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Cyclical TRIZ for brushless direct current motor evolution: From short-term adjustments to long-term transformation

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Abstract

As engineering systems accumulate increasing layers of functional, structural, and behavioral complexity, the ability to guide their evolution with coherent, theory-driven frameworks has become essential. This paper presents a cyclical theory of inventive problem solving (TRIZ)-based roadmap for the evolution of brushless direct current (BLDC) motors, guiding development from short-term corrective actions to long-term transformative strategies. The approach structures action into three coupled cycles that respectively prioritize rapid technical remedies, system-level contradiction resolution, and strategic system transition, enabling engineers to align interventions with the maturity and scope of each design challenge. It fuses core TRIZ instruments with the trends of engineering system evolution to couple contradiction handling with forward trajectories of system ideality. Applied to automotive BLDC applications, the method organizes recurrent issues such as acoustic anomalies, modal coupling, thermal stress, and control-layout interactions into an actionable roadmap that scales from quick design adjustments to modular, artificial intelligence-enabled capabilities. Experimental validation confirms the method's practical impact: acoustic noise in the H24 configuration decreased by approximately 13%, modal vibration in the H8 case reduced by nearly 28%, and rotational imbalance amplitude in the rotor–yoke assembly dropped by around 55% after structural and dynamic optimization. The resulting framework is both prescriptive and extensible, guiding short-term fixes without foreclosing mid-term harmonization or long-term transformation, and generalizes to electromechanical product families that must balance cost, noise, durability, and intelligence under evolving requirements.

Keywords: Brushless Direct Current Motors, Cyclical Theory of Inventive Problem Solving, Roadmapping, Trends of Engineering System Evolution

1. Introduction

Brushless direct current (BLDC) motors have become a standard choice for automotive heating, ventilation, and air conditioning (HVAC) applications due to their compact size, energy efficiency, and low acoustic output (Mohanraj et al., 2022; Shao, 2006). Over successive product generations, manufacturers have enhanced these motors to satisfy increasingly stringent cost, noise, and safety targets. Nevertheless, persistent technical challenges remain, including tonal noise, vibration, thermal stress, and printed circuit board assembly (PCBa) fatigue (Singh, 2024). These issues frequently co-occur, and their interdependencies make them resistant to resolution through isolated, short-term fixes.

To address such recurrent and multifaceted problems, this study applies the cyclical theory of inventive problem solving (TRIZ) framework (Altun, 2025), a methodology inspired by the Mayan calendar's cyclical view of time. The framework organizes innovation efforts into three interlinked cycles (as illustrated in Fig. 1): Tzolk'in (short-term), focused on rapid technical corrections; Haab (mid-term), aimed at resolving deeper system-level contradictions; and Long Count (long-term), dedicated to strategic transformation and future-proofing.

This structure integrates classical TRIZ instruments (Altshuller, 1984; Altshuller, 1996; Sheu & Lee, 2011; Sheu et al., 2020) with Trends

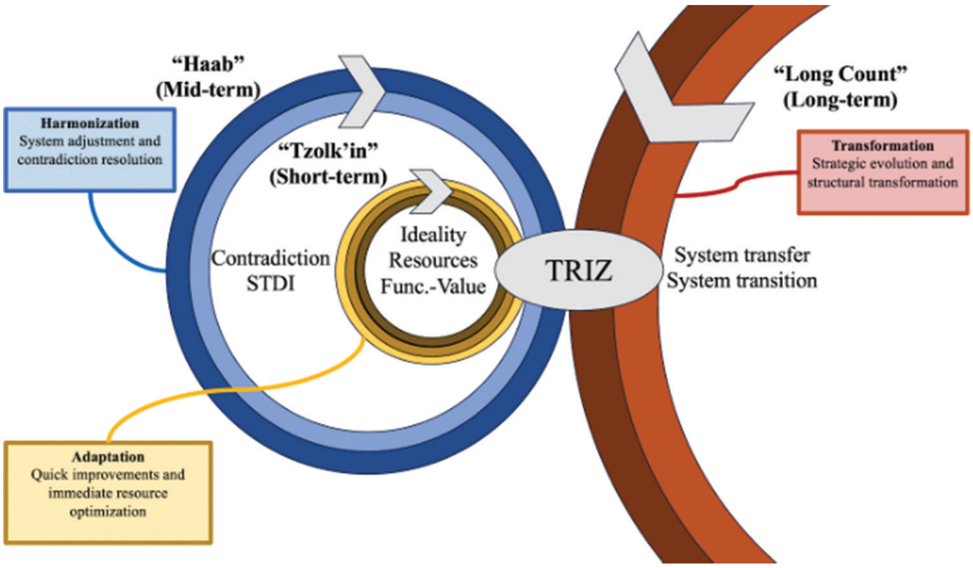

Fig. 1. An overview of the Mayan calendar inspired cyclical TRIZ. Reprinted from Altun (2025)
Abbreviations: Func.: Functionality; STDI: Space, time, domain, and interface; TRIZ: Theory of Inventive Problem Solving

of Engineering System Evolution (TESE) (Ghane et al., 2022; Sheu & Chiu, 2017) to form a roadmap that links present design adjustments with long-term technological trajectories.

Short-term interventions remain essential for keeping products competitive, especially in the automotive industry, as highlighted by Cakmak et al. (2021). However, addressing only immediate symptoms often fails to eliminate the root causes. For example, modifying a component's geometry may temporarily reduce noise, but without resolving underlying resonance issues, similar problems may reappear in subsequent generations. On the other hand, long-term innovation requires anticipating changes in both technology and user requirements, such as the need for enhanced cooling strategies when future BLDC designs demand higher power densities.

The cyclical TRIZ model provides a structured and repeatable process for aligning solution strategies with appropriate time horizons. Incremental modifications are assigned to the short-term cycle, systemic redesigns to the mid-term, and transformative innovations to the long-term. Importantly, each cycle builds upon the lessons of the previous one, enabling cumulative learning and guided product evolution rather than reactive troubleshooting.

In this work, the cyclical TRIZ model is applied to the evolution of automotive BLDC motors. Using empirical performance data and historical design modifications, we demonstrate how technical challenges can be mapped to the three innovation cycles, creating a forward-looking roadmap, a TRIZ-aided augmented technology roadmap (Altun & Babayev, 2023), for sustainable product development.

The remainder of the paper is organized as follows: Section 2 reviews the functional architecture and evolutionary trends of BLDC motors. Section 3 outlines persistent performance challenges. Section 4 presents the application of cyclical TRIZ to map these challenges across short-, mid-, and long-term innovation cycles. Section 5 discusses the practical implications for engineering problem-solving. Finally, Section 6 concludes with reflections on the method's role in supporting sustainable and strategically aligned innovation.

2. Functional Evolution of BLDC Motors

Brushless DC motors transform electrical input into rotational motion through electronic commutation, eliminating the need for mechanical brushes. In automotive HVAC applications (Ganesan et al., 2018; D.W. Lee, 2014; D.H. Lee, 2024; Ravineala et al., 2025), they primarily drive blower fans for heating, cooling, and ventilation. Their compact form factor, high energy efficiency, precise speed regulation, and extended operational life make them an industry standard for climate control systems.

A conventional BLDC motor comprises three primary subsystems: a stator with copper windings; a rotor containing permanent magnets; and a PCBa responsible for control, commutation, and feedback functions. They are complemented by auxiliary components (e.g., heat sinks, motor brackets, and fan wheels), which together form the complete electromechanical assembly (Fig. 2).

Design improvements have been implemented across several product generations (Gen 1, Gen 2, & Gen 3), with each iteration targeting specific performance objectives, including acoustic optimization, thermal management, structural robustness, and the integration of intelligent control features. Evolutionary changes are illustrated in Table 1, where successive redesigns demonstrate weight optimization for rotational balance, rotor–yoke reconfigurations to mitigate modal resonance, and PCBa layouts engineered for improved thermal dissipation and mechanical stress tolerance.

These generational transitions (Fig. 3) correspond to established trajectories described in TESE (Ghane et al., 2022), where technical systems advance by minimizing structural complexity, enhancing multifunctionality, and embedding adaptive intelligence.

3. Current Challenges in BLDC Motors

Despite successive design improvements, BLDC motors used in automotive HVAC systems continue to exhibit a set of recurring technical issues. These unresolved problems affect acoustic performance, mechanical stability, and long-term durability. The most critical cases identified in our analysis are summarized as follows:

Fig. 2. A typical brushless direct current motor and its main components
Abbreviation: PCBa: Printed circuit board assembly

Table 1. Brushless direct current motor generations

Component	Gen 1 (MEB)	Gen 2 (MRA2)	Gen 3 (BBG light)	Key improvement
Motor holder	123 g, basic structure, high modal transmission	121.86 g, minor rib optimization	114.69 g, redesigned structure, weight-optimized	7% lighter and structurally stiffened, improved modal isolation
Deflector	73.21 g, standard thickness	73.21 g, no structural change	53.6 g, reduced material, optimized ribs	27% mass reduction with maintained rigidity
Heatsink	139.77 g, large and imbalanced base	139.77 g, improved centering	116.02 g, minimized geometry, improved modal frequency	17% lighter and approximately 15% higher modal frequency
Magnet	Grade 7, 21.5 mm height	Grade 7, unchanged	Grade 9, 19.5 mm, better alignment, improved NHV	Higher magnetic grade and approximately 9% acoustic noise reduction
PCBa	Classical layout, strain due to thermal and torque	Redesigned layout, fixed screw torque	InRush layout, thermally robust, compact design	Improved thermal stability and lower mechanical stress

Abbreviations: BBG: Balanced brushless generation; MEB: Main engine bracket; MRA2: Motor revision architecture 2; NHV: Noise, harshness, and vibration; PCBa: Printed circuit board assembly.

- H24 acoustic anomaly: Detected between 1,200 and 1,500 rpm (Fig. 4), this phenomenon arises from structural resonance between the heatsink and the plastic cover. The resulting tonal noise occurs without noticeable vibration, which prevents detection by conventional end-of-line vibration sensors. Root cause analysis identified the natural frequency of the cover as the source of a hidden failure mode that standard monitoring cannot detect. Additional modal testing confirmed a peak response around 1,360 rpm, corresponding to the cover's first bending mode. The implementation of a decoupled interface and local stiffness optimization shifted the resonance to 1,460 rpm, reducing the acoustic peak from 29.7 to 25.9 dB(A). In TRIZ terms, this represents a contradiction between functional performance (mechanical operation remains nominal) and measurement capability (acoustic discomfort remains undetected)

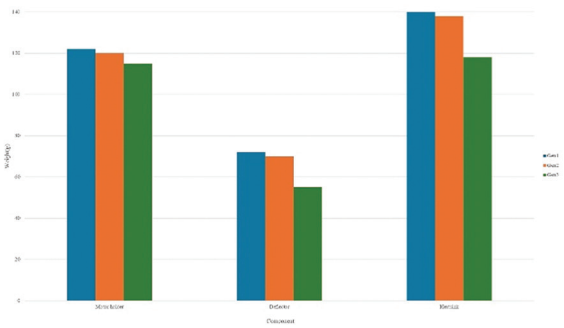

Fig. 3. Component weight comparison across generations

- H8 modal coupling: Observed at resonance frequencies near 266 Hz and 320 Hz (Fig. 5), this issue occurs when the rotor–yoke and fan wheel exhibit overlapping natural frequencies, resulting in structural mode coupling. The modal alignment amplifies the vibratory and acoustic response, as confirmed by hammer test frequency response functions and run-up order analysis. In the not okay configuration, a tonal peak of 31.6 dB(A) was detected around 1,970 rpm, corresponding to the coupled bending modes of the rotor–yoke and fan wheel. After the design modification, which introduced frequency separation and local stiffness optimization, the resonance shifted to 1,360 rpm, and the acoustic amplitude decreased to 23.1 dB(A). In TRIZ terms, this represents a contradiction in the space–frequency domain, resolved through the application of TRIZ's separation and local quality principles. According to TESE trends, the improvement aligns with harmonization and structural adaptation, enabling controlled

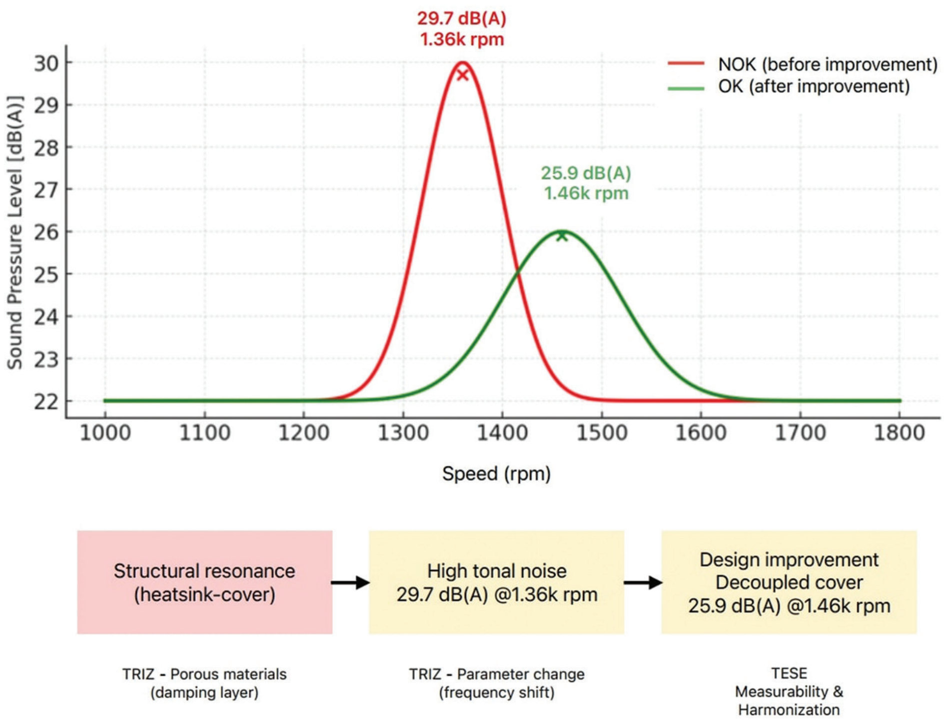

Fig. 4. Acoustic anomaly mitigation diagram (H24) observed at 1,200–1,500 rpm under free-run test conditions (fast Fourier transform-based noise analysis)
Abbreviations: NOK: Not okay; OK: Okay

modal decoupling and reduced vibratory amplification

- Rotor–yoke mass imbalance: Arising from asymmetric mass distribution between the rotor and yoke (Fig. 6), this defect generates an unbalanced centrifugal force during rotation, leading to a first-order (1×) vibration component.

The induced dynamic imbalance amplifies the modal response of the rotor–stator assembly, becoming especially pronounced under transient acceleration conditions. Vibration analysis confirmed a dominant synchronous peak, indicating mass–moment asymmetry rather than magnetic excitation. From a TRIZ perspective, this represents a hidden resource utilization problem, where the inertial distribution of rotating parts can be re-engineered through two-plane trim balancing and mass redistribution to restore dynamic balance.

This approach reflects TRIZ's pre-action and parameter change principles, aligning with the TESE trends of measurability and closed-loop control, to ensure sustained rotational stability and vibration reduction.

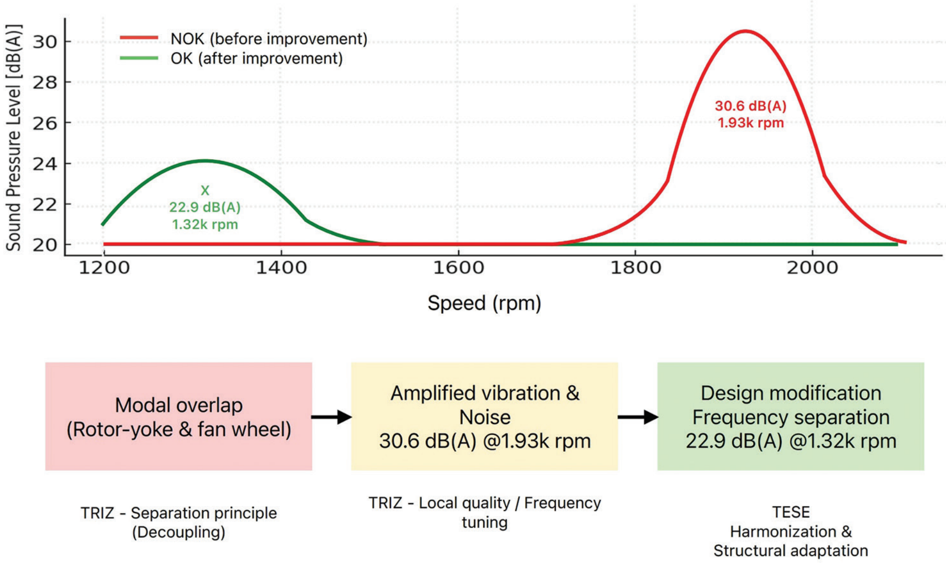

Fig. 5. Modal coupling mitigation diagram (H8) observed through hammer test at 266–320 Hz
Abbreviations: NOK: Not okay; OK: Okay

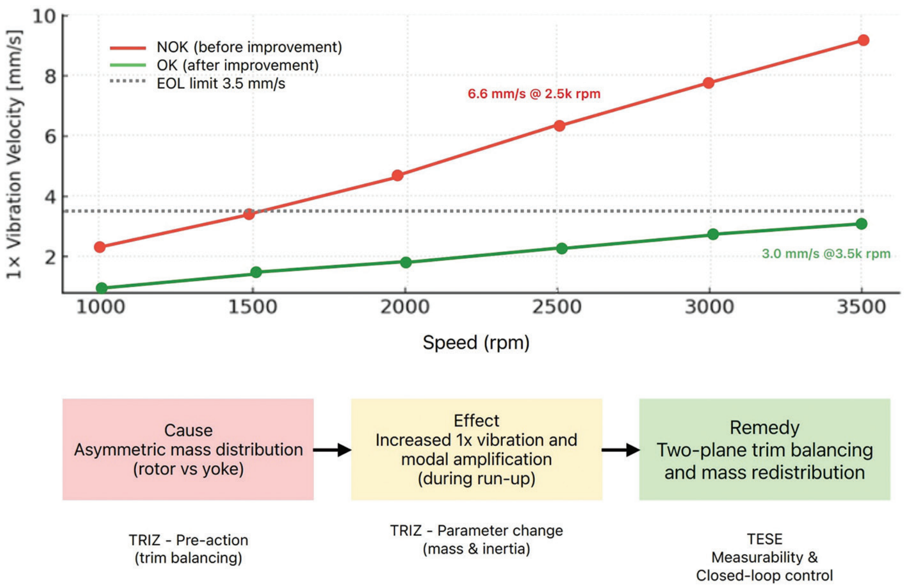

Fig. 6. Rotor–yoke mass imbalance measured through rotational dynamic test (displacement amplitude vs. speed)
Abbreviations: EOL: End of line; NOK: Not okay; OK: Okay

These challenges underscore the limitations of *ad hoc* corrective measures. Addressing them effectively requires a system-level innovation roadmap that coordinates short-, mid-, and long-term strategies. In the next section, the cyclical TRIZ model is applied to systematically align each problem with an appropriate innovation horizon, ensuring that temporary fixes, structural redesigns, and transformative upgrades are all embedded within a coherent development plan.

4. Trends Driving BLDC Motor Evolution

The cyclical TRIZ organizes innovation into three interlinked, time-bounded cycles, each aligned with a different depth of intervention in the BLDC motor evolution. This layered approach ensures that immediate corrective actions, mid-term systemic adjustments, and long-term transformative strategies are developed in a coordinated manner, preventing short-sighted optimizations from constraining future advancements.

4.1. Tzolk'in: Short-term Adaptation

Focus: Rapid, low-cost technical improvements that enhance current product performance without altering the core architecture.

In the context of BLDC motors, short-term adaptation addresses surface-level issues through resource reconfiguration and operational fine-tuning. Representative examples include (i) repositioning or reshaping the heatsink to minimize contact-induced resonance between structural components and (ii) leveraging residual thermal energy to enhance internal heat distribution without adding new cooling hardware.

Such interventions align with TRIZ principles of resource utilization and increasing ideality, thereby maximizing performance gains with minimal structural changes. Although these measures do not modify the motor's fundamental design, they directly improve efficiency, acoustic quality, or reliability in the current generation.

4.2. Haab: Mid-term Harmonization

Focus: Resolving deeper system-level contradictions by addressing interdependencies among mechanical, thermal, and control subsystems.

Mid-term interventions balance competing design targets through coordinated hardware–software refinements. Examples relevant to BLDC development include:

- Reconfiguring motor holder geometry to conserve space without compromising thermal dissipation pathways
- Optimizing firmware parameters such as dead-time adjustment to achieve a trade-off between high switching speed (responsiveness) and acceptable thermal load.

This stage applies TRIZ methodologies such as contradiction resolution and space, time, domain, and interface (STDI) analysis, ensuring that one subsystem's performance improvement does not inadvertently degrade another. The aim is to achieve harmonization, enabling the motor to meet conflicting objectives (e.g., compactness vs. cooling capacity, and dynamic responsiveness vs. thermal stability) without recurring design compromises.

4.3. Long count: Long-term Transformation

Focus: Strategic innovation that redefines the system's operational paradigm, preparing it for future demands and technology integration.

Long-term transformation in BLDC systems extends beyond incremental improvements, aiming to embed capabilities that anticipate market, regulatory, and technological shifts. Notable directions include:

- Integrating artificial intelligence (AI)-driven self-diagnostics for predictive maintenance and early fault detection
- Designing modular mechanical architectures to enable component reuse, rapid customization, and straightforward upgrades
- Embedding intelligent control units capable of real-time adaptation to changes in load, environment, or user preference.

Here, TRIZ strategies such as system transition, technology forecasting (aligned with TESE), and feature transfer from adjacent technological domains play a central role. These interventions ensure that the BLDC motor is not merely reactive to current requirements but is positioned to exploit emerging opportunities (e.g., autonomous HVAC optimization, energy-aware control algorithms, and integration into vehicle-level smart grids).

4.4. Integration Across Cycles

By explicitly structuring problem-solving into short-term adaptation, mid-term harmonization, and long-term transformation, engineers can deploy the most suitable TRIZ tools at the right moment. This staged approach reduces the risk of "local fixes" that later become barriers to systematic innovation. In the next section, this framework is applied to a problem–solution mapping, illustrating how the previously identified BLDC challenges can be systematically positioned within the appropriate innovation cycle for maximum strategic impact.

5. Discussion

The findings of this study demonstrate that the evolution of BLDC motors can be effectively guided when supported by a structured, time-segmented innovation framework. The cyclical TRIZ model facilitated the alignment of each identified problem with an appropriate time horizon and solution depth, ensuring that interventions were both contextually relevant and strategically timed.

In the short-term (Tzolk'in) cycle, corrective measures can be rapidly implemented through localized design modifications, thereby avoiding the cost and complexity of a full-system redesign. For example:

- Repositioning the heatsink eliminated the resonance responsible for the H24 acoustic anomaly
- Rechanneling residual heat enhanced thermal distribution without additional components.

These adjustments, although not altering the motor's architecture, delivered immediate functional gains within the constraints of limited time and budget. They also represented practical applications of TRIZ principles, resource utilization, and increasing ideality.

In the mid-term (Haab) cycle, challenges of higher systemic complexity required contradiction-focused analysis and integrated hardware–software solutions. Examples included:

- Mitigating H8 modal coupling by structurally decoupling rotor–fan interactions to prevent modal resonance overlap
- Optimizing firmware parameters (e.g., dead-time) to balance switching speed against thermal stress accumulation.

Such measures demanded deeper analysis using the contradiction matrix and STDI tools. They addressed root-level trade-offs (e.g., compactness vs. cooling efficiency or responsiveness vs. thermal stability), thereby reducing the likelihood of problem recurrence across product generations.

In the long-term (long count) cycle, certain innovation targets required strategic system transformation rather than incremental refinement. These forward-looking initiatives prepared the BLDC motor platform for future operating contexts and emerging technological landscapes. Representative cases included:

- Integrating AI-driven fault detection to enable predictive diagnostics and maintenance scheduling
- Implementing modular design for cross-platform reuse, upgradeability, and faster adaptation to evolving customer needs.

Long-term solutions relied on TRIZ tools such as system transition, technology forecasting (aligned with TESE), and feature transfer from other industries, enabling motors to evolve in parallel with advancements in vehicle electrification, autonomous control, and energy management systems.

The problem–solution mapping in Table 2 positions each BLDC challenge within its most suitable innovation cycle. This mapping supports engineering teams to prioritize actions based on urgency, resource availability, and strategic impact. Empirical observations from Gen 1 to Gen 3 BLDC motors validate the model: as system architectures advance, problem complexity increases, demanding progressively more sophisticated innovation strategies.

Table 2 also embeds the correspondence between TESE trends and representative TRIZ principles observed in BLDC evolution. For example, the TESE trend dynamization aligned with inventive principle (IP)15-Dynamics as reflected by variable-geometry heatsinks, increasing controllability related to IP23-Feedback exemplified by AI-based torque control, and harmonization of rhythms corresponded to IP19-Periodic Action as illustrated by pulse width modulation duty harmonization. These links clarify how TESE trends manifest through specific TRIZ principles within the proposed cyclical framework.

The cyclical segmentation proposed here could also inform the evolution of control architectures. For

Table 2. The problem–solution map

TRIZ cycle	Focus area	Relevant TESE trends	BLDC applications
Tzolk'in (short-term)	Rapid, local technical optimization	• Increasing Ideality • Resource Utilization	H24 acoustic anomaly: Repositioning heatsink and decoupling cover interface to shift resonance from 1,360 rpm to 1,460 rpm and reduce noise by~13%.
Haab (mid-term)	Resolving system-level contradictions	• Resolving Contradictions • Dynamization and Adjustability	H8 modal coupling: Redesigning rotor–yoke and fan interface to separate modal frequencies; achieving~28% vibration reduction and balanced frequency response.
Long count (long-term)	Strategic system transformation and foresight	• System Transition • Integration of Intelligence and Automation	Rotor–yoke imbalance: Implementing two-plane trim balancing and mass redistribution; ~55% reduction in 1×vibration amplitude and improved rotational stability.

Abbreviations: BLDC: Brushless direct current; TESE: Trends of engineering system evolution; TRIZ: Theory of inventive problem solving.

example, short-term cycles targeted parameter tuning in fuzzy or adaptive controllers, mid-term cycles addressed sensor-actuator coordination, and long-term cycles integrated AI-driven diagnostics for predictive adaptation. This alignment suggests that TRIZ-based evolutionary mapping can complement adaptive control research in guiding when and how structural or algorithmic changes should occur.

Beyond traditional control-based optimization methods, such as fuzzy, neural, or adaptive controllers (Boulkroune et al., 2025; Rigatos et al., 2023; Zouari et al., 2013), the cyclical TRIZ framework provides a structural complement that focuses on how systems evolve over time rather than how they stabilize under uncertainty. While adaptive control techniques achieve fast convergence and robust stability, the proposed method organizes these improvements within short-, mid-, and long-term innovation cycles, aligning control performance with product-level evolution.

By shifting from isolated problem-solving to a cyclical learning and adaptation loop, the framework supports a balanced innovation portfolio enabling short-term optimizations, mid-term harmonization, and long-term transformation. Such a dynamic, iterative process is critical in modern product development, where design stability, cost efficiency, and technology integration must co-evolve over time.

6. Conclusion

This study employed the cyclical TRIZ framework for the evolution of BLDC motors, structured across three sequential innovation horizons: short-term corrective optimization, mid-term system harmonization, and long-term strategic transformation. It illustrates the means for temporal alignment of TRIZ contradiction resolution and TESE evolutionary trends, providing an ongoing self-adaptive pathway forward.

Three case studies were designed to provide experiential validation of the approach. In each case study, a volume-based calculation of functional improvement was provided: in the H24 acoustic anomaly, structural–acoustic decoupling of the heatsink produced an approximate 13% reduction in tonal noise. In the H8 modal coupling case, frequency divergence was obtained, and stiffness was tuned to achieve an approximately 28% reduction in vibration amplitude. In the case of rotor–yoke imbalance, two-plane trim balancing and mass repartition yielded a 55% reduction in 1× vibration amplitude.

These examples demonstrate that the timing and scope of interventions, laid out within the Tzolk'in, Haab, and Long Count cycles of time, are as critical as the technical mechanisms themselves. The integration of TRIZ principles, such as taking out, parameter change, and separation, with TESE trends like dynamization and measurability provides a systematic process that evolves from reactive correction toward predictive intelligence.

Although the current validation was performed on internal data focused on the automotive HVAC BLDC motor platform, the cyclical framework has the potential to scale to other electromechanical domains (e.g., permanent magnet synchronous motor and traction drives). Future work integrating multi-motor datasets and a workshop experience with domain experts—i.e., patent evolution studies—may allow the cycle parameters to evolve iteratively and provide more transparency on how TRIZ–TESE logic can effectively inform real industry-related development processes.

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Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

Conceptualization: Koray Altun
Data curation: Merve Yildiz Ilhan
Methodology: All authors
Writing – original draft: All authors
Writing – review & editing: All authors

Availability of Data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Altshuller, G.S. (1984). *Creativity as an Exact Science: The Theory of the Solution of Inventive Problems*. Gordon and Breach Science Publishers, New York.

Altshuller, G.S. (1996). *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*. Technical Innovation Center, India.

Altun, K. (2025). A Maya calendar-inspired cyclical TRIZ approach: Enhancing systematic innovation and long-term problem-solving. *International Journal of Systematic Innovation*, 9(3), 8–19.

https://doi.org/10.6977/IJoSI.202506_9(3).0002

Altun, K., & Babayev, U. (2023). A novel approach to augment technology roadmapping through systematic innovation intelligence: A case of UAV technologies. *International Journal of Systematic Innovation*, 7(6), 1–11. https://doi.org/10.6977/IJoSI.202306_7(6).0001

Boulkroune, A., Zouari, F., & Boubellouta, A. (2025). Adaptive fuzzy control for practical fixed-time synchronization of fractional-order chaotic systems. *Journal of Vibration and Control*. https://doi.org/10.1177/10775463251320258

Cakmak, T., Altun, K., & Aksoy, M.O. (2021). Systematic customer value analysis: A case study in the automotive industry. *International Journal of Systematic Innovation*, 6(6), 22–36. https://doi.org/10.6977/IJoSI.202112_6(6).0004

Ganesan, A., Jaiswal, R., & Pitchaikani, A. (2018). A study of an integrated HVAC-vehicle model for automotive vehicles. *SAE International Journal of Passenger Cars Mechanical Systems*, 11, 151–166. https://doi.org/10.4271/06-11-02-0013

Ghane, M., Ang, M.C., Cavallucci, D., Kadir, R.A., Ng, K.W., & Sorooshian, S. (2022). TRIZ trend of engineering system evolution: A review on application, benefits, challenges and enhancement with computer-aided aspects. *Computers and Industrial Engineering*, 174, 108833. https://doi.org/10.1016/j.cie.2022.108833

Lee, D.H. (2024). An improved sensorless control of BLDC motor using 1-shunt current sensor for HVAC of EV. In: *2024 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia)*. IEEE, United States, p1–6.

Lee, D.W. (2014). Development of BLDC motor and multi-blade fan for HEV battery cooling system. *International Journal of Automotive Technology*, 15(7), 1101–1106. https://doi.org/10.1007/s12239-014-0114-7

Mohanraj, D., Aruldavid, R., Verma, R., Sathiyasekar, K., Barnawi, A.B., Chokkalingam, B., et al. (2022). A review of BLDC motor: state of art, advanced control techniques, and applications. *IEEE Access*, 10, 54833–54869. https://doi.org/10.1109/ACCESS.2022.3175011

Ravineala, T., Kurniawan, D., & Bennouna, S. (2025). Automotive HVAC blower blade pass noise sensitivity-a case study. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 271(2), 950–960. https://doi.org/10.3397/NC_2025_0163

Rigatos, G., Abbaszadeh, M., Sari, B., Siano, P., Cuccurullo, G., & Zouari, F. (2023). Nonlinear optimal control for a gas compressor driven by an induction motor. *Results in Control and Optimization*, 11, 100226. https://doi.org/10.1016/j.rico.2023.100226

Shao, J. (2006). An improved microcontroller-based sensorless brushless DC (BLDC) motor drive for automotive applications. *IEEE Transactions on Industry Applications*, 42(5), 1216–1221. https://doi.org/10.1109/TIA.2006.880888

Sheu, D.D., Chiu, M.C., & Cayard, D. (2020). The 7 pillars of TRIZ philosophies. *Computers and Industrial Engineering*, 146, 106572. https://doi.org/10.1016/j.cie.2020.106572

Sheu, D.D., & Chiu, S.C. (2017). Prioritized relevant trend identification for problem solving based on quantitative measures. *Computers and Industrial Engineering*, 107, 327–344. https://doi.org/10.1016/j.cie.2016.03.028

Sheu, D.D., & Lee, H.K. (2011). A proposed process for systematic innovation. *International Journal of Production Research*, 49, 847–868. https://doi.org/10.1080/00207540903280549

Singh, I. (2024). BLDC (Brushless Direct Current) Motors. Published in India 2024 by Pencil.

Zouari, F., Saad, K.B., & Benrejeb, M. (2013). Adaptive Backstepping Control for a Class of Uncertain Single Input Single Output Nonlinear Systems. In 10th *International Multi-Conferences on Systems, Signals and Devices 2013 (SSD13)*. IEEE, p1–6.

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