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Design and stability analysis of four-in-wheel drive electric vehicle based on variable structure control algorithm

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Abstract: *This work presents a hierarchical control structure for four in-wheel-drive electric vehicles consisting of a high-level variable structure mode control (VSMC) and a non-linear control prediction scheme utilizing regenerative braking torque distribution control and motor driving to improve vehicle stability. Optimal torque distribution can be obtained through this method. Variable structured mode control algorithm is developed to constrain the system state within the switching function and also the yaw stabilization was achieved. The system also improves the performance of vehicle handling while assuring driver comfort and actuation smoothness. The proposed scheme eliminates computational complexities and the Park's transformation. The simulation and experimental results are presented to shows that the closed loop response was insensitive to particular class of insensitivity.*

Keyword: *Differential braking; Robustness; Variable structure mode control (VSMC); Yaw stabilization.*

1. INTRODUCTION

Electric vehicles have been of increasing demand recently since they share the exact characteristics and benefits as internal combustion engine based vehicles. Electric vehicles (EVs) were cane into existence about two centuries ago. Although, the use of EVs was desisted in the later upcoming century because of both technical and economic aspects such as high cost, battery storage, and speed limitation. In recent days, the study on the EVs has been again started due to the environmental issues associated with the internal combustion engine based vehicles become more hazardous [1]. Nowadays, with the existence of various battery technologies, the environment-friendly EVs become a promising alternative to the ICE-based vehicles. On one end, the electrical machines and the energy management technology in hybrid electrical vehicles (HEV) and plug-in HEVs (PHEVs) have become mature, which could be inquisitively applied to EGVs [2]. On the other end, high power-density or energy-density batteries and the in-wheel motors with rapid and more accurate torque control capabilities endeavor more opportunities for the development of EVs with four independently actuated in-wheel electric motors. The corresponding concept vehicles with independently actuated four in-wheel motors which have already proceeded into the pre market phases.

To extend the capability of VSMC towards improving switching function and vehicle handling capability systemized torque bearing between the differential braking and the resorption torque had been proposed for stereotyped vehicles. The proturning vehicle yaw moment is obtained from differential braking; the propulsion torque is used to vector a portion of the brake torque to the traction torque on the outside driven wheel. Ideally, the sum of the resulted wheel forces is equal to zero in the vehicle's protensive direction in order generate the desiderate control yaw moment. Unfortunately, satisfactory torque vectoring coordination is not achieved in the power train because an internal combustion engine (ICE) and torque converter transmission does not have sufficient torque delivery bandwidth. Insufficient torque compensation leads to unexpected vehicle drag and jerk motions. As a result, such torque vectoring technology is not popular, and it is limited in vehicle handling with mild level of durability enhancement even in high-end luxury vehicles.

There are various control strategies proposed in survey, the slip controller for a hybrid electromagnetic brake system, multi model predictive control strategy to solve the uncertainties and nonlinearities in electric vehicle. Many of these strategies are studied based on vehicle with internal combustion engine. Although these techniques cannot be adapted to the EV due to the different driving structures and characteristics. Modeling the electric vehicle by a efficient and suitable model that the non-linear effects are taken into account. The dynamic model of a vehicle is

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presented such that the vehicle is integrated in wheels of it. Designing of controllers for electronic stability control of four in wheel vehicle systems to maintain the wheel speed or slip at a desired level. Achieving the control systems switching gain and robustness against certain parameters using simulink approximation and presenting the stability analysis of the vehicle [3]-[11].

Generally, in VSMC all the models are calculated in agnate and the best model would be preferred or a accepted model would be calculated based on various error at each instant. Thus the idea of choosing between various models has been introduced in many surveys and it is important to calculate the multi-model prognostic control. The selection among the various models occurs whenever a different model gives better result than the current one, and the control input parameters are generated using the parameters of the existing model. This has great advantage to vehicle stability control when VSMC strategy is being using on electric vehicle. Due to the advantages of multi-model control, the vehicle can be presented as various dynamic models in different working conditions, for example, if one motor suddenly broken or the brake system got damaged when driving. Further the different controllers are designed according to these available models.

The main aim of this paper is to present a stability allocations strategy for EVs, which permits us to consider the coercion of actuating motors, and in parallel considering the characteristics of wheel slip. Referring the results of [12], this paper provides results for a Model predictive based stability control algorithm for conditionally stable tracking of marginally stable input commands. And, we also propose an interspersed yaw stability control strategy for four in wheel motor drive electric vehicles. The complete control strategy comprises of two control loops. The upper controller is synoptic and comparable to the practice model of the modern automotive control, which bridge the gap between recent model-based control and practical implementation. The main benefaction is a variable control scheme allocation model to provide with the additional yaw torque rate. The VSMC problem is posed as a logical quadratic programming problem with the coercion. In order to control wheel slip on frictionless road, the smooth constraint of wheel longitudinal switching ratio is translated into a function to enforce the slip changing within the stable slip range. To figure out the improvement in performance that was achieved when electric vehicles are driven in discerning conditions, we also compare the VSMC scheme with the SCA scheme. The simulation results obtained from stability evaluation method is analyzed, thereby increasing the consequence highlighting the importance for disenchanted control allocation.

2. VEHICLE DYNAMICS MODEL

At the beginning of the survey, a vehicle simulation model can be constructed using simulink, which can basically specify the strategic performance of a 4-wheel-drive independent electric vehicle. The stability of the variable dynamic system is analyzed which are based on the following key assumptions: 1) The electric vehicle is driving on a smooth road and the front axle angles are different, and the wheel angles of back axle are always maintained zero; 2) The overall width of the vehicle is kept constant; 3) The suspension and tires always at right angles to the ground; 4) The front and back axle centers are situated in the same bisecting plane of the vehicle.

According to the Figure 1, the 4-in-wheel-drive independent electric vehicle can be described based on the d'Alembert principle by following equations

Longitudinal motion:

$$m(u - v.\gamma) = \sum P_{N\gamma}^{n} = K_{yfb}.cos\delta_{fb} + K_{yff}.cos\delta_{ff} - F_{\gamma}.sin\delta_{\gamma} + N_{\gamma sc} \quad (1)$$

Rotatory motion:

$$m(u + v.\gamma) = \sum P_{NG\gamma}^{n} = K_{rff}.cos\delta_{ff} + K_{rfb}.cos\delta_{fb} - F_{a\gamma}.sin\delta_{\gamma} + N_{Rsc} \quad (2)$$

Linear motion:

$$\sum P_{May}^{n}\, Q = P_{ay\delta}^{n}.cos\delta_{ay} + P_{ayN}^{n}.cos\delta_{ay} - F_{a\gamma}.sin\delta_{\gamma} + N_{DOB} \quad (3)$$

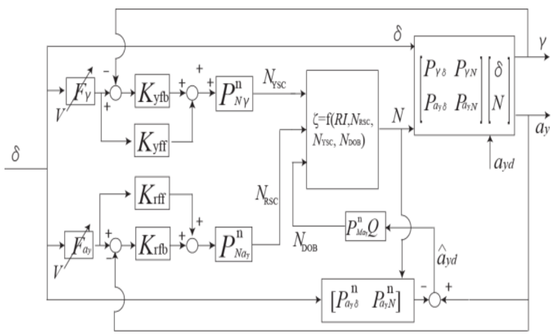

Figure 1 Rolling stability control of in-wheel motors

Where m is the total mass of the vehicle, u and v are the longitudinal velocity and linear velocity of vehicle, K_{yfb} and K_{yff} are longitudinal force of the front wheels, K_{rff} and K_{rfb} and are rotatory force of the front wheels. $P_{ay\delta}^{n}$ and P_{ayN}^{n} is the linear force of front wheels.

The wheel model is important in the close-loop simulations of the vehicle, which has a great impact on dynamic stability control. And the active road safety controls and moving of vehicle are achieved by wheel force. In this study, the formula for the tyre model is used for the calculation of the state of the wheel including longitudinal force, rotator force and four in wheel center position and the linear force by the state of electric vehicle.

Each independent motor drive wheel stability model is described by:

$$T_a - T_b = J_\omega . w$$

$$T_a = K_m . i_e$$

$$T_c = K_m . i_d$$

$$E_m - K_e . \varphi - R . i_e = L_a . i_e$$

Where,

T_a, is the hub motor actual output torque,

T_b, is the load provided by electric vehicle model,

J_ω., is hub motor wheel rotational inertia,

W, is the wheel rotating speed,

T_c, is the controller desired torque,

K_m, is the torque coefficient,

i_d *and* i_e , are desired current and actual current,

R and L_a, represent the motor resistant and inductance, E_m, is the input voltage.

From the previous analysis, the in-wheel motor independent electric vehicle model has been generated in Simulink, and this EV dynamic equivalent model is used as the prognostic mode for variable mode stability analysis strategy. In this study, the electric vehicle models on the error conditions were made in the usual way, for example, this paper has assumed that the motor was breakdown when driving. And also the actual output torque of the motor that has been failed is always the *K*<1 times of expected output torque. The various electric vehicle models in different conditions are analysed and combined in to a multi-model predictive control, which may contains atleast two models divided by working conditions.

The previous studies, which deals with the torque control methods for electric vehicles and results obtained from verification on real cars have been analysed, are from the late 1980s. Particularly, the variation of the torque control system using sliding mode control has been introduced for an all four in-wheel drive electric vehicles. The variant of model-following variable stability control has been later introduced by Hori *et al*. By now, future developments in this domain are being performed in various industrial research centres and academic centres with tendency to exhibit continuous growth of relevant scientific works around the world. It is hard to propose the thorough classification of TC systems vehicles, despite a reasonable quantity of published studies, of electric by the following reasons, 1) there are different power train architecture of design elements and various designs of electric motors. Thus, when a specific torque control method had been presented on a particular vehicle model and another vehicle configuration might have strategies for the same traction controller implementation; 2) it was observed that regarding stability control engineering methods in experimental studies of various research groups only few particular approaches have progressive advancement. The most important analyzed publications describe few examples of one or another approach utilized in stability control systems of electric vehicles. There are some reasons to put the barriers for unbiased analysis comparison of different stability control methodologies. Hence, there is a substantial demand for the development of technologies in this field.

An appended separation is proposed for the dynamic based stability control systems. The precursory analysis has revealed various strategies, which are adopted for various controllers. In contempt of existing studies of dynamic based stability control systems based on linear or soft computing strategies, most of them were scrutinized on the simulation level only. However, a comparable amount of studies with verification on hardware components belongs to the systems using dynamic model based and model-following techniques.

Thus, it makes sense to use these methods as the platform for more detailed analysis. Other hierarchy of stability control systems is allocated for some other methods with utilization of wheel and road friction parameters and methods without detection of switching function. In annexation to the studies inspecting different variants of dynamic controllers and stability control architecture, a number of various problems of stability control for fully independent electric vehicles can be found in recent surveys. These problems, in particular 1) the assimilation of stability control with another system such as shepherd control, electronic stability control, etc; 2) the design of internal controllers of electric motors with special attention to stability control mode; 3) the implementation of different methods implemented in dynamic controllers, methods of experimental validation and testing of systems for electric vehicles; 4) the analysis of dynamic conditions in various controllers of electric vehicles; 5) NVH and vibration control of motors.

2.1 Wheel Slip Controller

The slip ratio *Si* (*i* = 1, 2, 3, and 4) of each tire should be controlled to no more than 0.2,Considering the longitudinal friction coefficient, rotational coefficient friction and the linear friction coefficient of the wheel. This improved performance and vehicle stabilization restriction is imposed because it can be achieved and if the slip ratio exceeds 0.175, with the slip ratio from 0.08 to 0.2, then the performance will considerably falls. To calculate the relative torques *Tii* (*i* = 1, 2, 3, and 4), the wheel slip controller is designed to keep the wheel slip ratio of each wheel below a certain value. When the magnitude of the wheel slip ratio, the wheel slip controller is only activated at the *i*th wheel is larger than a limit value *S*max. The input is the error of the slip ratio to the fuzzy controller. The fuzzy controller generates Tii using these error inputs, to track the desired wheel speed for the ith in-wheel motor. In the slip calculator by the actual wheel speed ni (i = 1, 2, 3, and 4), the actual wheel slip ratios can be computed and vehicle speed v. By the road friction coefficients the desired wheel slip ratios S−des can be estimated. The stability control rules used in the dynamic wheel slip controller. The definition of the primary input terms for the and output linguistic variables, Tii, and the categories of the fuzzy sets are all the same input linguistic variables, error ($e(s)$), and change of error ($\Delta e(s)$).

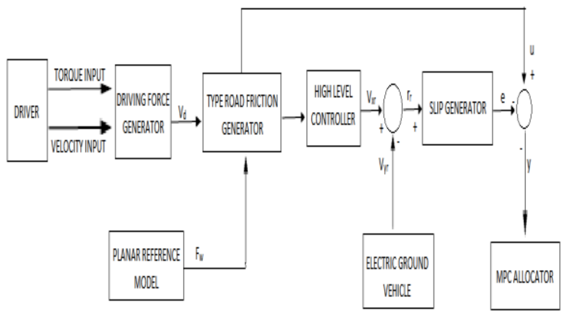

Figure 2 Overall block diagram of the proposed VSMC scheme

A common approach to obtain the parametric values is to solve the corresponding least-square problem. Moreover, the constant gain matrices may not be mathematically efficient for the complicated optimal strategy in VSMC. Thus, a Newton-like updated form with different gains at various steps may be considered to accelerate the optimal search process in VSMC. Considering that the problematic optimal process of VSMC, reflected by three main strategies, namely boundary constraints, switching gain errors, power consumptions, and in terms of 12 dynamic updates, expanding the parameter coordinate steps are necessary for good VSMC results. Coordination less issue of cost functions needs to be considered since the, power consumptions and boundary constraints, scales of errors are quite different. The easiest way is to divide ui by the respective maximum value by ui max $\_u$. Next, the weighting parameters, such as W, v, σ, and μ can be updated step by step through observing the values of respective terms during VSMC. Let us consider for example, $\sigma = 0$ first, W, v and μ can be considerably perceived to ensure that the stability analysis effects involving the virtual actuators u within certain related constraints. At last, linearly increasing σ can find a graduate balance between the power savings and the switching gains.

2.2 Electric Stability Control Algorithm

The proposed VSMC algorithm schematic is shown in Fig.2. An upper level controller, a stability judgment controller, and a torque distribution algorithm are designed for the VSMC system. The desired yaw rate and sideslip angle for vehicle stability and the two-degree-of-freedom bicycle dynamic model is designed to generate. Whether the control mode is usual driving mode or VSMC mode is confirmed by the measurement signal inputs mentioned in the driver input model and stability judgment controller according to the driver inputs.

The upper level controller consists of a yaw moment controller, speed tracking controller, and four wheel-slip controllers. The yaw moment input and the traction force input are calculated in the speed tracking controller and the yaw moment controller to track the desired vehicle speed, the desired yaw rate, and the desired sideslip angle based on the dynamic model and drive inputs. The wheel slip controller calculates the four net torque inputs of the four respective in-wheel motors to keep the wheel slip ratio of each wheel below a limit value to achieve maximum adhesion force of each wheel tire. An average torque distribution strategy, a tire-dynamic-load-based torque distribution strategy, and a minimum-objective-function based optimal torque distribution strategy are designed separately in the torque distribution algorithm to distribute the motor driving torques or the regenerative braking torques Ti (i = 1,2, 3, and 4) to track the desired vehicle speed, yaw rate, and sideslip angle for vehicle stability enhancement. $T*i$ (i = 1, 2,3, and 4) are the commands to four motor controllers from the torque distribution algorithm.

2.3 Stability Judgment Controller

The stability judgment controller is proposed to determine the control mode, which is normal driving mode or VSMC mode, corresponding to the driver inputs and measurement signal inputs. The VSMC algorithm is activated in VSMC mode. The commonly used three stability judgment methods are as follows:1) The yaw rate error constraint or the sideslip angle error constraint is used to judge the electronic stability condition, but the error constraint value is limited by factors such as vehicle speed and steering wheel angle; 2) the phase plane stability Judgment method of yaw rate-side slip angle, which is not effective for a vehicle on a low-adhesion-coefficient road due to the large sideslip angle; and 3) the sideslip-angle–sideslip-angle rate phase plane stability judgment method, which can achieve better identification for the electronic stability condition [22]. The schematic of electronic stability judgment in this paper is shown in Fig. 4. The sideslip-angle–sideslip-angle-rate phase plane method is used, and the influence on the stability caused by the yaw rate is considered [23]. The phase plane method can be expressed as $|B1\,\dot{\beta} + \beta| \le B2$ (1) where β and $\dot{\beta}$ denote the sideslip angle and the sideslip angle rate of the vehicle, respectively, $B1$ and $B2$ are the boundary parameters. $\Delta\gamma$ and γ−des are, respectively, the error and the desired value of γ, and γ denotes the yaw rate

International Journal of Advances in Computer and Electronics Engineering
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of the vehicle. The process of judging is as follows. First, *B*1 and *B*2 can be chosen according to Table II; based on the desired vehicle speed and the steering wheel angle, the vehicle running status, the difference between the desired and the actual yaw rate, the actual sideslip angle and the sideslip angle rate can be calculated. Next, the VSMC algorithm will be activated if (1) is false. If not, then the difference between the desired and the actual yaw rate will be compared with the limit value *K*. If the difference is larger than the limit value *K*, then the VSMC algorithm is also activated. The limit value *K* is chosen according to the vehicle speed [22]. In Fig. 4, *K* represents the limit value of the yaw rate difference. The value of *K* is related to factors, such as the road adhesion coefficient and the speed.

2.4 Tire-Dynamic-Load-Based Torque Distribution Strategy

The vertical load on each wheel is not equal during the vehicle actual operational process, particularly the steering process, due to the existence of longitudinal and lateral accelerations, which leads to the transformation of the vehicle vertical load.In addition, the maximum adhesion force of the wheel is related to both the road friction coefficient and the wheel vertical load. The maximum adhesion force will increase with the wheel vertical load when the road friction coefficient is assumed to be constant. Therefore, the influence of the wheel vertical load on the electronic stability should be taken into account in the torque distribution algorithm. That is, the traction torque distributed to the wheel with greater adhesion ability should be higher, and vice versa. In this case, the adhesion force of each wheel can be used more effectively, which prevents the wheel from slipping and improves vehicle stability. The tire-dynamic load-based torque distribution strategy is used to distribute the traction torque and the yaw moment according to the change of each wheel's vertical load.

3. SIMULATION RESULTS

In order to investigate the behaviour of the driver model in the nonlinear operating regime of the vehicle, the double-lane-change maneuver is repeated at a speed of 75 km/h. Figure 3 illustrates the vehicle trajectory when driving through the double-lane-change maneuver. Due to the fact that the vehicle is operating at its physical limit, the path-following driver model is unable to exactly match the actual vehicle trajectory with the desired one; however, the driver model is able to keep the vehicle under control throughout the entire maneuver, using counter-steering at some points. Figure 4 shows the driver's steering wheel input which, in comparison to that shown in Figure 4, is much larger. Figure 5 illustrates the vehicle yaw rate with respect to the drivers steering wheel input, which is considered to be a handling performance figure. Comparing this plot with Figure 3, it is clear that the phase shift between the vehicle yaw rate and the drivers steering wheel input is much larger when driving through the double-lane-change maneuver at a high speed, which ultimately indicates that the vehicle responsiveness has been reduced. Figure 4 illustrates the vehicle yaw rate and sideslip angle for this maneuver, and confirms that the vehicle was operating within its physical limits.

The second test maneuver that is used to evaluate the performance of the multiple-preview-point path-following driver model is a steady-state constant radius cornering maneuver. Here, the AUTO21EV is driven through a circular path with a radius of 75 meters. The driver model attempts to keep the vehicle on the predefined path while the vehicle speed is continuously increasing from an initial speed of 5 km/h to a maximum speed of 90 km/h. As illustrated in Figure 6, the driver model is able to keep the vehicle on the predefined circular path even at higher velocities. As can be seen, the driver model

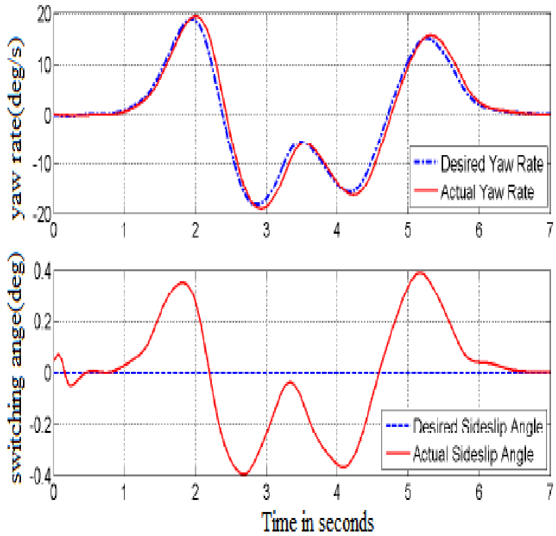

Figure 3 Desired and actual switching angle and yaw rate when driving at 40km/h

continuously adjusts the steering wheel angle in order to keep the vehicle on the desired path. As the vehicle speed is increased, the driver model applies a larger steering wheel angle, thereby generating larger lateral forces on the front axle in order to compensate for the larger centripetal acceleration. This figure confirms the performance of the gain scheduling PID speed controller, as the actual vehicle speed precisely follows the driver"s speed request.

In order to further evaluate the performance of the gain scheduling PID speed controller, the vehicle is accelerated and then braked in a stepwise speed-variation mode while driving in a straight line. In this test, the driver first increases the vehicle speed from 10 km/h to the maximum speed of 90 km/h in increments of 20 km/h. Next, the driver reduces the vehicle speed back to 10 km/h, again in a stepwise manner. Figure 4 illustrates the driver's speed request and the actual vehicle speed response for this maneuver. As can be seen, the actual vehicle velocity follows the driver‟s request very well, without causing any overshoot or significant over-damped conditions. Note that the torque of the in-wheel motors reduces as the vehicle drives faster as a result of the undesirable induction voltage produced by the permanent magnets.

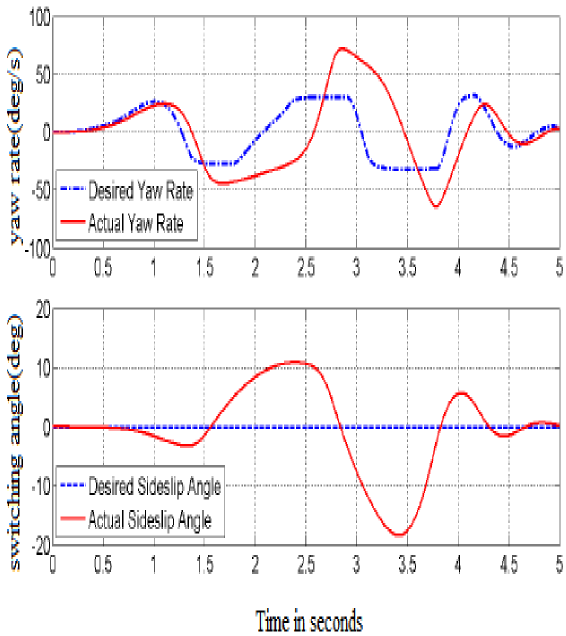

Figure 4 Desired and actual switching angle and yaw rate when driving at 75km/h

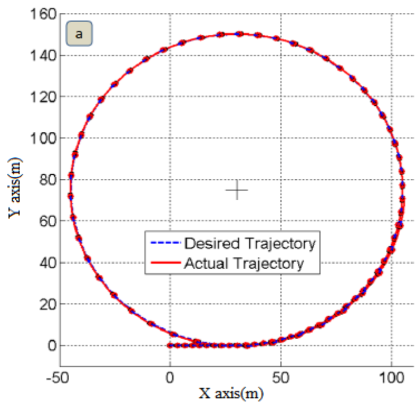

Figure 5 Desired and actual vehicle trajectories

Consequently, the acceleration response at lower speeds is faster than that at higher speeds. Note that, at the beginning and end of the test maneuver, where the vehicle is travelling at lower speeds, the maximum motor torque is available at each wheel; as the vehicle speed increases, the maximum possible motor torque decreases. It is important to notice that the slip controllers on the front axle have limited the motor torques at the beginning of the maneuver in order to avoid tire spin-out, and the slip controllers at the rear wheels have limited the motor torques at the end of the maneuver in order to avoid tire lock-up.

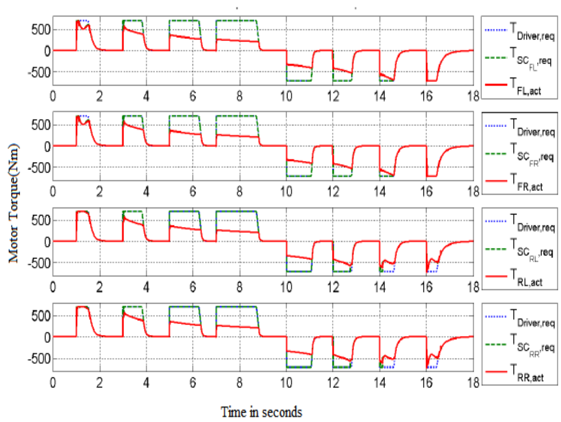

Figure 6 Motor torques during the stepwise speed variation test when driving in a straight line

4. CONCLUSION

A vehicle stability control system for a four in wheel motor independent electric vehicle is presented. The proposed control method does not need the accurate vehicle parameters or tire force models but still can control the vehicle to follow the desired trajectories. An analytic solution was found to distribute the required control efforts from the higher-level controller to the four wheels without explicit considerations on actuator constraints. Simulations using a high-fidelity, full-vehicle model show the effectiveness of the control approach. Tire force constraints are not explicitly considered in the proposed tire force distribution design and will be incorporated in the future study.

This paper has presented VSMC algorithm for the a four in wheel motor independent electric vehicle using motor driving and regenerative braking torque distribution control to improve vehicle stability. A stability judgment controller, an upper level controller, and a torque distribution strategy are designed for the VSMC system. The stability judgment controller is designed to generate the desired yaw rate and the sideslip angle for vehicle stability, and the control mode, which is normal driving mode or ESC mode, is determined according to the driver inputs and measurement signal inputs. The upper level controller consists of a speed tracking controller, a yaw moment controller, and four wheel-slip controllers based on the control, the fuzzy control, and the fuzzy control method, respectively, to calculate the desired value of the traction force, the desired value of yaw moment, and the four net torque inputs off our in-wheel motors, respectively. The torque distribution strategy is designed to generate each motor driving torque or regenerative braking torque input for vehicle stability enhancement.

The proposed ESC algorithm based on the average torque distribution strategy, the tire-dynamic-load-based torque distribution strategy, and the minimum-objective-function-based optimal torque distribution strategy for vehicle lateral stability was evaluated using simulations of a single-lane-change, a double lane-change, and a snake-lane-change maneuver.

The torque distribution rules for four in-wheel motors were obtained. The simulation studies demonstrated that the performance in vehicle lateral stability and maneuverability can be significantly improved by using the three proposed torque distribution strategies. Unlike the average torque distribution strategy and the tire dynamic-load-based torque distribution algorithm, the optimal torque distribution algorithm accounts for the dynamic load friction; as a result, the optimal torque distribution algorithm provides better tracking of the trajectory, the sideslip angle, and the yaw rate at high speed on roads with a low adhesion coefficient. Decreasing the driving torques of the inside motors or increasing the regenerative braking of the inside motors can increase the yaw moment, which is required to ensure lateral stability. In the case of optimal control, the four wheels are independently driven by the driving or braking torques generated by the four in-wheel motors, whereas only the two inside motorshave braking torques to enable the regeneration of energy backto the battery.

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