

VSSystem-Level Optimization of Electric Vehicle Powertrains: Comparative Analysis of PMSM, PMaSynRM, and Induction Machine Technologies

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Abstract

The rapid growth of electric vehicles (EVs) has increased the demand for highly efficient, cost-effective, and sustainable powertrain solutions. Traditional powertrain design approaches often optimize individual components independently, resulting in suboptimal system-level performance. This study presents a comprehensive system-level optimization methodology for EV powertrains incorporating electrical machines, power electronic converters, and mechanical transmissions. Three traction machine technologies—Permanent Magnet Synchronous Machines (PMSM), Permanent Magnet-assisted Synchronous Reluctance Machines (PMaSynRM), and Induction Machines (IM)—were modeled and evaluated using electromagnetic, thermal, efficiency, and cost models. Finite Element Method (FEM)-based simulations were employed to generate machine databases, while analytical models were used for thermal analysis, power electronics, transmission losses, and manufacturing cost estimation. The proposed optimization framework minimizes both investment and operational costs while satisfying vehicle performance requirements. Results demonstrate that PMSM-based powertrains provide superior efficiency and energy consumption performance, whereas IM systems offer lower material costs and PMaSynRM configurations present a balanced compromise between cost and rare-earth material dependency. The proposed methodology enables informed decision-making during EV powertrain design and provides a robust platform for future multi-objective optimization studies.

Keywords: Electric Vehicle, Powertrain Optimization, PMSM, PMaSynRM, Induction Machine, System-Level Design

Introduction

The electrification of transportation has become a major strategy for reducing greenhouse gas emissions and improving energy efficiency. Global EV adoption continues to grow due to advances in battery technology, supportive government policies, and expansion of charging infrastructure. As EV performance is strongly influenced by the electric powertrain, optimizing the interaction between electrical machines, power electronics, and transmissions is essential.

Most conventional design methodologies focus on individual subsystem optimization. However,

component-level optimization often neglects interactions among powertrain elements. Consequently, a system-level approach is necessary to balance efficiency, cost, power density, thermal performance, and sustainability.

This study develops a comprehensive optimization framework that integrates detailed models of electrical machines, power electronics converters, and mechanical transmissions. The framework is used to compare PMSM, PMaSynRM, and IM technologies from a holistic powertrain perspective.

Materials and Methods

Electronics Converter (PEC) Mechanical Transmission (MT) Vehicle Dynamics Model

Powertrain Architecture: The EV powertrain consists of: Electrical Machine (EM), Power

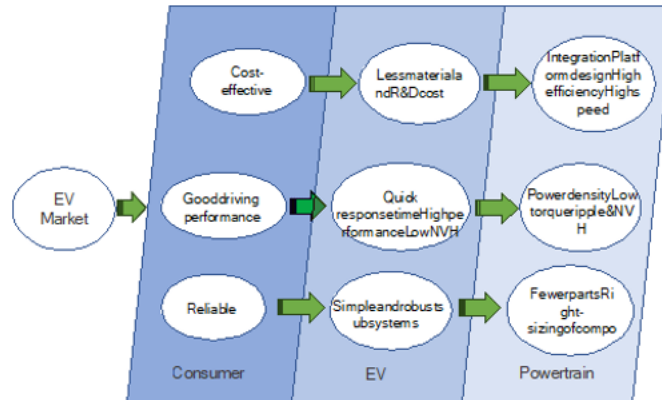


Figure 1: Overall Electric Vehicle Powertrain Optimization Framework

Electrical Machine Modeling

Finite Element Analysis (FEA) was used to evaluate electromagnetic characteristics.

- PMSM
- PMaSynRM
- IM

Machine Types Studied

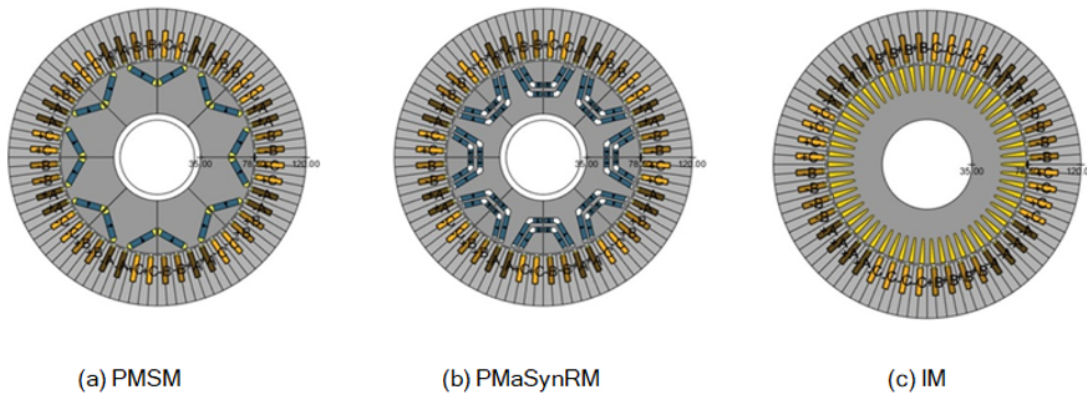


Figure 2: Geometry of Investigated Electrical Machines: PMSM, PMaSynRM, and IM

Table 1: Electrical Machine Technologies Considered

| Machine Type | Main Advantage | Main Limitation |
|--------------|-----------------------------------|------------------------------|
| PMSM | High efficiency and power density | Rare-earth magnet dependency |
| PMaSynRM | Reduced rare-earth usage | Demagnetization risk |
| IM | Low material cost and robustness | Lower efficiency |

Geometry Parameterization

Fully parameterized stator and rotor geometries were developed to generate large machine databases.

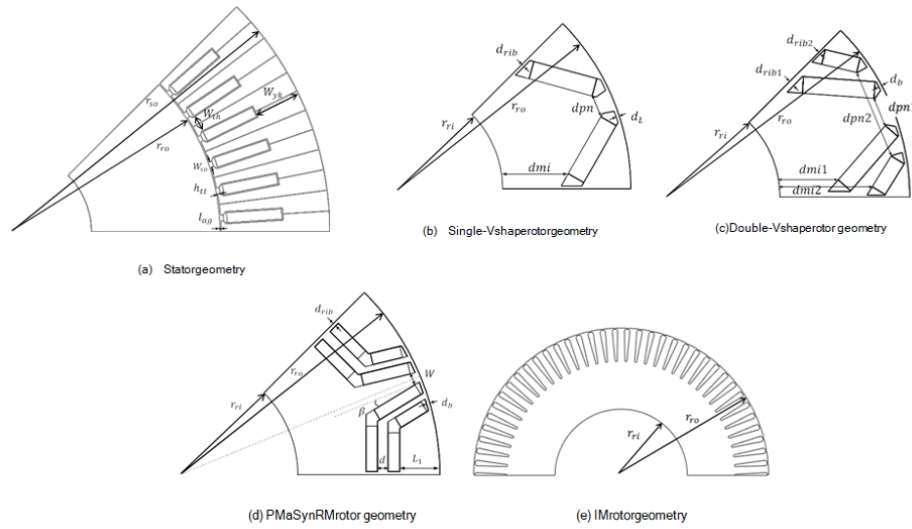


Figure 3: Parameterized Stator and Rotor Geometry Variables

Table 2: Key Design Parameters Used in Machine Modeling

| Parameter | Description |
|-----------|----------------------|
| rso | Stator outer radius |
| rro | Rotor outer radius |
| lag | Air-gap length |
| Np | Number of poles |
| Nbar | Number of rotor bars |
| hpm | Magnet height |

Winding Design

Hairpin winding technology was incorporated to improve slot fill factor and torque density.

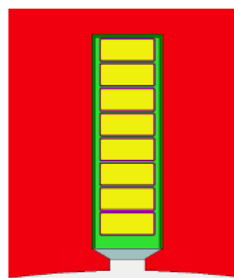


Figure 4: Hairpin Winding Configuration

Table 3: Feasible Hairpin Winding Configurations

| Number of Layers | Turns per Phase |
|------------------|-----------------|
| 4 | 24 |
| 6 | 36 |
| 8 | 48 |

Loss Modeling

Losses considered include:

Copper Losses

- DC Copper Losses
- AC Copper Losses

Iron Losses

- Hysteresis Losses
- Eddy Current Losses
- Excess Losses

Magnet Losses

- Eddy Current Losses in Magnets

Mechanical Losses

- Bearing Friction
- Windage Losses

Thermal Modeling

A lumped-parameter thermal network model was used to estimate temperature rise and evaluate machine operating limits.

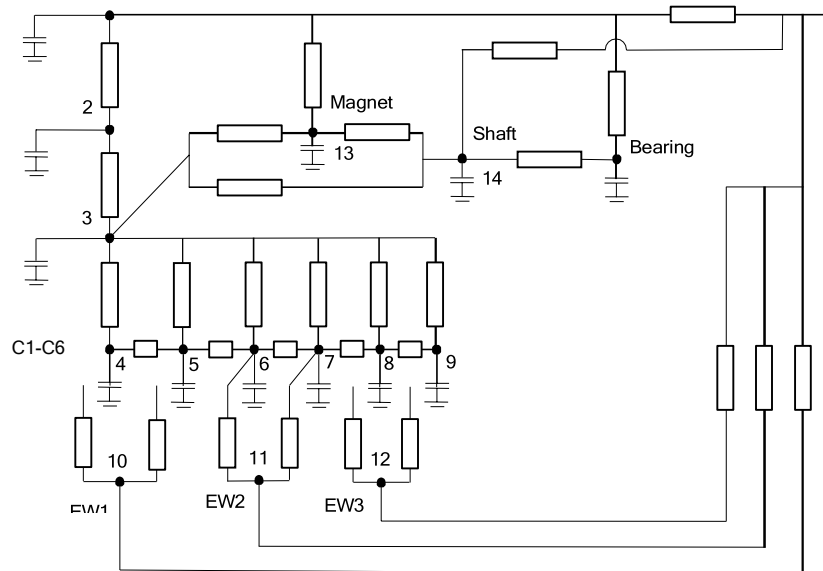


Figure 4: Thermal Network Model of Electrical Machine

Power Electronics Converter Modeling

An electro-thermal inverter model was developed to estimate:

- Switching losses
- Conduction losses
- Semiconductor temperatures

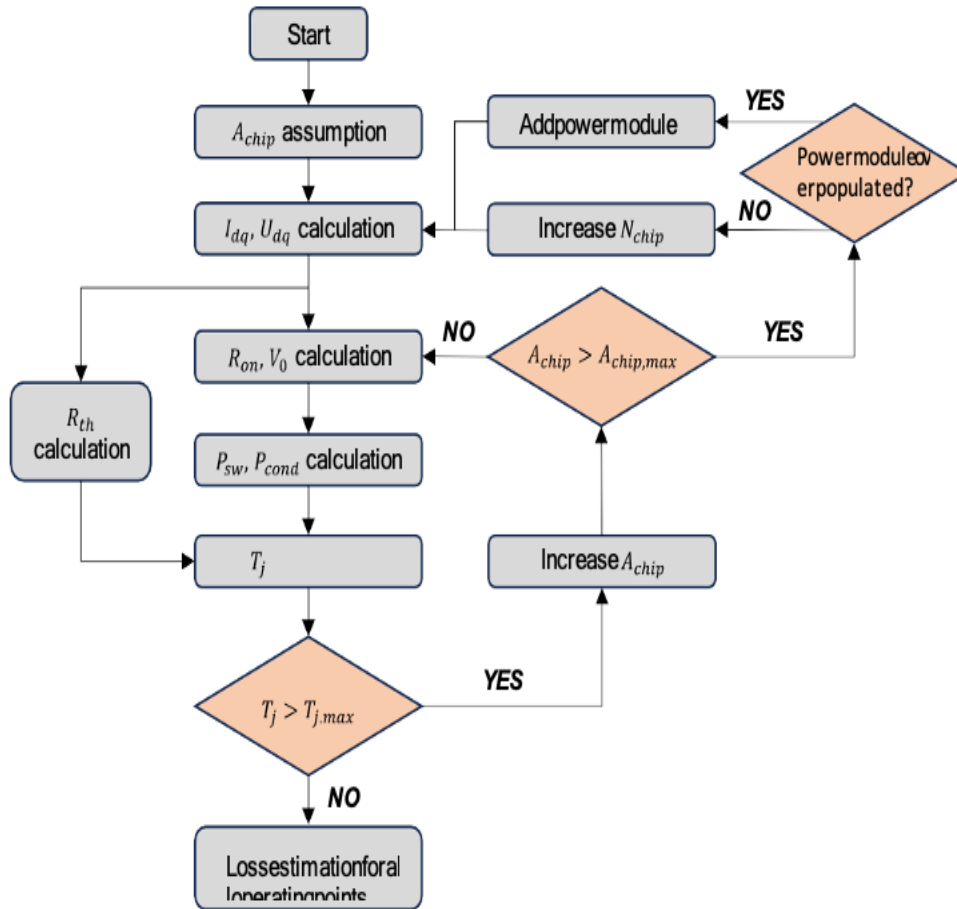


Figure 7: Power Electronics Converter Modeling Structure

Transmission Modeling

Transmission losses and gear ratio selection were included in the optimization framework.

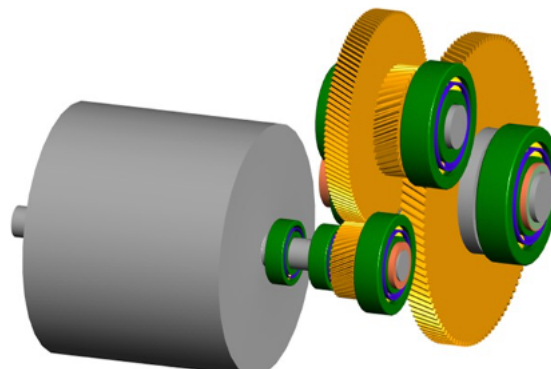


Figure 8: Mechanical Transmission Modeling Approach

Optimization Methodology

A Particle Swarm Optimization (PSO) algorithm was employed.

Objective Function

Minimize:

- Powertrain Cost

- Operating Cost
- Energy Consumption

Subject to:

- Acceleration constraints
- Maximum speed requirements
- Thermal limitations
- Efficiency targets

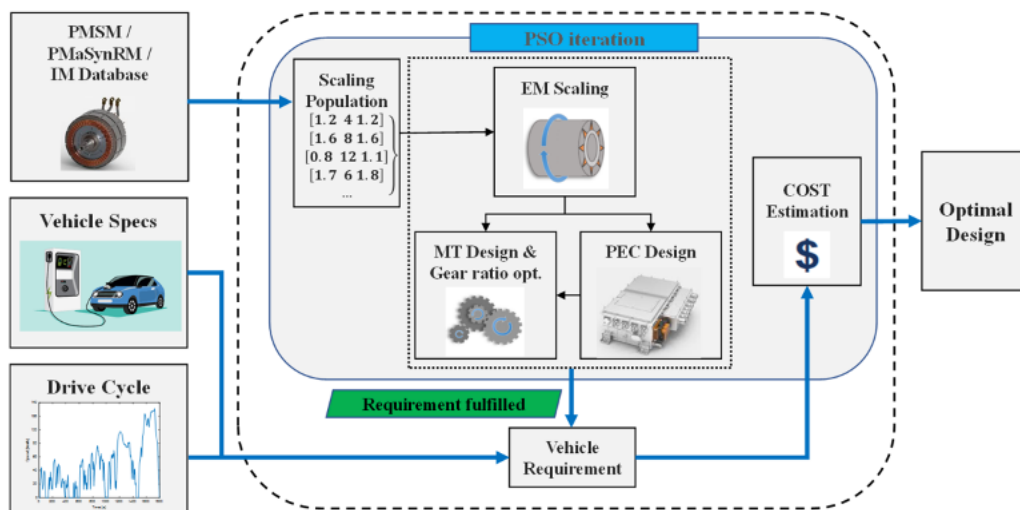


Figure 9: Optimization Workflow Using PSO

Results and Discussion

Electrical Machine Comparison

PMSM achieved the highest efficiency among the investigated machines due to the presence of permanent magnets and reduced rotor losses.

PMSynRM demonstrated competitive efficiency while significantly reducing dependence on rare-earth materials.

IM provided the most economical solution in terms of material cost but suffered from increased energy consumption.

Table 4: Comparative Performance of Electrical Machine Technologies

| Parameter | PMSM | PMSynRM | IM |
|------------------------|----------|----------|----------|
| Efficiency | Highest | High | Moderate |
| Power Density | Highest | Moderate | Moderate |
| Material Cost | High | Moderate | Low |
| Rare-Earth Requirement | High | Low | None |
| Robustness | Moderate | Moderate | High |

Effect of Hairpin Windings

Hairpin windings improved slot fill factor and torque density. However, increasing frequency

caused higher AC copper losses due to skin and proximity effects.

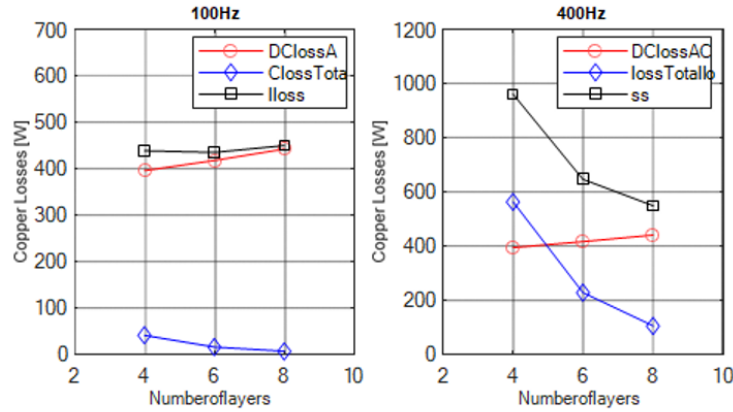


Figure 10: Variation of AC and DC Copper Losses with Number of Hairpin Layers

Powertrain-Level Optimization

Optimization revealed that overall vehicle performance depends strongly on component

interactions rather than individual component efficiencies.

Table 5: Impact of System-Level Optimization on EV Performance

| Metric | Improvement |
|--------------------|-------------|
| Energy Consumption | Reduced |
| Operating Cost | Reduced |
| Overall Efficiency | Improved |
| System Cost | Optimized |

Sustainability Considerations

PMSynRM emerged as an attractive compromise between efficiency and sustainability by

minimizing rare-earth material usage while maintaining competitive performance.

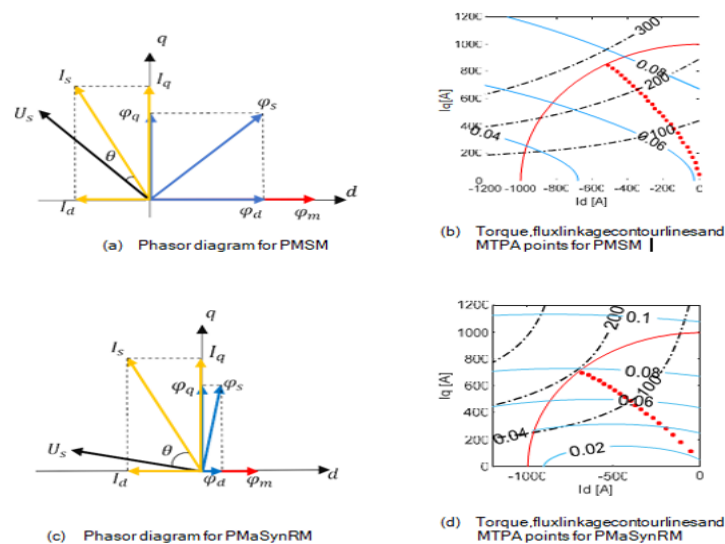


Figure 11: Trade-Off Between Cost, Efficiency, and Sustainability

Conclusion

A comprehensive system-level EV powertrain optimization framework was successfully developed by integrating electrical machine, power electronics, transmission, thermal, and cost models. The methodology enables simultaneous evaluation of performance and economic objectives.

Among the investigated machine technologies, PMSM provided the best efficiency and energy consumption performance, while IM offered the lowest material cost and highest robustness. PMSynRM emerged as a promising alternative due to its reduced reliance on rare-earth materials and balanced performance characteristics.

The proposed framework demonstrates the importance of system-level optimization in achieving cost-effective and energy-efficient EV powertrain designs. Future work should focus on multi-objective optimization, advanced thermal management, and platform-based powertrain standardization.

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