Design of Electronic Differential System for An Electric Vehicle with In-Wheel Motor

Merve Yıldırım[1], Eyyüp Öksüztepe[2], Burak Tanyeri[3], and Hasan Kürüm[4]
[1,4]Department of Electrical and Electronics Engineering, University of Fırat, Elazığ, Turkey
[2]School of Aviation, University of Fırat, Elazığ, Turkey
[3]Department of Automotive Engineering, University of Fırat, Elazığ, Turkey

Abstract—**This paper presents design of Electronic Differential System (EDS) for an Electric Vehicle (EV) with in-wheel motor. EDS is generally used in EVs due to some drawbacks of mechanical differential such as being heavy systems and mechanical losses caused by the powertrains. According to the turning angle of the wheel, task of EDS for front wheels is to adjust rpm of the wheels. On the contrary for rear wheels, only rpm control is realized due to not steering. Hence, there are less studies on EDS for front wheels of EV in the literature. In this study, an EDS for front wheels of EV is designed. According to steering angle and speed of EV, the speeds of the front wheels are estimated by equations derived from Ackermann-Jeantand model using Codesys Software Package. The estimated speeds are sent to Induction Motor (IM) Drives via Controller Area Network-Bus (CAN-Bus). EDS is also simulated by Matlab/Simulink. Then, the speeds of the front wheels are experimentally measured by a tachometer. Codesys results are verified by both Simulink and experimental results. It is observed that the designed EDS is convenient for EVs with in-wheel motor.**

Keywords—electric vehicle; in-wheel motor; electronic differential system design

I. INTRODUCTION

In recent years, EVs are commonly used to eliminate the emission of the harmful gases, reduce dependency on the countries imported oil by providing fuel-saving, and prevent the air pollution. Developments in drive and battery technology, using of efficient electric motors, and safe driving increase using of EVs [1]. Motors of an EV which has one traction-motor driving two wheels using a differential gear are fitted into the wheels to reduce increased EV mass due to the batteries and using of the drive-trains, get fast response from the motors, and provide independent torque control of each wheel [2, 3]. Differential systems for the vehicles are utilized in slippery and sloping roads to distribute power and torque equally to the traction wheels. The inner wheel speed has to be different from the outer wheel speed for a vehicle driving on a curved road to ensure safe driving [4]. An EDS instead of mechanical differential is used for EVs to eliminate mechanical losses, maintenance, and repair costs of gears caused by the powertrains.

As examining the studies on EDS in the literature, modeling and simulation of EDS for an EV with two-motor-wheel drive are realized by the fuzzy logic control method used to estimate the slip rate of each wheel in [2]. Designed EDS is verified by Matlab/Simulink results. In [5], an electric differential system for two independent rear wheels of EV is presented and analysis of speed and torque observer for DC motor is carried out. Rear wheel torque vectoring algorithm based on Ackermann Jeantand model is designed for dual motor electric drive system in [6]. The simulation of the system is realized in Excel to show different cornering cases. Authors in [7] propose a speed control method for differential steering of four wheel independent driving EV. The equations are given by Ackermann Jeantand model based on the vehicle speed. The accuracy of designed system is proved by both simulation and experimental results. In another paper [8], an EDS for EV with two independent rear wheel drives is designed by neural network control used for estimating the vehicle speed. According to the change of the vehicle speed, the speeds of the rear wheel drives are obtained by this method. The simulation results are verified by testing two 37-kW IMs. [9] presents a new EDS control architecture for the traction system in rear electric traction passenger hybrid electric vehicles (HEVs). The simulation results are tested successfully taking experimental results by a HEV in Low Scale (HELVIS)-Sim simulation. As a result, it is observed that the studies on the EDS for rear wheels of EV are generally realized in the literature. Conversely in this paper, an EDS for front wheels of EV is designed. According to the change of the steering angle and speed of EV, the speeds of the front wheels are estimated by Codesys Software Package using mathematical equations obtained from Ackermann-Jeantand model. The steering angle is obtained by a position encoder via CAN-Bus protocol which are commonly used in EVs due to having significant advantages for EV such as being fast, flexible, and reliable, using fewer cables thus, low cost and vehicle weight. The estimated speeds of the front wheels are sent to the IM drives via CAN-Bus and the speeds are experimentally measured by a tachometer. Then, Matlab/Simulink modeling is realized by using the equations. Codesys results are verified with both Simulink and experimental results.

This paper is organized that Section II describes EDS for EV. Besides, Ackermann-Jeantand model of driving trajectory at low speeds is comprehensively explained in this section. In Section III, Matlab/Simulink modeling of EDS is carried out.

This work is supported by TUBITAK (The Scientific and Technological Research Council of Turkey) with the project, 113M090.

978-1-5090-0261-0/16/$31.00 ©2016 IEEE

Section IV includes the experimental results. Codesys results are compared with both Simulink and experimental results. Conclusions are given at the end.

II. Electronic Differential System for EV

In this study, Ackermann-Jeantand model discovered by Rudolf Ackermann in the 19th century is used for EDS design [10]. When an EV is driven on a curved road, this model is generally preferred at low speeds due to the effect of centrifugal force and centripetal forces. Depending on the road curve, the speed of the outer wheel must be higher than the speed of the inner wheel. Ackermann-Jeantand model of EDS for an EV with in-wheel motor is given in Fig. 1.

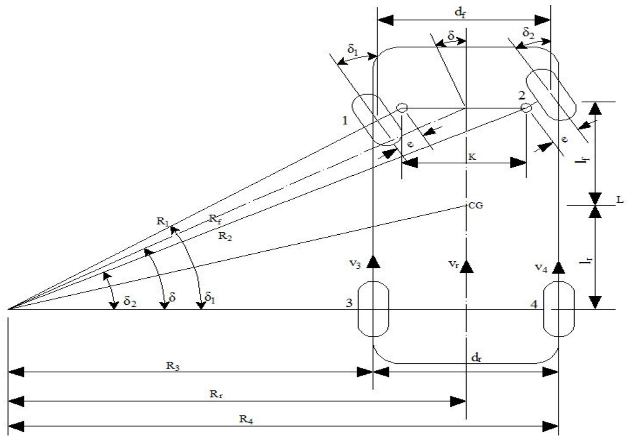

Fig. 1. Ackermann-Jeantand model of driving trajectory at low speeds [2].

A position encoder is used for the steering angle (δ). Once δ is zero, it is explained that EV drives on a straight road. If δ is different from zero, it means that EV turns left or right. According to the turning direction, the speed of the outer wheel has to be higher than that of the inner wheel [2, 11]. In this situation, the EDS is activated. The equations derived from this model are as follows

The inner steering angle of the front wheel is given by

$$\delta_1 = \arctan\left[\frac{L \cdot \tan(\delta)}{L - ((K/2) \cdot \tan(\delta))}\right] \tag{1}$$

The outer steering angle of the front wheel is given by

$$\delta_2 = \arctan\left[\frac{L \cdot \tan(\delta)}{L + ((K/2) \cdot \tan(\delta))}\right] \tag{2}$$

where K is the distance between the left and right kingpin, L is the distance between the front and rear wheel.

To estimate the speeds, the turning radii of the front inner and outer wheels, rear inner and outer wheels can be respectively expressed by

$$R_1 = \frac{L}{\sin(\delta_1)} \tag{3}$$

$$R_2 = \frac{L}{\sin(\delta_2)} \tag{4}$$

$$R_3 = \frac{L}{\tan(\delta)} - \frac{d_r}{2} \tag{5}$$

$$R_4 = \frac{L}{\tan(\delta)} + \frac{d_r}{2} \tag{6}$$

where d_r is the distance between rear wheels.

The radius of the gravity centre of EV is

$$R_{cg} = \sqrt{(R_3 + (d_r/2))^2 + (l_r)^2} \tag{7}$$

where l_r is the distance between the rear wheel and gravity centre.

The angular speeds of front inner and outer wheels, and rear inner and outer wheels can be respectively expressed by

$$w_1 = \frac{V \cdot R_1}{(R_{cg}) \cdot r} \tag{8}$$

$$w_2 = \frac{V \cdot R_2}{(R_{cg}) \cdot r} \tag{9}$$

$$w_3 = \frac{V \cdot R_3}{(R_{cg}) \cdot r} \tag{10}$$

$$w_4 = \frac{V \cdot R_4}{(R_{cg}) \cdot r} \tag{11}$$

where r is the radius of the wheel and V is the speed of EV.

The equations derived from Ackermann-Jeantand geometry are given into Codesys Software Package. L, l_r, d_r, r, and K parameters in Table 1 are taken from a vehicle model and these parameters are used as the constant values in the Codesys programme.

TABLE I. EDS Model Parameters

Parameters	L	l_r	d_r	r	K
Values (mm)	2.285	0.835	1.35	0.395	1.219

The speeds of the front wheels are estimated by Codesys Software based on the different steering angles and speed of the EV. Codesys simulation of EDS is shown in Fig. 2.

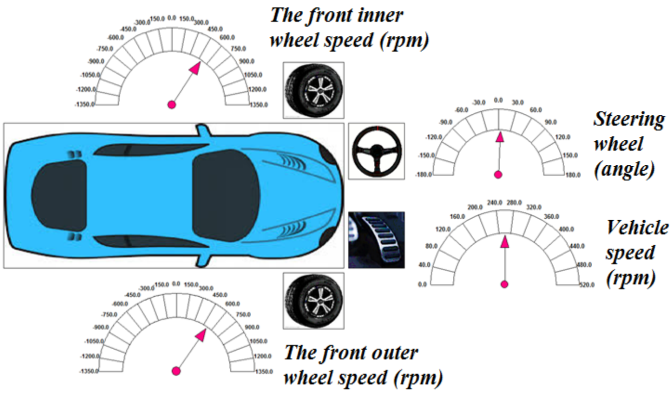

Fig. 2. Codesys simulation model of EDS

III. MATLAB/SIMULINK MODEL OF EDS

EDS is also simulated by Matlab/Simulink to validate the speeds of the front wheels of EV estimated by Codesys using the equations obtained from Ackermann Jeantand model. The simulation model is shown in Fig. 3. While the speed of an EV having 21-inch wheel size is 50 km/h, the angular speed value corresponding this value is 505.538 rpm. Hence, this value is utilized in the simulation. When the steering angle and the speed of the EV are respectively taken as 2˚ and 505.538 rpm, the wheel speeds obtained by Simulink are given in Fig. 4.

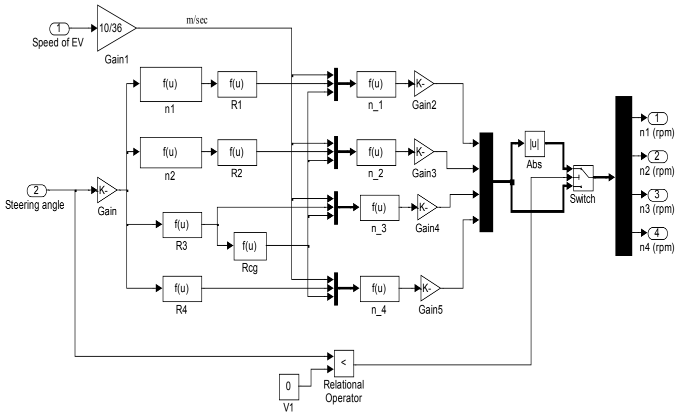

Fig. 3. Matlab/Simulink model of EDS

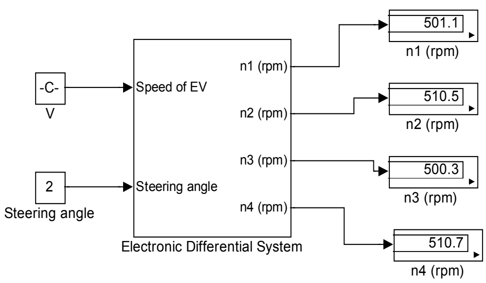

Fig. 4. Matlab/Simulink results of EDS

IV. EXPERIMENTAL RESULTS OF DESIGNED SYSTEM

The experimental setup has been established in Fig. 5. Three-phase IM drives (VFD C2000), HY-TTC 60 and encoder which are fed from 24 V power supply have been connected to CAN-Bus. CAN-Bus connection of the IM drives has been shown in Fig. 6. Characteristic line impedances have been used in beginning and end of the line. In our study, CANopen master unit is HY-TTC 60 processor which is an advanced model of 16-bit controller family produced by TTControl Company and consists of power and control cards. Two drives connected to IM motors and encoder are slave units on the CAN-Bus line.

Fig. 5. The experimental setup

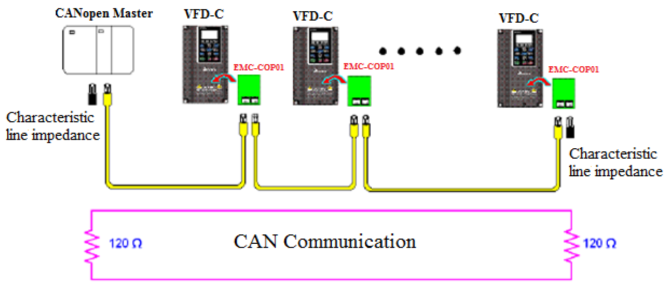

Fig. 6. CAN communication of the drives [12].

The steering angle has been changed from 1˚ to 15˚ with a degree range. Maximum maneuverability can be calculated by minimum circle radius of outer wheel trace at 10 km/h vehicle speed. Turning radius is given as follows

$$\varsigma = \frac{L}{\sin(\delta_1 - \delta_2)} \tag{12}$$

Turning radius changes between 7 m and 9 m in passenger cars. Another factor limited the steering of the wheel is also movement area where is placed in the wheels. Therefore, the steering angle has been taken as maximum value, 15˚. Then, the speeds of the front wheels (n_1, n_2) have been experimentally measured by a tachometer. Codesys results of n_1 and n_2 have been verified by both Simulink and experimental results in Table 2 and Table 3 based on the direction of the steering wheel. Codesys, Simulink, and experimental results of n_1 and n_2 have been also plotted in Fig. 7, 8, 9, and 10, respectively.

TABLE II. COMPARISON OF SIMULINK, CODESYS, AND EXPERIMENTAL RESULTS

Steering Angle (Degree)	Codesys Results (rpm)		Simulink Results (rpm)		Exp. Results (rpm)		Error % (According to the exp. results)	
	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2
0	505.538	505.538	505.5	505.5	505.5	505.5	0.007	0.007
1	503.251	507.958	503.3	508	503.1	508.0	0.03	0.008
2	501.099	510.510	501.1	510.5	501.0	510.3	0.019	0.041
3	499.083	513.195	499.1	513.2	498.9	512.8	0.036	0.076
4	497.204	516.01	497.2	516	497.1	515.9	0.061	0.021
5	495.464	518.957	495.5	519	495.3	518.9	0.033	0.010
6	493.865	522.035	493.9	522	493.6	521.7	0.053	0.064
7	492.409	525.243	492.4	525.2	492.5	524.8	0.018	0.084
8	491.098	528.583	491.1	528.6	491.0	528.2	0.019	0.072
9	489.936	532.054	489.9	532.1	489.8	531.8	0.027	0.047
10	488.924	535.657	488.9	535.7	488.9	535.6	0.004	0.010
11	488.065	539.394	488.1	539.4	488.0	538.9	0.013	0.091
12	487.364	543.264	487.4	543.3	487.1	543.0	0.054	0.048
13	486.822	547.270	486.8	547.3	486.6	546.9	0.045	0.067
14	486.444	551.412	486.4	551.4	486.3	551.1	0.029	0.056
15	486.234	555.693	486.2	555.7	486.0	555.3	0.048	0.070

TABLE III. COMPARISON OF SIMULINK, CODESYS, AND EXPERIMENTAL RESULTS FOR THE STEERING WHEEL IN THE OPPOSITE DIRECTION

Steering Angle (Degree)	Codesys Results (rpm)		Simulink Results (rpm)		Exp. Results (rpm)		Error % (According to the exp. results)	
	n_1	n_2	n_1	n_2	n_1	n_2	n_1	n_2
0	505.538	505.538	505.5	505.5	505.5	505.5	0.007	0.007
1	507.958	503.251	508	503.3	507.9	503.5	0.011	0.049
2	510.510	501.099	510.5	501.1	510.2	500.9	0.060	0.039
3	513.195	499.083	513.2	499.1	512.9	498.8	0.057	0.056
4	516.01	497.204	516	497.2	515.7	497.0	0.060	0.041
5	518.957	495.464	519	495.5	518.5	495.3	0.088	0.033
6	522.035	493.865	522	493.9	521.9	493.6	0.025	0.053
7	525.243	492.409	525.2	492.4	524.8	492.2	0.084	0.042
8	528.583	491.098	528.6	491.1	528.3	490.9	0.053	0.040
9	532.054	489.936	532.1	489.9	531.8	489.8	0.047	0.027
10	535.657	488.924	535.7	488.9	535.2	488.7	0.085	0.045
11	539.394	488.065	539.4	488.1	539.0	488.0	0.073	0.013
12	543.264	487.364	543.3	487.4	543.1	487.2	0.030	0.033
13	547.270	486.822	547.3	486.8	546.8	486.7	0.085	0.025
14	551.412	486.444	551.4	486.4	551.3	486.3	0.020	0.029
15	555.693	486.234	555.7	486.2	555.4	486.0	0.052	0.048

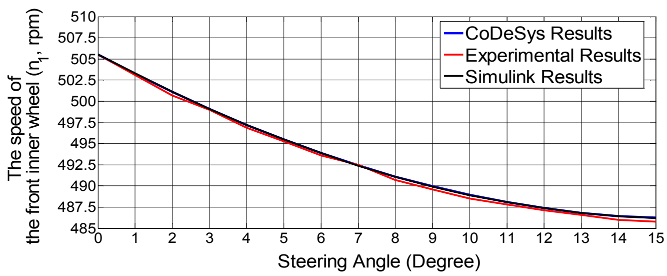

Fig. 7. Simulink, Codesys, and experimental results of n_1

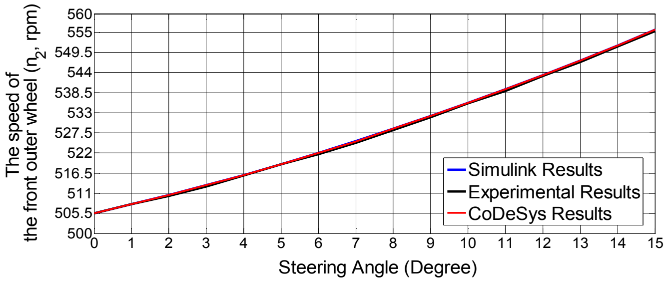

Fig. 8. Simulink, Codesys, and experimental results of n_2

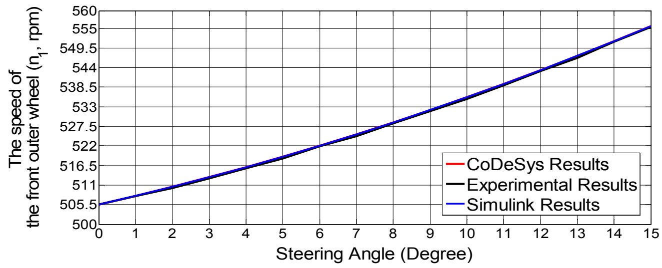

Fig. 9. Simulink, Codesys, and experimental results of n_1 for steering wheel in the opposite direction

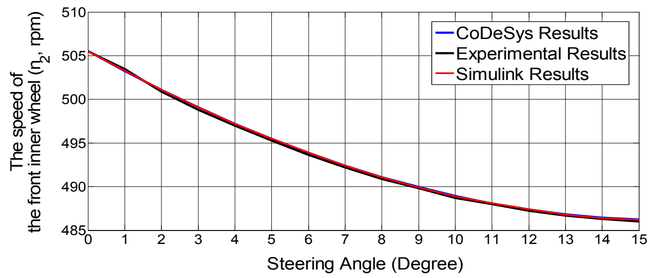

Fig. 10. Simulink, Codesys, and experimental results of n_2 for steering wheel in the opposite direction

V. CONCLUSION

In this paper, an EDS for front wheels of EV is designed. While rpm of the wheels is adjusted based on the turning angle of the wheel in EDS design for front wheels, only rpm control is realized for rear wheels due to not steering. According to the steering angle and speed of the EV, the speeds of the front wheels are estimated by mathematical equations derived from Ackermann-Jeantand model using Codesys Software Package. The estimated speeds are sent to the IM drives via CAN-Bus and measured experimentally by a tachometer. Then, Matlab/Simulink modeling is also realized using the equations. By changing of the steering angle from 1° to 15° with a degree range, the speed values of the front wheels are obtained by Codesys, Simulink, and experimental results. The results show that while the inner wheel speed of the EV decreases, the outer wheel speed increases by rising the steering angle value. Codesys results are verified by comparing with both Simulink and experimental results. In conclusion, it is observed that the simulation results are satisfactory. In future studies, the designed EDS can be tested on an EV, road experiments can be realized, and the studies can be also made at different vehicle speeds.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of The Scientific and Technological Research Council of Turkey (No: 113M090)

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