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Optimizing the Motor Efficiency of Different Electrical Vehicles for Indian Road

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Abstract- The improvement of both the stability and economy of the four in-wheel motor drive (4IWMD) electric vehicle under complex drive cycles is currently a difficult problem in this field. A torque distribution method with the comprehensive goals of optimal torque distribution and energy efficiency, considering economy through energy efficiency for the 4IWMD electric vehicle, is proposed in this paper. Each component of the 4IWMD electric vehicle is modelled. The dynamic programming (DP) control algorithm is utilized for torque distribution between the front and rear in-wheel motors to obtain optimal torque distribution and energy efficiency in the 4IWMD electric vehicle. The simulation is performed on a co-simulation platform with the software of AVL Cruise and MATLAB/Simulink, considering a straight road. The hardware-in-the loop (HIL) experimental results also indicate that the effectiveness of the proposed DP algorithm is verified under the NEDC, WLTC and IM240 driving cycles, when a straight road is considered. The proposed DP control algorithm not only reduces the vehicle energy consumption and guarantees the optimization of torque distribution, but also increases the driving range of the vehicle.

Keywords- energy consumption optimization; torque distribution; energy efficiency; motor efficiency; four in-wheel motor drive electric vehicle.

I. INTRODUCTION

Over the years, owing to the increasingly severe energy crisis and environmental pollution, there has been an increase in the demand and manufacture of electric vehicles. Researchers have carried out extensive research on electric vehicles, especially on in-wheel motor drive (IWMD) electric vehicles. Amongst electric vehicles, IWMD electric vehicles possess distinct advantages, some of which are a simple and compact structure, flexible maneuverability and steering, high transmission efficiency and easy control including the independent torque control of each wheel. Substations serve as vital nodes in the power transmission and distribution network, facilitating the transformation of electricityfrom high voltage to low voltage or vice versa.

Efficient insulation and cooling of high-voltage equipment within substations are essential for maintaining system reliability and safety. The possibility for individual torque control has led to ample research in this area, including research focus on torque distribution, with a large focus on safety. Safety-based torque distribution utilizes torque vector/torque distribution to improve traction, handling and stability performances in vehicles.

Li et al proposed an optimal torque distribution approach for the improvement of vehicle handling and stability in spite of slippery road conditions. Joa et al presented an integrated chassis control method for front/rear torque distribution and four-wheel independent braking based on tire slip which improves handling performance. A novel torque vectoring algorithm was proposed by Park et al to improve cornering performance in electronic-four-wheel drive vehicles, meanwhile Deng et al. and Chatzikomis et al. studied a torque vectoring algorithm, with a consideration of stability and economy, as well as safety and energy efficiency improvement, respectively. The total longitudinal slip of an electric vehicle can also be reduced through novel torque distribution strategies to improve the vehicle safety. When considering safety, results from a torque distribution study indicate that the improved stability of the vehicle can be derived when a greater weight coefficient is applied to the rear wheels, as this causes the rear axle to bear a larger weight. Four IWMD electric vehicles which have four in-wheel motors positioned inside each of the vehicle wheel possess several advantages as stated earlier, including the delivery of the desired torque directly to each wheel, providing increased possibilities for economy management and improvement.

Considering vehicle economy, methods for acquiring optimal torque distribution are diverse, and this includes utilizing motor loss models for gaining optimal torque distribution. The motor loss model has the possibility of increasing system efficiency by some margin. However, the boundary conditions, such as motor parameters and control algorithms, could affect the possibility of getting the desired positive results. The steering controlled by the driver and longitudinal forces restricted from yaw result in the increase in the vehicle's maximum acceleration ability. Furthermore, mathematical models and quadratic programming methods are used to provide driving force.

Additionally, energy management strategies, such as strategies based on optimal driving torque distribution, can be considered to reduce electric energy consumption. Braking torque distribution between the front and the rear wheels in an electric vehicle can also significantly improve energy regeneration efficiency.

It is necessary to investigate the torque distribution approach of the 4IWMD electric vehicle considering the coordinated control of stability and economy. However, there are few scholars working from this perspective. Deng et al. proposed a novel torque vectoring algorithm based on a novel type of mechanical elastic electric wheel, which ensures the stability of the vehicle and reduces the energy consumption of the power train.

An optimized torque distribution method considering energy efficiency optimization based on DP strategy for a 4IWMD EV is proposed in this paper. This was considered under the constraint of straight-line driving.

The main contributions made by this research are stated as follows:

- A torque distribution method with the comprehensive goals of optimal torque distribution and energy efficiency considering economy through energy efficiency is proposed in this paper.
- The DP control algorithm is utilized for toque distribution between the front and rear in-wheel motors to obtain optimal torque distribution and energy efficiency in the 4IWMD EV.
- The proposed torque distribution based on the DP algorithm for the 4IWMD electric vehicle considering energy efficiency optimization is effectively verified through simulation and experiment under the NEDC, WLTC and IM240 driving cycles.

II. IWMD ELECTRIC VEHICLE MODEL

A four-in-wheel motor drive (4IWMD) electric vehicle model is built to verify the effectiveness of the proposed strategies under various driving cycles. The AVL Cruise and MATLAB/Simulink platforms are utilized in building the co-simulation model. The complete vehicle model consists of the vehicle, in-wheel motor and battery model established in the AVL Cruise software, meanwhile the vehicle dynamics model and the torque distribution control models are built in the MATLAB/Simulink software.

1. Vehicle Dynamics Model

The vehicle model consists of four electric motors located inside each wheel of the electric vehicle. The total vehicle mass can be expressed using the following equation:

$$Mv = mc + mem + mbat$$

where $mem = mfl + mfr + mrl + mrr$, m_c is vehicle curb weight, mem is total mass of the in- wheel motors, m_{bat} is battery mass, m_{fl} is the mass of the front left in-wheel motor, m_{fr} is the mass of the front right in-wheel motor, m_{rl} is the mass of the rear left in-wheel motor and m_{rr} is the mass of the rear right in-wheel motor.

Table 1. Below shows the parameters of thefour IWMD electric vehicles modelled in this study.

Vehicle Parameter	Symbol	Value (Unit)
Curb weight	M	1270 kg
Coefficient of rolling friction	C_r	0.017
Cross-sectional area	A	1.97 m^2
Aerodynamic drag coefficient	C_D	0.35
Rolling radius	R	0.31 m

The vehicle torque calculation is carried out in MATLAB/Simulink, in which the input variables are vehicle speed u and acceleration ax. Figure shows the free body diagram of the 4IWMD electric vehicle on a slope, with the resistance forces that act on the vehicle.

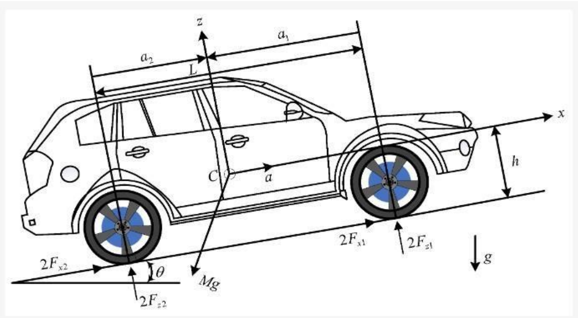

Fig 1. Longitudinal model diagram of vehicle accelerating up a slope.

2. In-Wheel Motor Model:

The efficiency map of the in-wheel motor is shownin Figure. The output power of the in-wheel motor is bounded by the output torque and motor speed conditions, which can be defined as:

□□(□)∈[□□,min(□□(□)),□□,max(□□(□))]

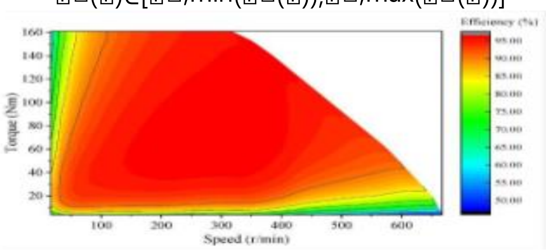

Fig 2. Efficiency map of in-wheel motor.

Where Pm is the output power of the in- wheel motor, Tm is the output torque of the in-wheel motor and ωm is the speed of the in-wheel motor. The in-wheel motor power demanded by the4IWMD electric vehicle need to be supplied by the battery through the following equation:

$$Pdem=Pm+Ploss.m$$

Where Pdem represents the power demanded by the power system of the 4IWMD electric vehicle, and Ploss.m is the power loss of the in-wheel motor, especially as a result of motor heat losses and mechanical losses.

The efficiency η of the in-wheel motor can be calculated by the formula:

$$\eta=Pout/Pin$$

Where Pout and Pin are the output and input power of the in-wheel motor, respectively.

3. Battery Model:

The battery pack is made up of rows and columns of battery cells modelled as voltage sources with resistance. The total power of the battery can be described as follows:

$$Pem,tot=Pdem+Paux$$

Where Paux is the auxiliary power demanded by the vehicle.

The simplified battery equivalent circuit model utilized by theoretically deriving the state of charge (SOC) of the EV is shown in Figure below.

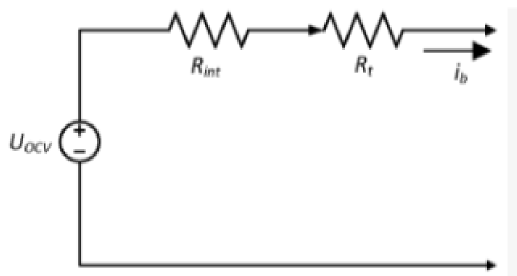

Fig 3. Simplified battery equivalent circuit model.

III. TORQUE DISTRIBUTION STRATEGIES

1. Torque Optimization Approach:

Torque distribution and energy saving can be achieved by the proper control allocation method [28]. The overall framework for torque distribution control is illustrated in Torque can be allocated utilizing different control allocation methods. In this study, the DP algorithm is proposed for optimizing the torque distributed to the in-wheel motors. Meanwhile, the fuzzy logic control (FLC) algorithm, based on the fuzzy set theory which operates very precisely and responds rapidly, ascertained by other studies, is used in comparison.

The triangular membership function with the input variables of vehicle speed, vehicle acceleration and output variable being the coefficient of torque distribution k, were utilized for the fuzzy logic controller. Additionally, the simulated FLC algorithm is designed considering equal torque distribution between front and rear axles under a straight-line driving scenario. The optimal operation of the in-wheel motor is improved by the optimal distribution of the required drive torque, so as to ensure that the in-wheel motor operates in high efficiency areas during operation at specified motor working speeds.

As a result, optimal torque distribution control can be expressed as a problem of determining the torque distribution coefficient k of the front wheels and rear wheels. The coefficient k is described as the torque distribution characteristic between the front wheels and rear wheels, which can be expressed by the following Equation:

$$k=TfTf+Tr$$

2. Torque Distribution Based on DP:

To derive a better efficiency optimizing effect, the torque distribution by DP is utilized to solve the torque optimization problem.

Torque distribution through DP optimization involves the establishment of the constrained optimization problem and solving the numerical solution. The utilization of the mathematical optimization and computer programming method developed by Richard Bellman in the 1950s for torque distribution in an electric vehicle requires utilizing the DP algorithm to solve and derive an optimal shorter path for the working points of the in-wheel motor, in such a way that it brings about increased in-wheel motor and vehicle efficiency.

The DP computational technique extends the decision-making concept to sequences of decisions, which as a whole define an optimal policy and trajectory. To determine the optimal trajectory and enable the in-wheel motors to work in high efficiency regions, the DP algorithm is defined by these mathematical equations:

$$C*axih=Jaxi+J*xih$$

IV. SIMULATION RESULTS AND ANALYSIS

To compare the effectiveness of the proposed DP-based torque distribution strategies for the 4IWMD electric vehicle, simulations were carried out using the co-simulation platform of MATLAB/Simulink and AVL Cruise. The simulations ran under the WLTC driving cycle, the NEDC driving cycle and the IM240 driving cycle to simulate the driving. The simulation results of the torque distribution based on DP control algorithm carried out under these different driving cycle conditions are compared with the torque distribution based on the FLC strategy. This comparison documents a comprehensive energy saving analysis of both torquedistribution strategies.

The FLC distribution strategy is developed considering the equal distribution of torque, as well as the effective torque distribution to both sets of in-wheel motors of the front and rear axle [35]. When the required torque is low, the rear in-wheel motors supply most of the torque. When the required torqueis supposed to increase and enlarge, the front in- wheel motors will supply more torque and compensate for the remaining required torque.

The DP controller is developed considering maximum in- wheel motor efficiency, in which both of the rear in- wheel motors handles the vehicle propulsion request when the calculated total required torque is less than 300 Nm. When the required torque is over 300 Nm, both of the front in-wheel motors assist the rear in- wheel motors and supply the left-over share of the required torque that is needed to propel the vehicle. The simulations are carried out under the assumption that the 4IWMD electric vehicle drives on a straight line without cornering. The low-speed– low-torque characteristic of the in-wheel motor keeps the electric vehicle within a maximum speed under 60 km/h. The main parameters of the 4IWMD electric vehicle utilized in the co-simulation studies are shown in Table.

1. WLTC Driving Cycle:

The worldwide harmonized light vehicle test cycle

(WLTC) with a distance of 23,266 m, a duration of 1800s and a maximum speed around 130 km/h is utilized, as it is the classified test cycle for a broader category of vehicles and diverse electric power train vehicles. The speed profile of the WLTC drive cycle is shown in Figure.

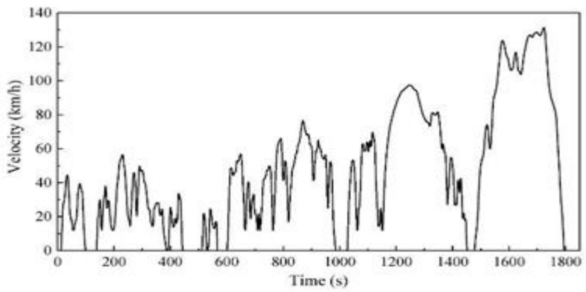

Fig 4. WLTC driving cycle.

The required total torque under the WLTC drive cycle is shown in Figure, as the control distribution method controls the amount of torque that is needed to navigate through the entire driving cycle. The torque that is individually distributed to the pair of front and rear motors when FLC is utilized for torque distribution is shown in Figure. The torque that is individually distributed to the pair of front and rear motors when the DP algorithm is utilized for torque distribution is depicted in Figure.

It can be noted that the calculated required torque by vehicle dynamics (Ttoll) is different from the required total torque to navigate through the driving cycles, as the latter is the total torque which the control algorithm utilizes to navigate through the driving cycle, considering the control parameters, constraints and objectives. Therefore, it is the result calculated by the torque distribution control algorithm, using the total desired torque by vehicle dynamics and in–wheel motor speed for the front and rear in-wheel motors.

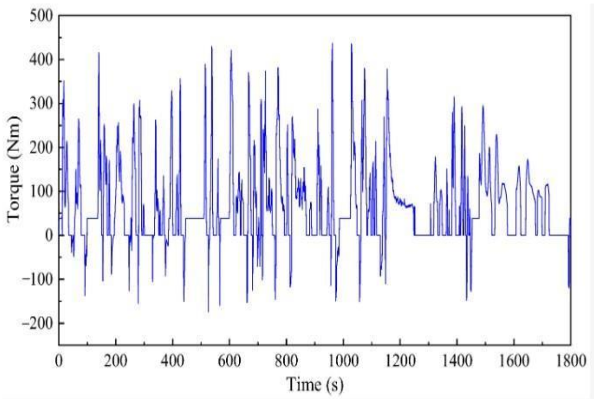

Fig 5. WLTC Driving Cycle.

2. NEDC Driving Cycle:

The new European driving cycle (NEDC) with a total distance of about 11,017 m, a duration of 1180 s and a maximum speed of 120 km/h, is the one used for the determination of a vehicle's consumption and emission values. The speed profile of the NEDC driving cycle is shown in Figure.

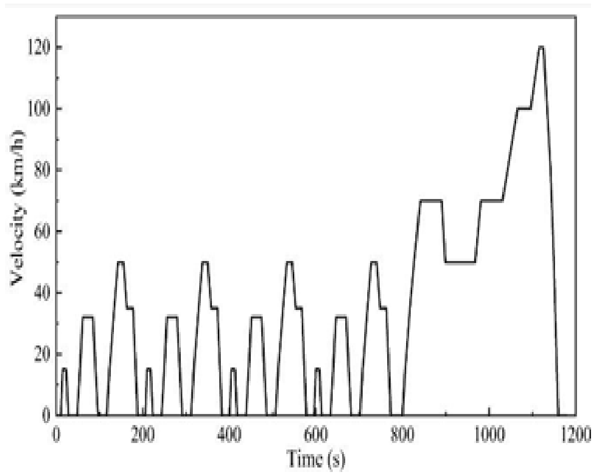

Fig 6. NEDC driving cycle.

The in-wheel motors effectively work as required in higher efficiency working regions of the electric motors when the DP-based torque distribution strategy is applied. Therefore, the proposed DP-based torque distribution method achieves a better efficiency optimization effect than that with the FLC-based torque distribution method, as both the front and rear in-wheel motors work mostly in highly efficient regions.

The motor operating points in the NEDC driving cycle, under the proposed DP- based torque distribution strategy, clearly shows that the rear in-wheel motor provides more torque for vehicle propulsion than the front in-wheel motor

3. Customized IM240 Driving Cycle:

A customized driving cycle called the custom IM240 drive cycle based on the inspection and maintenance driving cycle with a total distance of about 3100 km, a duration of 240 s and maximum speed of 56.7 km/h is also utilized in this study as it is a representation of a low-speed driving cycle, which represents the driving pattern in urban areas with traffic and low speed limitations. The speed profile of the custom IM240 driving cycle is shown in Figure. The required total torque with the entire custom IM240 drive cycle is presented in Figure.

The torque individually distributed to the front and rear motors based on FLC and the proposed DP algorithm strategy are shown in Figure. The torque requirement with the IM240 drive cycle is low and the rear in-wheel motor supplies most of the required torque throughout the driving cycle. This has the benefit of reducing the battery consumption, as only the rear in-wheel motor supplies the needed torque, therefore increasing the final SOC of the battery, which can be used to cover more travel range.

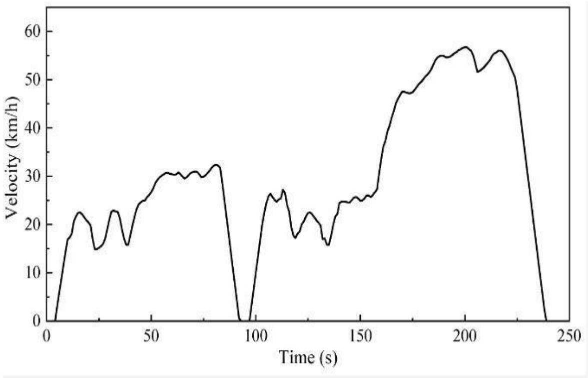

Fig 7. Custom IM240 driving cycle.

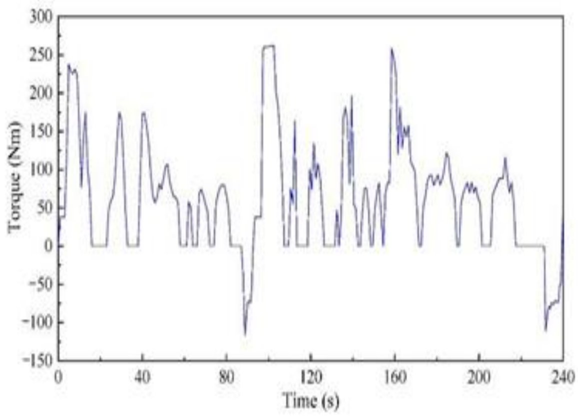

Fig 8. Total torque required to navigate through customIM240 driving cycle.

4. Energy Saving Analysis:

The energy consumption of the 4IWMD electric vehicle with FLC and the proposed DP strategy for torque distribution under different drive cycles are shown in Table 3. From Table 3, it can be seen that the energy consumption of the 4IWMD electric vehicle with FLC and the proposed DP strategy for torque distribution under the WLTC drive cycle are 10.01 kWh/100 km and 7.74 kWh/100 km, respectively. It can be seen that the energy consumption with the proposed DP strategy is less than that with the FLC strategy, in which the energy consumption is reduced by 22.68%.

The energy consumption of the vehicle with FLC and the proposed DP strategy for torque distribution under the NEDC drive cycle are 9.89 kWh/100 km and 7.84 kWh/100 km, respectively. It also can be seen that the energy consumption with the proposed DP strategy is less than that with the FLC strategy, in which the energy consumption is reduced by 20.73%.

The energy consumptionwith FLC and the proposed DP strategy for torque distribution under the custom IM240 drive cycle are 9.11 kWh/100 km and 7.12 kWh/100 km, respectively. We see that the energy consumption is reduced by 21.84% with the proposed DP strategy compared to the FLC strategy.

Table 2. Energy consumption of the 4IWDEV over the studieddriving cycles.

	FLC-Based Torque Distribution Energy Consumption (kWh/100 km)	DP-Based Torque Distribution Energy Consumption (kWh/100 km)	Improvement in Energy Consumption (%)
WLTC	10.01	7.74	22.68
NEDC	9.89	7.84	20.73
Custom IM240	9.11	7.12	21.84

V. EXPERIMENTAL VALIDATION

Experimental studies were carried out to verify the effectiveness of the proposed DP-based torque distribution strategy, which is achieved on a NI Veristand IWMD electric vehicle test bench. The above-mentioned three drive cycles are used for experimental studies. Figure shows the utilized experimental test bench setup.

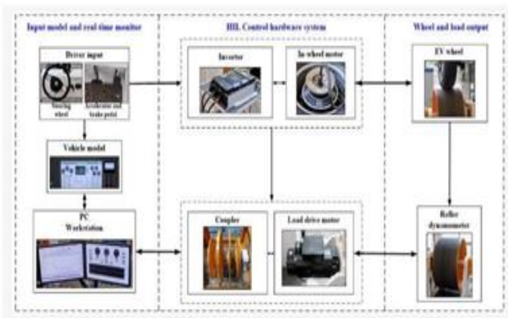

Fig 9. Experiment test bench setup.

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1. WLTC Drive Cycle:
A comparison of both the experimental and simulation results of torque distribution for the front and rear in-wheel motors with the FLC and the proposed DP strategy under the WLTC drive cycle. It can be seen that the experimental results of torque distribution track most of the simulation results. The torque distribution results obtained by the proposed DP strategy follow those obtained by the FLC strategy, in which the track accuracy is improved and the fluctuation is reduced. It is confirmed that the proposed DP strategy is a better option for torque distribution than the FLC strategy in the 4IWMD electric vehicle.

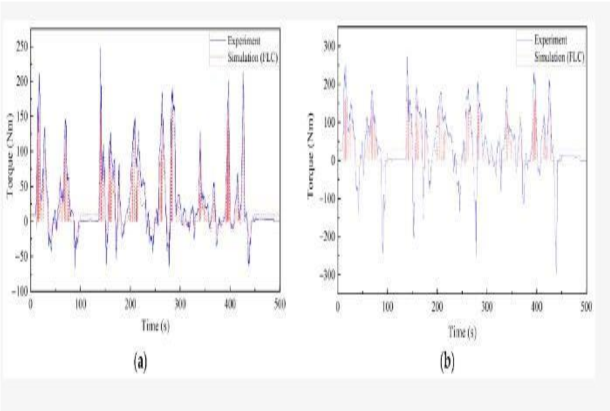

Fig 10. Torque distribution to front motor and rear motor obtained in experiment and FLC simulation of WLTC driving cycle: (a) Front motor; (b) Rear motor.

2. Energy Saving Analysis:
Energy saving analysis is conducted in line with the energy consumption during the experimental studies. The quantitative analysis of the vehicle energy consumption during the experiment was derived based on the torque distribution coefficient, for torque distribution based on the FLC algorithm and the DP algorithm, respectively. The total energy consumed by the in-wheel motor during the experiment based on the FLC algorithm and the DP algorithm in the WLTC driving cycle is 359.714 kJ and273.765 kJ, respectively. Meanwhile, in the NEDC driving cycle, the in-wheel motor consumed energy of 528.834 kJ and 406.549 kJ during the experiment based on the FLC algorithm and the DP algorithm, respectively.

For the custom IM240 driving cycle, the in-wheel motor consumed energy of 163.051 kJ and 125.527 kJ during the experimentbased on the FLC algorithm and the DP algorithm, respectively. The WLTC urban driving experiment covered 0–500 s of the WLTC driving cycle, while thatof NEDC covered 0–438 s of the NEDC driving cycle; meanwhile, the custom IM240 experiment covers the entire 240 s of the custom IM240 driving cycle.

The energy consumption in Kilowatt-hour per 100 km, calculated from the Watt-hour calculation, is assumed to showcase the consumption per km for the three driving cycles, for torque distribution methods with FLC and the proposed DP algorithm. The percentage of improvement in energy consumption during the experiments based on the FLC and DP torque distributions is shown in Table.

Table 3. In-wheel Motor Energy Consumption during Experimental Studies.

	Energy Consumption with FLC Algorithm (kWh/100 km)	Energy Consumption with DP Algorithm (kWh/100 km)	Improvement in Energy Consumption (%)
WLTC	9.992	7.605	23.89
NEDC	14.690	11.293	23.12
Custom IM240	4.529	3.487	23.01

The IM240 driving cycle during the experiments based on the FLC and DP torque distributions is presented in Figure. Compared to the FLC-based strategy, it can be seen that there is a reduction in energy consumption with the DP-based torque distribution strategy.

The energy consumed in the WLTC, NEDC and custom IM240 driving cycles during the experiment clearly verifies that DP-based torque distribution is a more optimal torque distribution method than the FLC strategy, for which less energy is consumed when the DP-based torque distribution is applied in the 4IWMD EV.

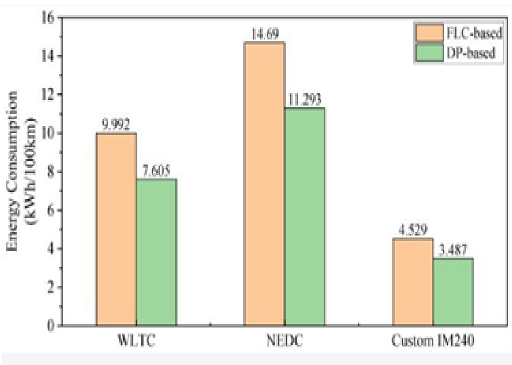

Fig 11. Energy consumption in the three drive cycles using FLC-based and DP-based torque distribution duringexperiment.

VI. CONCLUSIONS

Centered on the aim of improving energy saving, the economy-based torque distribution strategy is proposed in this paper. Upon the building of a complete four-in-wheel motor drive electric vehicle model, featuring a comprehensive vehicle model, a motor model and a battery model, torque distribution methods based on the FLC algorithm and a proposed DP algorithm are investigated through co-simulation studies carried out in AVL Cruise and MATLAB/Simulink software. Additionally, further experimental studies were implemented to verify the simulation results. These were performed considering a straight-line road.

This article produces very interesting results, as shown by the simulation and experimental results. The simulation results show that the torque distribution based on the DP algorithm is the optimal option for optimized front and rear torque distribution, as it effectively reduces the vehicle's energy consumption by 2.27 kWh, 2.05 kWh and 1.99 kWh for every 100 km of distance travelled in the WLTC, NEDC and custom IM240 driving cycle conditions, respectively, when compared to the torque distribution based on the FLC algorithm.

Furthermore, compared to the FLC algorithm, the experimental results show that the energy consumption under the WLTC, NEDC and IM240 drive cycles is reduced by 23.89%, 23.12% and 23.01% with the proposed DP algorithm, respectively. Hence, the proposed DP algorithm produces an optimized front and rear torque distribution that effectively reduces vehicle energy consumption, which leads to an improved energy saving and overall vehicle efficiency in four-in-wheel motor drive electric vehicles. The online global optimization method with the proposed DP algorithm which can be monitored in real-time during simulation and the vehicle experiment studies may assist in optimization and real time control, enabling better simulation results and even experimental results to be obtained with minimal or negligible errors.

It should be noted that DP is an exhaustive search that requires more time and space for its computation. Future work will focus on the algorithmand the reduction of the computation load.

REFERENCES

[1] Li, B.; Goodarzi, A.; Khajepour, A.; Chen, S.K.; Litkouhi, B. An optimal torque distribution control strategy for four- independent wheel drive electric vehicles. Veh. Syst. Dyn. 2015, 53, 1172– 1189. [Google Scholar] [CrossRef]

[2] Joa, E.; Park, K.; Koh, Y.; Yi, K.; Kim, K. A tyre slip-based integrated chassis control of front/rear traction distribution and four-wheel independent brake from moderate driving to limit handling. Veh. Syst. Dyn. 2018, 56, 579–603. [Google Scholar] [CrossRef]

[3] Park, G.; Han, K.; Nam, K.; Kim, H.; Choi, S.B. Torque Vectoring Algorithm of Electronic-Four Wheel Drive Vehicles for Enhancement of CorneringPerformance. IEEE Trans. Veh. Technol. 2020, 69, 3668–3679. [GoogleScholar] [CrossRef]

[4] Deng, H.; Zhao, Y.; Feng, S.; Wang, Q.;Lin, F. Torque Vectoring Algorithm Based on Mechanical Elastic Electric Wheels with Consideration of the Stability and Economy. Energy 2021, 219, 119643. [Google Scholar] [CrossRef]

[5] Chatzikomis, C.; Zanchetta, M.; Gruber, P.; Sorniotti, A.; Modic, B.; Motaln, T.; Blagotinsek, L.; Gotovac, G. An energy-efficient torque-vectoring algorithm for electric vehicles with multiple motors. Mech. Syst. Signal Process. 2019, 128, 655–673. [Google Scholar] [CrossRef]

[6] Debada, E.; Marcos, D.; Montero, C.; Camacho, E.F.; Bordons, C.; Ridao, M.A. Torque distribution strategy for a four In- wheel fully electric car. Jorn. Autom. 2015, 517–525. Available online: https://idus.us.es/handle/11441/92138 (accessed on 6 September 2022).

[7] Mokhiamar, O.; Abe, M. How the four wheels should share forces in an optimum cooperative chassis control. Control Eng. Pract. 2006, 14, 295–304. [GoogleScholar] [CrossRef]

[8] Yong, L.; Deng, H.; Xing, X.; Jiang, H. Review on torque distribution strategies for four in-wheel motor drive electric vehicles. IOP Conf. Ser. Mater. Sci. Eng. 2018, 394, 042041. [Google Scholar]

[9] Wang, Y.; Su, Y. A research for brake strategy based on fuzzy control in pure electric vehicles. In Proceedings of the 2015 4th International Conference on Computer Science and Network Technology (ICCSNT), Harbin, China,