ISSN: 2348 - 2117

IJETCR
Open Access

International Journal of Engineering Technology and Computer Research (IJETCR)

Available Online at www.ijetcr.org

Volume 12; Issue 04; 2024; Page No. 09-15

# Multi-Objective Optimization of Dual-Motor Four-Wheel-Drive Electric Vehicle Power trains for Enhanced Energy Efficiency and Reduced Cost

**Kunal Abhay Patil[1], Dr. Shashi Kumar Jain[2]**

**[1]Sabarmati University Ahmedabad, India**
**[2]Sabarmati University, Ahmedabad, India**

**Conflicts of interest: Nil**

**Corresponding author: Kunal Abhay Patil**

## Abstract

The increasing demand for high-performance four-wheel-drive (4WD) electric vehicles (EVs) has intensified the need for powertrain architectures that simultaneously deliver superior dynamic performance, high energy efficiency, and reduced manufacturing cost. This study presents a multi-objective optimization framework for the design and control of dual-motor 4WD EV powertrains by jointly optimizing motor power ratings and torque distribution strategies. Three different powertrain configurations were investigated: (i) two identical permanent magnet synchronous motors (PMSMs), (ii) two PMSMs with optimized power ratings, and (iii) a hybrid configuration comprising a PMSM and an induction motor (IM). The optimization process was divided into two stages. First, the optimal power rating of each electric machine was determined through independent powertrain optimization considering both investment and operating costs. Second, an offline map-based torque distribution strategy was employed to identify the optimal torque split between the front and rear axles for minimizing total powertrain losses under different operating conditions. The proposed methodology was evaluated using a high-performance passenger EV with a peak power demand exceeding 350 kW and a target acceleration of 0–100 km/h in 3.8 s. The benchmark configuration employing two identical PMSMs achieved an energy consumption of 14.7 kWh/100 km. Optimization of motor characteristics while retaining two PMSMs reduced energy consumption to 14.4 kWh/100 km, representing a 2.1% improvement. The hybrid PMSM–IM configuration further reduced energy consumption to 13.9 kWh/100 km, corresponding to improvements of 5.8% and 3.6% compared with the benchmark and optimized dual-PMSM configurations, respectively. In addition, the PMSM–IM configuration lowered powertrain cost by approximately 6.7% owing to the reduced reliance on rare-earth permanent magnets. The optimized torque distribution strategy effectively exploited the complementary efficiency characteristics of the two motor types, assigning high-speed, low-torque operating conditions to the IM while utilizing the PMSM for high-torque demands. The results demonstrate that coordinated optimization of motor sizing and torque distribution significantly enhances both energy efficiency and cost-effectiveness in dual-motor 4WD EVs, providing a practical framework for the development of next-generation high-performance electric vehicle powertrains.

**Keywords:** Four-wheel-drive electric vehicle, Dual-motor powertrain, Permanent magnet synchronous motor, Induction motor, Motor sizing optimization, Torque distribution, Multi-objective optimization, Energy efficiency, Powertrain cost.

## Introduction

The rapid growth of battery electric vehicles (BEVs) has increased the demand for powertrain systems that provide high efficiency, excellent driving performance, and reduced manufacturing cost. Compared with internal combustion engine (ICE) vehicles, electric vehicles (EVs) offer higher energy conversion efficiency, lower emissions, and simpler drivetrain architectures. Permanent magnet synchronous motors (PMSMs) are widely used in EVs because of their high power density, superior torque characteristics, and efficiencies exceeding 95% under optimal operating conditions. However, their efficiency decreases during low-speed, high-torque and high-speed, low-load operating conditions, leading to increased energy consumption (Nguyen et al., 2023; Tiwari et al., 2023). To improve vehicle performance and efficiency, many modern EVs employ dual-motor four-wheel-drive (4WD) architectures. Independent motors on the front and rear axles enable better traction, acceleration, regenerative braking, and vehicle stability while allowing intelligent torque distribution between the two axles. Proper torque allocation enables each motor to operate closer to its maximum efficiency region, thereby reducing overall energy consumption (Nguyen et al., 2023).

Recent commercial EVs such as the Tesla Model 3 Dual Motor, Audi e-tron GT, BYD Seal, and Polestar 4 utilize either dual PMSMs or a combination of a PMSM and an induction motor (IM). PMSMs provide high efficiency and torque density, whereas IMs are less expensive, eliminate the need for rare-earth magnets, and perform efficiently during high-speed, low-torque operation. Combining these two motor technologies can improve overall drivetrain efficiency while reducing manufacturing cost (Nguyen et al., 2023).

Several studies have investigated motor sizing and torque distribution strategies for dual-motor EVs using optimization techniques such as efficiency-map-based control, fuzzy logic, and model predictive control. Although these approaches improve drivetrain efficiency, most studies optimize either motor sizing or torque distribution separately, with limited consideration of both energy consumption and powertrain cost simultaneously (Liu et al., 2022; Nguyen et al., 2023).

Therefore, this study proposes a multi-objective optimization framework for a high-performance dual-motor 4WD electric vehicle. Three powertrain configurations are investigated: (i) two identical PMSMs, (ii) two PMSMs with optimized power ratings, and (iii) a hybrid PMSM–IM configuration. The optimization simultaneously determines the optimal motor power rating and torque distribution strategy to minimize energy consumption and powertrain cost while satisfying vehicle performance requirements.

## Materials and Methods

### Vehicle Configuration

A high-performance dual-motor four-wheel-drive (4WD) battery electric vehicle (BEV) was selected as the reference vehicle for this study. The vehicle consists of two independently controlled electric machines, one driving the front axle and the other driving the rear axle through fixed single-speed reduction gearboxes. The independent drive architecture enables flexible torque allocation between the two axles to improve vehicle performance and drivetrain efficiency (Liu et al., 2022). The vehicle specifications used in the simulation are summarized in Table 1.

**Table 1. Vehicle specifications**

| **Parameter** | **Value** |
|---|---|
| Vehicle mass | 2270 kg |
| Wheel radius | 0.35 m |
| Drag coefficient | 0.26 |
| Rolling resistance coefficient | 0.008 |
| Frontal area | 2.36 m² |
| Maximum speed | 225 km/h |
| Acceleration (0–100 km/h) | 3.8 s |

These specifications were selected to represent a modern high-performance passenger electric vehicle capable of delivering excellent acceleration and cruising performance (Nguyen et al., 2023).

### Power train Configurations

Three dual-motor configurations were investigated to evaluate the influence of motor type and power rating on vehicle efficiency and cost.

1. **Case 1:** Two identical PMSMs with equal power ratings.
2. **Case 2:** Two PMSMs with independently optimized power ratings.
3. **Case 3:** One PMSM and one induction motor (IM) with optimized power ratings.

The PMSM was selected because of its high torque density and superior efficiency, whereas the induction motor was chosen for its lower manufacturing cost, reduced dependence on rare-earth materials, and good efficiency at high-speed, low-load operating conditions (Tiwari et al., 2023).

### Power train Optimization

The optimization procedure consisted of two sequential stages: motor power rating optimization and torque distribution optimization.

In the first stage, the total required power was divided between the two motors using a **power rating factor ($\alpha_1$)**. The motor peak power was calculated as:

$$P_{EM1}=\alpha 1 P_{total}$$

$$P_{EM2}=(1-\alpha 1)P_{total}$$

where:

- $P_{EM1}$= Peak power of Motor 1
- $P_{EM2}$ = Peak power of Motor 2
- Ptotal = Total vehicle peak power
- α1 = Power rating factor

The optimization aimed to determine the motor sizes that satisfied vehicle performance while minimizing the combined manufacturing and operating costs (Liu et al., 2022).

### Torque Distribution Optimization

After determining the optimal motor sizes, the torque demand was distributed between the front and rear motors using a torque distribution factor ($\alpha_2$).

The motor torque was calculated as:

$$T1=\alpha 2 Td$$

$$T2=(1-\alpha 2)Td$$

where

- Td = Total vehicle torque demand
- T1 = Front motor torque
- T2 = Rear motor torque

The torque distribution factor was varied between 0 and 1, representing front-wheel drive, rear-wheel drive, and four-wheel-drive operating modes. An offline efficiency-map search was used to identify the torque split that minimized total drivetrain power losses at every operating point (Nguyen et al., 2023).

### Objective Function

The optimization objective was to minimize the total system cost while reducing energy consumption throughout the driving cycle.

The objective function included:

- Electric machine manufacturing cost
- Inverter cost
- Energy consumption
- Electricity operating cost

The optimization process ensured that the vehicle satisfied acceleration, maximum speed, and continuous power requirements while achieving the minimum overall lifecycle cost (Nguyen et al., 2023).

### Simulation Procedure

Powertrain simulations were carried out for all three configurations using motor efficiency maps and vehicle longitudinal dynamics. For each case:

- Vehicle power and torque requirements were calculated.
- Motor power ratings were optimized.

- Powertrain components were independently optimized.
- Torque distribution maps were generated.
- Total energy consumption and powertrain cost were calculated.
- The three configurations were compared to identify the optimum solution.

Vehicle energy consumption was expressed in kWh/100 km, while powertrain cost was estimated using the optimized electric machine and inverter models.

### Performance Evaluation

The optimized powertrains were evaluated using the following performance indicators:

- Peak motor power (kW)
- Energy consumption (kWh/100 km)
- Powertrain manufacturing cost (€)
- Vehicle acceleration performance
- Maximum vehicle speed
- Optimal torque distribution strategy

The comparison of these parameters enabled assessment of the trade-off between vehicle efficiency and manufacturing cost among the three dual-motor configurations (Liu et al., 2022; Nguyen et al., 2023).

## Results and Discussion

### Optimization of Dual-PMSM Configuration (Case 1)

The first case considered two identical permanent magnet synchronous motors (PMSMs) with equal power ratings for the front and rear axles. The torque demand was equally distributed between the two motors (50:50), providing a simple and balanced drivetrain configuration. The optimization process resulted in two PMSMs, each having a peak power of 202 kW, producing a total system output of 404 kW, which satisfies the vehicle performance requirements.

The optimized powertrain exhibited an energy consumption of 14.7 kWh/100 km, while the manufacturing cost of each powertrain was estimated at €1486. Although this configuration offers a simple design and reduced development complexity, equal torque distribution cannot fully exploit the efficiency characteristics of the motors over different operating conditions.

**Table 2. Optimization Results for Case 1 (Dual Identical PMSMs)**

| **Parameter** | **EM1** | **EM2** |
|---|---|---|
| Peak power (kW) | 202 | 202 |
| Powertrain cost (€) | 1486 | 1486 |
| Energy consumption (kWh/100 km) | 14.7 | |

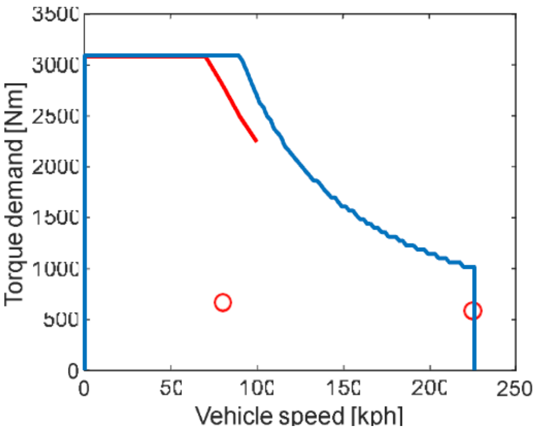

**Figure 1. Speed–Torque Characteristics of the Optimized PMSM Compared with Vehicle Requirements**

The optimized PMSM exceeded the required operating range of the vehicle, ensuring adequate acceleration and top-speed capability. However, several operating points fell outside the motor's maximum efficiency region, leading to relatively higher energy consumption.

### Optimization of Dual PMSMs with Variable Power Rating (Case 2)

The second configuration investigated two PMSMs with independently optimized power ratings. Unlike Case 1, the optimization simultaneously determined the motor geometry and the optimal torque distribution strategy. The optimized solution again selected motors with 202 kW peak power for both axles but adopted an adaptive torque distribution strategy based on motor efficiency maps.

The optimized torque allocation reduced energy consumption to 14.4 kWh/100 km, representing approximately 2.1% improvement compared with Case 1.

**Table 3. Optimization Results for Case 2 (Optimized Dual PMSMs)**

| **Parameter** | **EM1** | **EM2** |
|---|---|---|
| Peak power (kW) | 202 | 202 |
| Powertrain cost (€) | 1486 | 1486 |
| Energy consumption (kWh/100 km) | 14.4 | |

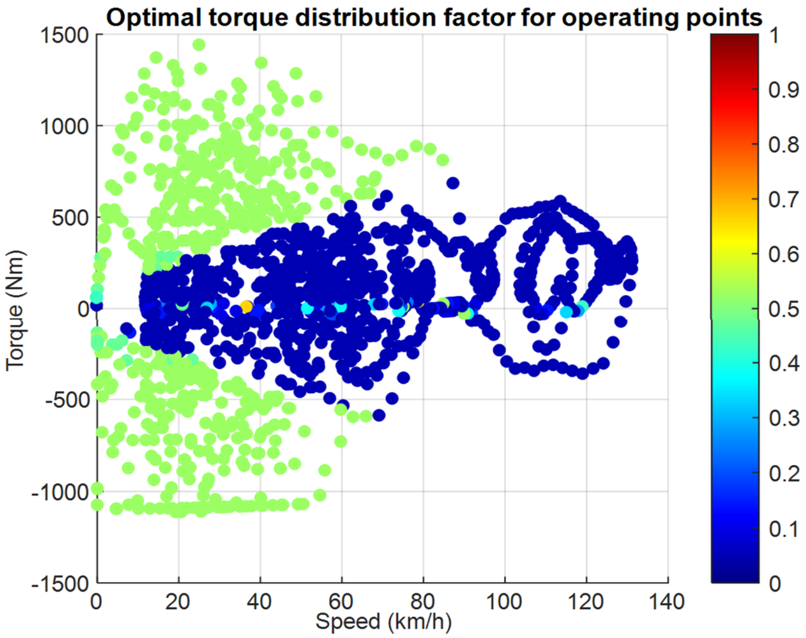

**Figure 2. Optimal Torque Distribution Map for Case 2**

The adaptive torque distribution allocated torque according to the instantaneous efficiency of each motor instead of maintaining a fixed 50:50 split. Consequently, the motors operated more frequently within their high-efficiency regions, reducing electrical losses during normal driving conditions.

### Optimization of PMSM–Induction Motor Configuration (Case 3)

The third configuration combined a 185 kW PMSM with a 268 kW induction motor (IM). The optimization selected a power rating factor of 0.41, allowing each motor to operate in its most efficient region. The PMSM primarily supplied high torque during vehicle acceleration, whereas the induction motor handled high-speed cruising where its efficiency is comparatively higher.

This configuration achieved the lowest energy consumption of 13.9 kWh/100 km, corresponding to reductions of 5.8% compared with Case 1 and 3.6% compared with Case 2. Furthermore, the overall powertrain cost decreased because induction motors do not require expensive rare-earth permanent magnets.

**Table 4. Optimization Results for Case 3 (PMSM–IM)**

| **Parameter** | **PMSM** | **IM** |
|---|---|---|
| Peak power (kW) | 185 | 268 |
| Powertrain cost (€) | 1343 | 1442 |
| Energy consumption (kWh/100 km) | 13.9 | |

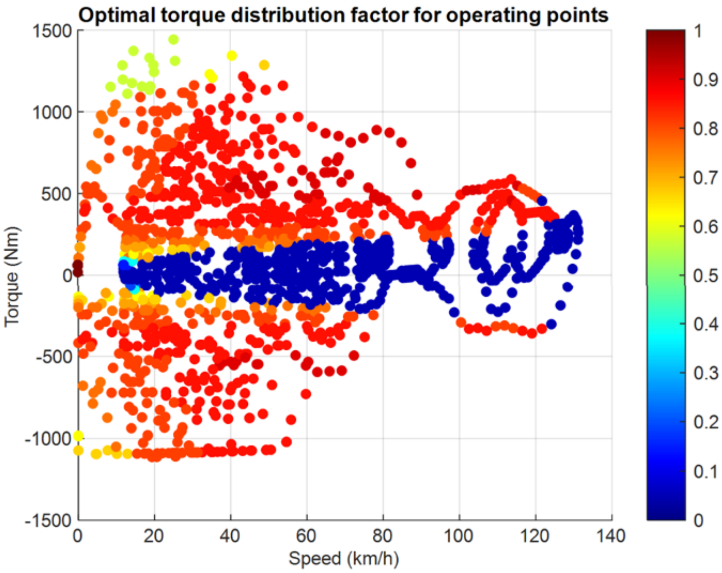

**Figure 3. Optimal Torque Distribution Map for the PMSM–IM Configuration**

The optimized control strategy allocated low-torque, high-speed operating conditions to the induction motor while assigning high-torque requirements to the PMSM. This complementary utilization significantly reduced total drivetrain losses and improved overall system efficiency.

## Comparative Performance Analysis

The optimized configurations were compared in terms of energy consumption and powertrain cost. The hybrid PMSM–IM system demonstrated the best overall performance among the investigated cases.

**Table 5. Comparison of Optimized Powertrain Configurations**

| **Configuration** | **Peak Power (kW)** | **Energy Consumption (kWh/100 km)** | **Improvement** | **Power train Cost** |
|---|---|---|---|---|
| Case 1 (Dual PMSM) | 404 | 14.7 | — | Highest |
| Case 2 (Optimized Dual PMSM) | 404 | 14.4 | 0.021 | Similar |
| Case 3 (PMSM–IM) | 453 | 13.9 | 0.058 | Lowest |

Although Cases 1 and 2 employed identical motor technologies, optimization of torque distribution in Case 2 reduced energy consumption without increasing manufacturing cost. The introduction of an induction motor in Case 3 further enhanced efficiency and lowered system cost by exploiting the complementary characteristics of the two motor technologies. These findings demonstrate that combining different electric machine technologies with optimized torque allocation provides superior overall performance.

## Conclusion

The results demonstrate that both motor sizing and torque distribution strategy play critical roles in determining the efficiency and cost of dual-motor electric vehicle powertrains. Equal torque sharing between identical motors simplifies the drivetrain design but does not maximize energy efficiency. Adaptive torque distribution allows each motor to operate closer to its peak efficiency region, thereby reducing electrical losses.

Among the investigated configurations, the PMSM–IM architecture achieved the best balance between performance, energy efficiency, and manufacturing cost. The induction motor effectively handled high-speed cruising conditions, while the PMSM delivered superior low-speed and high-torque performance. Consequently, the hybrid configuration achieved the lowest energy consumption (13.9 kWh/100 km) and reduced powertrain cost compared with the dual-PMSM systems.

The proposed multi-objective optimization framework successfully identified the optimal combination of motor power rating and torque distribution strategy for a high-performance four-wheel-drive electric vehicle. The findings indicate that integrating complementary motor technologies with intelligent energy management can significantly improve the efficiency and economic feasibility of future electric vehicle powertrains.

## Reference

1. Liu, C., Zhang, Y., & Wang, J. (2022). A review of architectures and control strategies of dual-motor coupling powertrain systems for battery electric vehicles. Renewable and Sustainable Energy Reviews, 162, 112453.
2. Liu, C., Zhang, Y., & Wang, J. (2022). A review of architectures and control strategies of dual-motor coupling powertrain systems for battery electric vehicles. Renewable and Sustainable Energy Reviews, 162, 112453. https://doi.org/10.1016/j.rser.2022.112453
3. Nguyen, C. T. P., Nguyen, B.-H., Trovão, J. P. F., & Ta, M. C. (2023). Torque distribution optimization for a dual-motor electric vehicle using adaptive network-based fuzzy inference system. IEEE Transactions on Energy Conversion, 38(4), 2784–2795.
4. Nguyen, C. T. P., Trovão, J. P. F., Nguyen, B.-H., & Ta, M. C. (2023). Dual-motor dual-source high performance electric vehicle: A comprehensive review. Energies, 16(20), 7048.
5. Nguyen, C. T. P., Trovão, J. P. F., Nguyen, B.-H., & Ta, M. C. (2023). Dual-motor dual-source high-performance electric vehicle: A comprehensive review. Energies, 16(20), 7048. https://doi.org/10.3390/en16207048
6. Tiwari, N., Yadav, S., & Arya, S. R. (2023). A comprehensive review of Indian market scenario and motors used in electric vehicles. Recent Patents on Engineering, 17(4).
7. Tiwari, N., Yadav, S., & Arya, S. R. (2023). A comprehensive review of Indian market scenario and motors used in electric vehicles. Recent Patents on Engineering, 17(4), 531–548.