International Journal of Research Publications in Engineering, Technology and Management (IJRPETM)

|www.ijrpetm.com | ISSN: 2454-7875 | editor@ijrpetm.com |A Bimonthly, Peer Reviewed & Scholarly Journal|

||Volume 3, Issue 3, May-June 2020||

DOI:10.15662/IJRPETM.2020.0303001

Optimization and Design of Hybrid Powertrain Architectures for Next-Generation Automobile Systems

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ABSTRACT: The drive for lower emissions, improved fuel economy, and high performance has propelled hybrid powertrain systems to the forefront of automotive research. This paper examines the **optimization and design of hybrid powertrain architectures** using multi-objective frameworks, modeling tools, and advanced optimization techniques—all from pre-2019 research. Core methodologies include exhaustive clutch-topology search in multi-planetary-gear (PG) power-split systems, genetic algorithm-based optimization of series hybrids, bi-level topology and control optimization, and simulation-based architecture comparison, supported by platforms such as Autonomie. We propose a generalizable methodology: (1) model candidate architectures (series, parallel, power-split, multi-mode); (2) employ component sizing and energy-management control optimization; (3) apply multi-objective optimization algorithms (e.g., NSGA-II, Pareto front selection); (4) evaluate performance metrics like fuel economy, acceleration, cost, and component count. Case studies reveal that optimized three-PG systems can outperform benchmark designs with fewer clutches; genetic algorithms enable holistic sizing and control co-optimization; and Autonomie permits rapid architecture evaluation across drive cycles. Multi-objective strategies allow trade-off exploration between fuel efficiency and performance. Advantages include systematic architecture exploration, performance transparency, and reduced prototyping cost. Challenges remain in computational demand, model fidelity, and real-world validation. We conclude that combining topology, component, and control optimization offers powerful pathways for hybrid powertrain innovation. Future work should integrate battery health modeling, real-time model predictive control, and digital twin frameworks for dynamic adaptation.

KEYWORDS: Hybrid powertrain; architecture optimization; power-split; multi-objective design; planetary gear; genetic algorithms; Autonomie; control strategy; component sizing; series/parallel hybrid.

I. INTRODUCTION

Automotive hybrid powertrain design balances multiple objectives: maximizing fuel economy, ensuring responsive performance, managing cost and complexity, and adhering to emissions regulations. Hybrid systems—covering series, parallel, power-split, and multi-mode topologies—provide diverse trade-off spaces. Efficiently navigating these design landscapes requires optimization-driven methodologies.

Early systems like Honda's Integrated Motor Assist (IMA) demonstrate parallel hybrid benefits, whereas Toyota Prius employs power-split architecture with Atkinson-cycle engines. Platform tools like Autonomie (Argonne National Lab, circa 2010) enable rapid evaluation across numerous configuration combinations, facilitating control architecture testing via model-in-the-loop approaches.

To systematically pinpoint superior hybrid architectures, modern approaches before 2019 explored exhaustive layout searches (e.g., three-PG power-split systems), multi-objective genetic algorithm-based sizing, bi-level topology/control optimization, and simulation-supported design trade-off navigation. This paper reviews such methodologies and proposes an integrated workflow to optimize powertrain architecture, component sizing, and control strategies.

II. LITERATURE REVIEW

Three-PG Power-Split Optimization (2017)

Zhuang et al. performed exhaustive searches of clutch topologies and modes in three-planetary-gear systems, applying near-optimal energy management and yielding designs with superior launch performance and fuel economy using fewer clutches arXiv.

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Genetic Algorithms for Series Hybrid Design (2015–2016)
Dimitrova & Maréchal applied multi-objective optimization via genetic algorithms to series hybrid configuration and control parameter design, balancing efficiency, cost, and environmental impact ResearchGate.

Topology & Control Co-Optimization (2014)
A chapter on topology optimization argued that bi-level or simultaneous design-control strategies outperform iterative approaches for hybrid system-level optimization SpringerLink.

Autonomie Simulation Platform (2010)
Autonomie supports plug-and-play evaluation of hybrid architectures, enabling rapid comparison across drive cycles for fuel consumption, emissions, and performance metrics, reducing reliance on physical prototyping WIRED.

Multi-Objective Design Strategies (2013–2014)
Boehme et al. examined optimal design strategies for parallel and plug-in hybrids, jointly optimizing powertrain configuration, control strategy, fuel efficiency, and driving performance SpringerLink.

Control Strategy and Simulation Modeling (2016–2017)
Subramanian's modified series hybrid work focused on component sizing and optimization under performance constraints TRID. Modeling approaches leveraging MATLAB/Simulink and ECMS for component sizing are also well-established MDPI.

III. RESEARCH METHODOLOGY

We propose a comprehensive methodology for hybrid powertrain optimization:

1. **Architecture Definition**
2. Enumerate candidate hybrid layouts: series, parallel, power-split, multi-mode power-split (e.g., three-PG).
3. **Modeling & Simulation**
4. Construct component-level models (engine, motor, battery) in tools like Autonomie or MATLAB/Simulink.
5. **Control Strategy Integration**
6. Incorporate energy management strategies (e.g., ECMS, DP-based optimal control).
7. **Optimization Framework**

o Topology search: exhaustive or heuristics (e.g., clutch combinations in multi-mode systems).

o Component and control co-optimization: employ genetic algorithms (e.g., NSGA-II) for multi-objective sizing against fuel economy, performance, cost.

8. **Simulation & Evaluation**
9. Run drive cycle simulations; extract metrics such as fuel consumption, acceleration, emissions, and complexity (e.g., number of clutches).
10. **Pareto Selection**
11. Identify non-dominated solutions and compare trade-offs.
12. **Selection & Refinement**
13. Choose architectures meeting performance-cost balance; refine with increased-fidelity models or hardware-in-the-loop if needed.

This methodology unifies topology, sizing, and control strategy optimization in a structured design process.

IV. KEY FINDINGS

1. **Three-PG Systems Outperform**
2. Designs using three planetary gears via exhaustive search often achieve improved launch performance and fuel economy under fewer clutches arXiv.
3. **Genetic Optimization Efficient**
4. Multi-objective genetic algorithms generate Pareto-optimal designs balancing technical and economic attributes in series hybrid models ResearchGate.
5. **Co-Optimization Enhances Outcomes**
6. Simultaneous topology and control optimization yields system-level improvements outperforming sequential design workflows SpringerLink.
7. **Simulations Accelerate Design Cycles**

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8. Autonomie enables rapid architecture evaluation, reducing prototype cost and accelerating model-based control integration WIRED.
9. **Efficient Parallel Plug-In Hybrid Designs**
10. Multi-objective optimization delivered high fuel economy and performance balancing in parallel plug-in hybrids SpringerLink.
11. **Component Sizing Matters**
12. Modified series hybrids with integrated starter-generator improve electric range and fuel efficiency via optimized component sizing TRID.
13. **Model-Based Control (ECMS)**
14. Integrating ECMS in component sizing processes helps align system design and energy management for optimal economy MDPI.

V. WORKFLOW

1. **Identify Design Objectives**
2. Define metrics: fuel economy, acceleration, cost, complexity.
3. **List Architecture Candidates**
4. Series, parallel, power-split, multi-mode.
5. **Create Baseline Models**
6. Build component and control models in simulation tools.
7. **Perform Topology Search**
8. For complex systems (e.g., three-PG), exhaustively evaluate feasible configurations.
9. **Optimize Components & Control**
10. Use GA or other multi-objective algorithms to co-optimize sizing and energy management.
11. **Simulate Drive Cycles**
12. Evaluate performance across representative scenarios.
13. **Select Pareto-Optimal Designs**
14. Analyze trade-offs and choose final configurations.
15. **Prototype or High-Fidelity Refinement**
16. Increase fidelity via hardware-in-loop or advanced modeling.
17. **Finalize Design**
18. Validate manufacturability, cost, and compliance.

VI. ADVANTAGES & DISADVANTAGES

Advantages

- Systematic exploration of complex design spaces.
- Balanced multi-objective evaluation.
- Reduced physical prototyping via simulation.
- Co-optimized performance and efficiency.

Disadvantages

- High computational load with exhaustive or GA processes.
- Model fidelity crucial; poor modeling can mislead optimization.
- Complexity in managing simulation, optimization, and control integration.

VII. RESULTS AND DISCUSSION

Applying this methodology yields powerful insights: multi-mode systems with optimized gear and clutch layouts achieve superior dynamic performance and economy. Genetic algorithms effectively converge on designs that manufacturers may overlook via empirical methods. Co-optimization ensures that control strategies match hardware capabilities, providing real-world efficiency. Simulation tools like Autonomie shorten development time, enabling early architecture pruning.

Challenges include the computational burden of simulating many configurations, especially when integrating real-time control strategies. Ensuring model accuracy across thermal effects, transient events, and degradation remain essential.

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Despite these challenges, simulation-based multi-objective optimization emerges as the most efficient and insightful pathway for next-generation hybrid powertrain development.

VIII. CONCLUSION

By combining architecture topology search, component sizing, and control strategy optimization within simulation frameworks, engineers can identify high-performing hybrid powertrain designs before physical prototyping. Pre-2019 studies provide strong evidence that approaches like exhaustive PG system search, genetic optimization, and Autonomie-powered simulations deliver superior designs efficiently. For next-gen systems, this integrated optimization methodology forms a robust foundation for achieving fuel economy, performance, cost, and complexity balance.

IX. FUTURE WORK

- **Battery Health Integration**
- Incorporate battery degradation and state-of-health modeling into optimization loops.
- **Real-Time MPC Integration**
- Integrate model predictive control in design-phase simulation for more realistic performance.
- **Digital Twin Implementation**
- Create live mirroring of powertrain to continuously refine models based on field data.
- **Cloud-Based Optimization**
- Leverage parallel computing to reduce optimization time.
- **Thermal and Climate Modeling**
- Include thermal management and environmental effects in design optimization.

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