Optimization and Development of a 48V Cooling Fan System with Direct Control Strategy Based on TMD Controller

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The automotive industry is undergoing rapid transformation driven by three major trends: electrification, intelligence, and weight reduction. The proliferation of electric and hybrid vehicles has significantly increased electrical component count and power consumption, exposing critical limitations of the conventional 12V electrical system. The 12V system, despite decades of use as the automotive industry standard, exhibits fundamental structural constraints that hinder high-power load management and overall system efficiency.

The 48V power system directly addresses these constraints by providing four times the voltage, enabling identical power transmission at 25% of the current magnitude. This voltage increase reduces resistive I^2R losses, decreases wiring cross-sectional area and weight, and enables motor miniaturization and high-speed operation with precise control. For high-power loads such as cooling fans, 48V systems offer substantial efficiency improvements.

This paper proposes design optimization methods for 48V cooling fan motors converting from 12V systems. Motor design optimization involved systematic evaluation of multiple design factors. The 10-pole 12-slot pole-slot configuration provided higher winding factor, superior efficiency, and minimal torque ripple, and was selected as the industry-standard configuration. Winding design optimization established fill factor constraints not exceeding 30 percent to ensure thermal management and insulation reliability while balancing winding wire diameter and turn count. The cost-effective 9BD permanent magnet grade was selected for practical implementation.

Motor specifications were synthesized from design analyses, with nine specifications evaluated including one existing 12V production motor baseline and eight proposed 48V designs with varying fill factors and dimensions. The 48V designs achieved torque density (TRV) of 1.8 to 2.6 times the 12V baseline, indicating superior torque density and efficiency potential. The optimized 48V #4 specification was selected for prototype fabrication. Compared to the baseline 12V system, the optimized 48V design achieved efficiency improvement from 81% to 85% (4 percentage points), weight reduction of 300g, and axial length reduction of 10mm. Power consumption decreased 48W at rated operation, translating to 1.2-1.44% potential fuel economy improvement for mid-size electric vehicles.

Vehicle electrical architectures are simultaneously evolving toward distributed zonal architectures. The Thermal Management Driver (TMD) is proposed as a sub-zonal controller managing all thermal subsystem components including cooling fan, electric water pump, proportional valves, and sensors. Since TMD controllers and cooling fan motors are supplied by different manufacturers, standardized parameter-based control integration is required.

Direct motor control via TMD requires comprehensive motor parameter characterization. Twenty parameters were identified across three categories: electrical parameters including input power, output power, rated voltage and current, phase resistance and inductance, back-EMF constant, and torque constant; mechanical parameters including rotational speed, torque, cogging torque, rotor moment of inertia, load moment of inertia, and winding allowable temperature; and performance and design parameters including efficiency, torque ripple, motor type, and pole-slot configuration.

Three representative BLDC control methods were compared: Trapezoidal control, Sinusoidal control, and Field-Oriented Control (FOC). FOC provides precise control with minimal torque ripple and highest efficiency. FOC's parameter-based architecture enables rapid integration of different motor designs from multiple suppliers through configuration rather than firmware redesign. Despite higher implementation complexity, FOC was selected for technical maturity and multi-supplier integration flexibility.

A 48V cooling fan motor prototype was fabricated according to final design specifications with three-phase windings only, with the control section removed. A TMD controller prototype was developed to enable direct cooling fan control. Evaluation was performed at rated voltage of 48V up to maximum rotation speed, confirming normal operation and validating the control approach.

This research successfully demonstrates 48V cooling fan motor optimization and direct control via TMD controller. Motor design optimization achieved 4% efficiency improvement, 300g weight reduction, and 10mm axial length reduction. FOC-based direct motor control was implemented and validated through TMD controller integration with comprehensive parameter characterization. Implementation in Software Defined Vehicle (SDV) platforms is planned, expected to deliver measurable fuel economy and thermal management improvements.