta-connected PMSM is illustrated in Fig. 4.

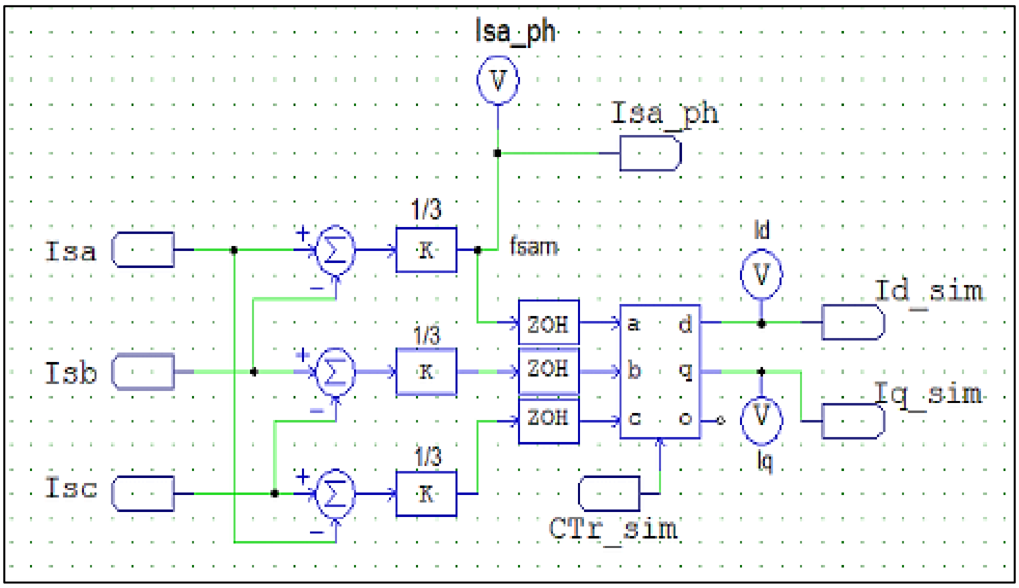

Fig 4 Park Transformation Block for Delta-Connected PMSM.

Space Vector Modulation (SVM) was used to produce PWM signals for the inverter switches, maintaining a carrier frequency of 10 kHz. The current-loop crossover frequency (f_{cr_i}) is tuned such that the normalized voltage command V_{ma} remains within ±1, guaranteeing system controllability and stability under all tested operating points.

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Feedback signals include stator currents, rotor speed, and rotor electrical angle. The electrical angle is used in the dq transformations to maintain alignment with the rotor flux and ensure accurate torque production and stable closed-loop behavior.

Table 2 Selected Torque–Speed Operating Points Used for Inverter Loss and Thermal Evaluation.

Operating Point	1	2	3	4	5	6	7	8	9	10
Speed	1000	2000	3000	4000	5000	6000	7000	8000	10000	12000
Torque Command	72	48	56	72	72	54	20	28	12	8
Electromagnetic Torque	72.42	48.44	56.49	72.58	72.63	54.62	20.54	28.57	12.52	8.51

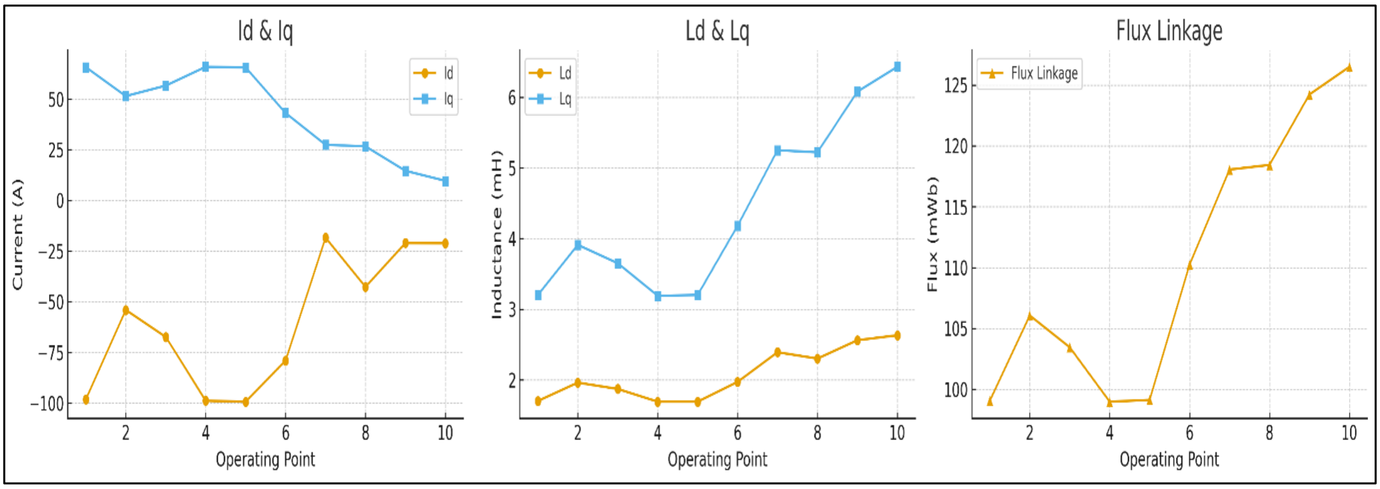

Fig 5 PMSM Input Parameters (Id, Iq, Ld, Lq, and Flux Linkage) Corresponding to the Operating Points Listed in Table II.

III. INVERTER THERMAL MODELING FOR LOSS EXTRACTION

➢ *Semiconductor Device Configuration*

Thermally enabled MOSFETs and diodes model conduction loss via temperature-dependent $R_{DS(on)}(T_j)$ and switching loss via instantaneous voltage–current overlap. DC-link ESR is included to capture capacitor heating and ripple-related losses. The Detailed schematic of the inverter model including DC-bus, thermal-enabled switches, and measurement blocks is shown in Fig. 6.

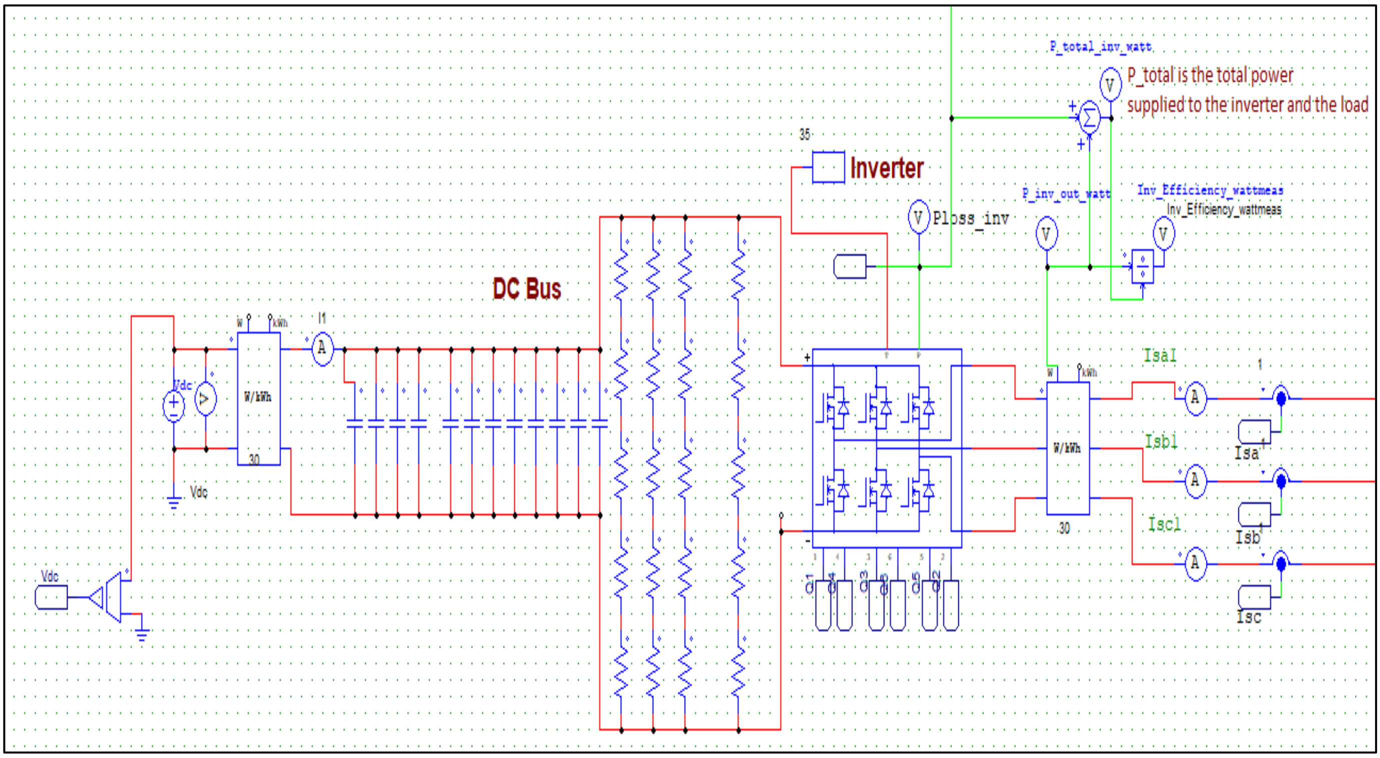

Fig 6 Detailed Schematic of the Inverter Model

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The MOSFET used in this study is the E4M0015075J2, selected to meet requirements on voltage rating (>1.2× DC-link voltage), continuous drain-current capability (greater than peak PMSM phase current), and sufficient thermal margin. Four MOSFETs are paralleled per switch to achieve the required current capability. Key device parameters are listed in Table III.

Table 3 Key Mosfet Parameters

Parameter	**Symbol**	**Value**	**Unit**
Parallel MOSFETs per Switch	N_{par}	4	—
Gate Drive Voltage (High)	V_{GG^+}	15	V
Gate Resistance (Turn-On)	$Rg_{(on)}$	15.5	Ω
Gate Resistance (Turn-Off)	$Rg_{(off)}$	15.5	Ω
Initial Junction Temperature	Tj_{init}	35	°C
Safe Junction Temperature Limit	Tj_{safe}	175	°C
Ambient Temperature	T_{amb}	35	°C
Drain–Source Voltage Rating	$V_{DS(max)}$	750	V
Continuous Drain Current	$I_{D(max)}$	156	A
On-State Resistance	$R_{DS(on)}$	2.1	mΩ
Temperature coefficient	K_T	0.0025	—
Gate Threshold Voltage	$V_{GS(th)}$	2.6	V
Transconductance	g_{fs}	42	S
Total Gate Charge	Q_g	180	nC
Reverse Recovery Charge	Q_{rr}	0.496	uC
Input Capacitance	C_{iss}	5128	pF
Junction-to-Case Thermal Resistance	$R_{\theta JC}$	0.26	°C/W

The electrical characteristics of MOSFET and Diode and thermal characteristics are embedded into PSIM's PCD device files for dynamic temperature computation as shown in Fig. 7.

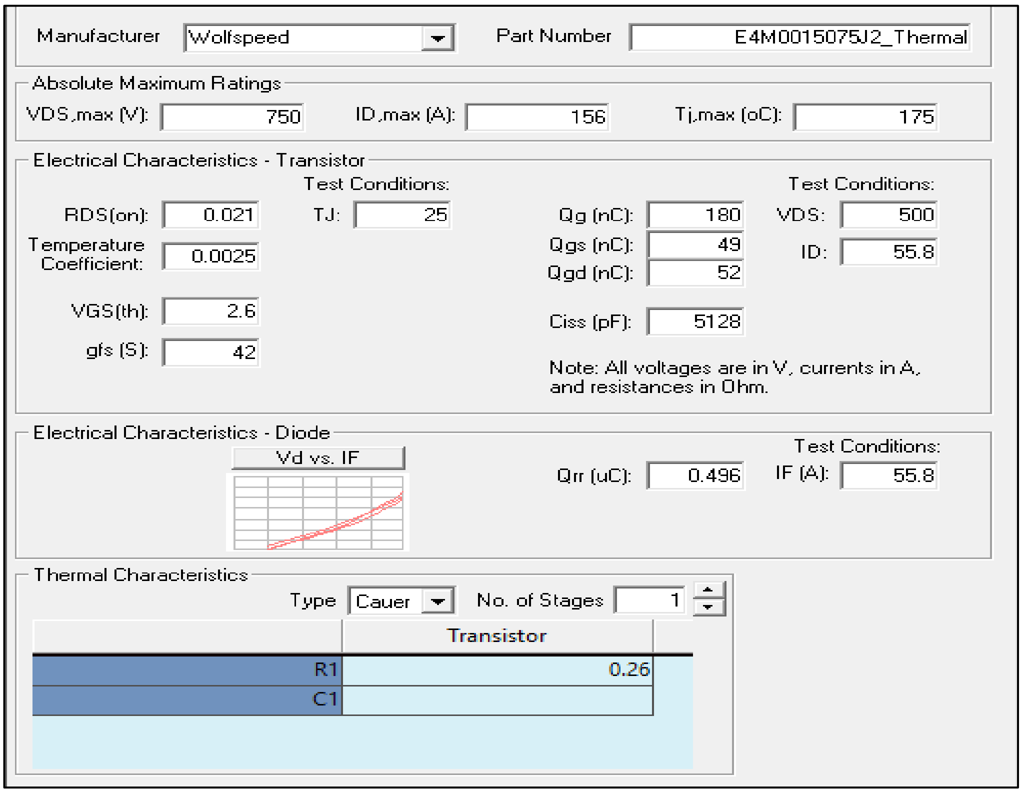

Fig 7 PCD Editor Setup for MOSFET Electrical and Thermal Parameters.

➢ *Diode Characteristics*

Temperature-dependent diode forward curves are imported to model conduction and reverse-recovery losses accurately in the PCD editor. The diode forward characteristics are presented in Fig. 8.

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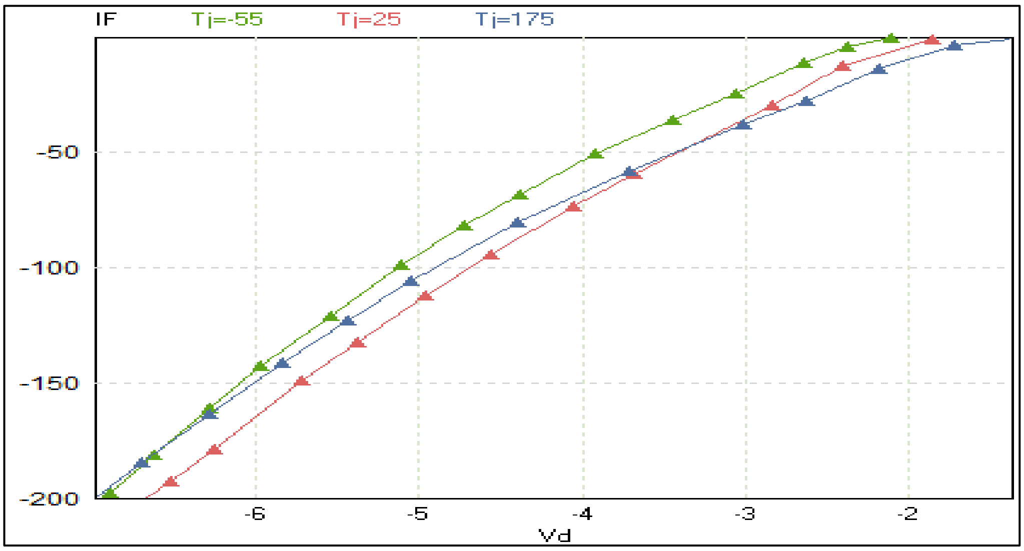

Fig 8 Diode Vd-IF Curve.

IV. SIMULATION AND RESULTS

➢ *Operation Point Sweeping*

The complete inverter–PMSM system is simulated under FOC using the model shown in Fig. 9. Torque–speed operating points are selected over a range of 0–72 N·m and 1000–12000 rpm. At each operating point, torque or speed commands are applied, and the system is simulated until electrical variables (torque, stator currents, and speed) reach steady state.

➢ *Thermal Stabilization and Waveform Capture*

For each operating point, the system is run until the thermal model converges such that the MOSFET junction temperature reaches steady state. Thermal convergence is essential because conduction loss depends on temperature-dependent $R_{DS(on)}(T_j)$, and switching loss increases with device temperature. A steady-state detection block monitors the dq-axis currents and total inverter loss. When their variation remains below a predefined threshold for a fixed duration, the system is considered thermally settled. A window of 3–5 electrical cycles is then used to compute average conduction, switching, and diode losses to eliminate transient effects.

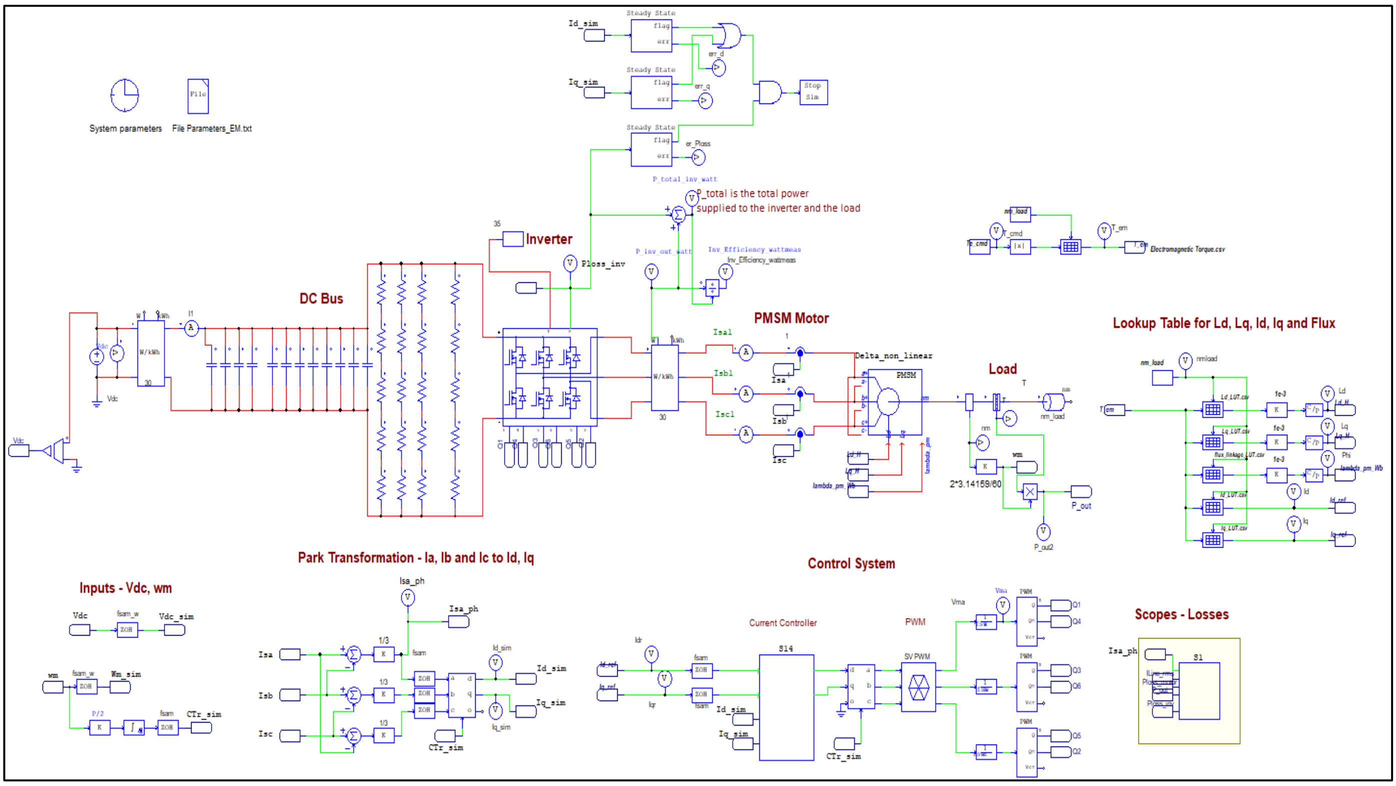

Fig 9 Plant Model of PMSM for Inverter Analysis.

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➢ *Device-Level Loss Extraction*

PSIM's semiconductor thermal probes compute switching energy by integrating the instantaneous device voltage and current waveforms. Conduction losses are evaluated using the temperature-dependent on-state resistance $R_{\mathrm{DS(on)}}$, while diode reverse-recovery losses are modeled using the intrinsic diode characteristics and stored charge Q_{rr}. The total inverter loss is obtained by summing the individual contributions from switch conduction loss, switching loss, diode recovery loss, and diode forward-conduction loss. These calculated losses form the basis for the thermal evaluation and efficiency trends.

➢ *Inverter Efficiency Calculation*

Inverter efficiency is computed using the wattmeter-measured output power and the sum of output power and inverter losses, with DC-bus losses included in the calculation.

V. DISCUSSIONS

Representative steady-state waveforms of switch-level losses (one switch consisting of four MOSFETs in parallel), total inverter loss, efficiency, and MOSFET junction temperature for the operating point of 72 N·m and 5000 rpm are shown in Fig. 10. These confirm stable FOC operation, accurate torque tracking, and smooth sinusoidal phase currents with SVM-based PWM.

The detailed inverter loss and thermal performance at representative operating points are illustrated in Fig. 11. These operating points span the full speed–torque envelope, including continuous-power, peak-torque, peak-power, and partial-load regions, enabling a comprehensive assessment of semiconductor loss distribution and thermal behavior. The bar-chart visualization provides a clearer comparison of conduction loss, switching loss, total switching loss, inverter loss, junction temperature, and efficiency across all operating points, eliminating the need for a large numerical table.

The results follow expected trends: conduction losses dominate at low speed and high torque due to higher RMS current, while switching losses become more significant at high speed and moderate torque as electrical frequency and switching activity increase. Junction temperature rises with total loss until thermal equilibrium is reached.

In all simulated points, peak junction temperature stays well below the 175 °C device limit, confirming adequate thermal margin with the selected device and cooling assumptions.

The nonlinear PMSM lookup tables improve torque prediction by using loss-inclusive torque data, so the electromagnetic torque calculated in PSIM closely matches the shaft torque predicted by electromagnetic simulation tool. This enhances the fidelity of the loss and efficiency maps, particularly in regions where iron and stray losses are non-negligible.

Analytical conduction-loss models often assume constant current and worst-case $R_{DS(on)}$, leading to conservative but less accurate results. Analytical switching-loss models usually use fixed rise/fall times and average current per switching event. In contrast, PSIM evaluates losses using real device waveforms at each switching instant and updates semiconductor characteristics with junction temperature, leading to more realistic and physics-consistent loss predictions across the full operating envelope.

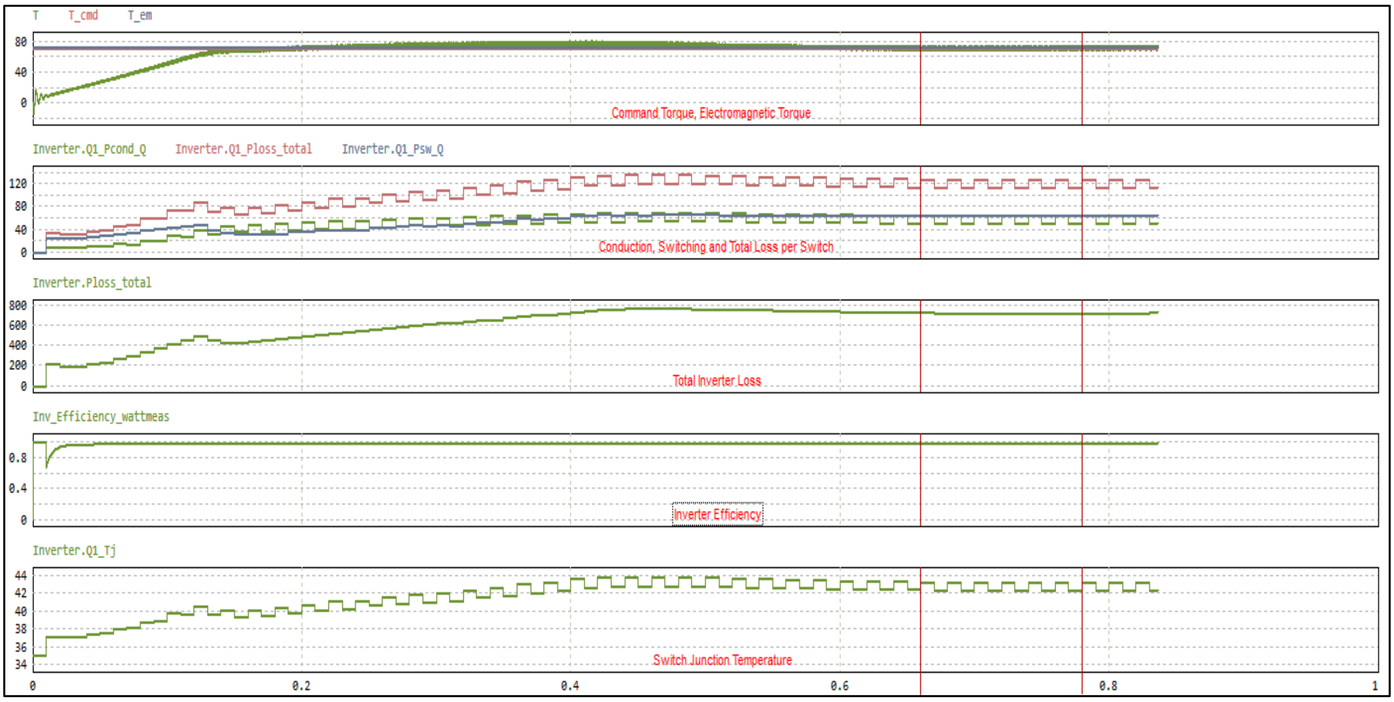

Fig 10 Torque Response, Switch-Level Losses, Total Inverter Loss, Inverter Efficiency, and MOSFET Junction Temperature at the 72 Nm, 5000 Rpm Operating Point.

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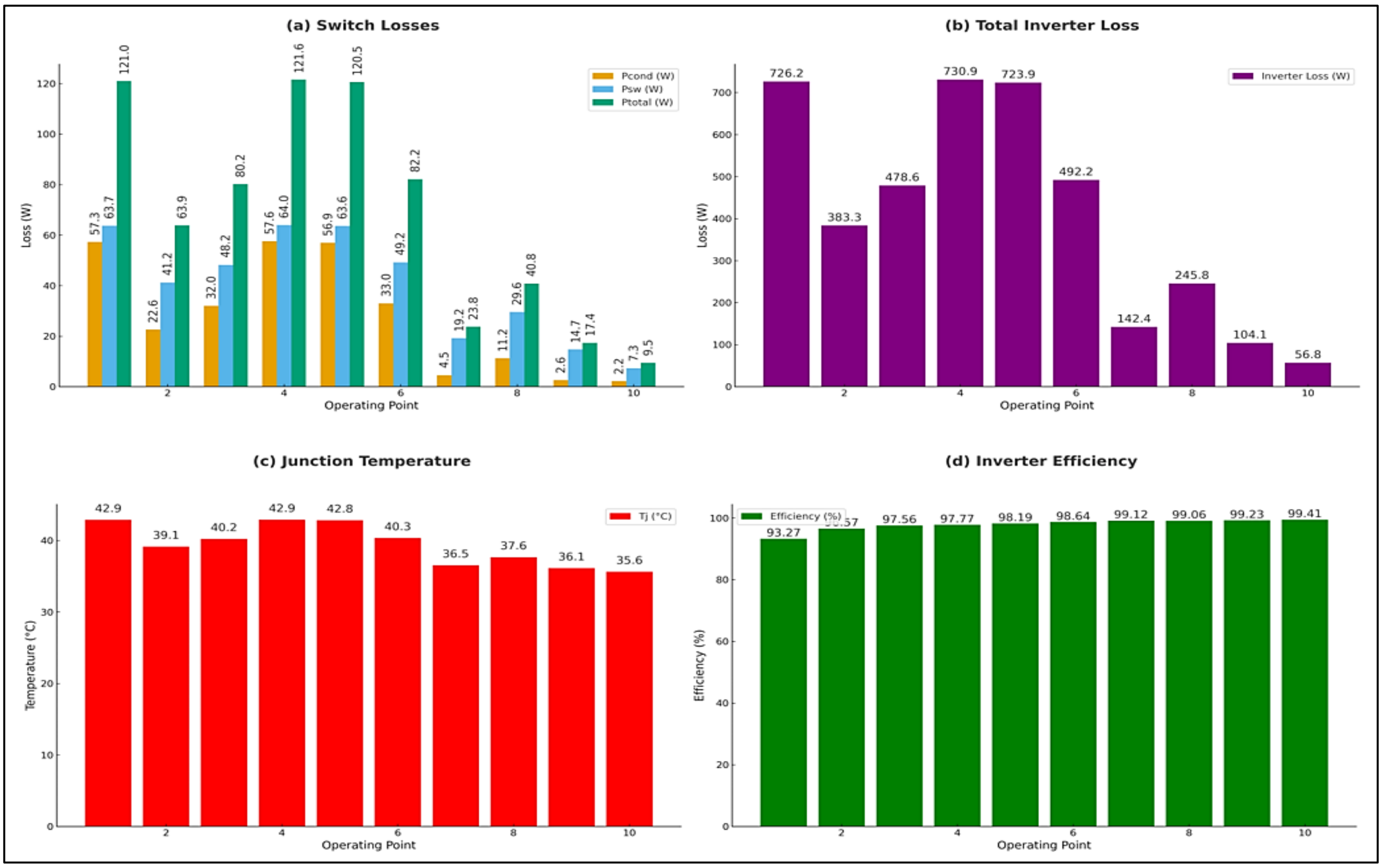

Fig 11 Summary of Inverter Losses, Thermal Behavior, and Efficiency at Selected Operating Points, Showing (a) Switch Conduction, Switching, and Total Losses, (b) Total Inverter Loss, (c) Device Junction Temperatures, and (d) Inverter Efficiency. These Points Span Continuous-Power, Peak-Torque, Peak-Power, and Other Practical Load Conditions.

VI. CONCLUSION

This work presented a comprehensive inverter loss and thermal analysis for a delta-connected PMSM drive using PSIM's nonlinear machine model and thermally enabled semiconductor devices. The integration of MCIS-derived lookup tables ensured accurate machine behavior representation, while the inclusion of temperature-dependent MOSFET and diode models enabled precise estimation of conduction, switching, and reverse-recovery losses. Across the evaluated torque–speed range, the inverter achieved an efficiency above 92%, with peak junction temperatures remaining well within the 175°C safe operating limit, demonstrating the robustness of the selected device set and thermal design.

The generated device-level loss profiles can directly serve as heat-source inputs for CFD-based heatsink and cooling-system design, reducing prototype iterations and improving system reliability. Because the PSIM-based methodology captures dynamic loading, temperature dependence, and instantaneous switching behavior, it offers substantial advantages over purely analytical approaches for pre-hardware inverter design and optimization.

Overall, the developed simulation methodology serves as a powerful pre-hardware evaluation tool, supporting inverter design validation, reducing prototype iterations, and improving system reliability.

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