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Electric Differential for an Electric Vehicle with Four Independent Driven Motors and Four Wheels Steering Ability Using Improved Fictitious Master Synchronization Strategy

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ABSTRACT

Using an Electric Differential (ED) in electric vehicle has many advantages such as flexibility and direct torque control of the wheels during cornering and risky maneuvers. Despite its reported successes and advantages, the ED has several problems limits its applicability, for instance, an increment of control loops and an increase of computational effort. In this paper, an electric differential for an electric vehicle with four independent driven motors is proposed. The proposed ED is easy-to-implement and hasn't the problems of previous EDs. This ED has been developed for four wheels steering vehicles. The synchronization action is achieved by using an improved fictitious master technique, and the Ackerman principle is used to compute an adaptive desired wheel speed. The proposed ED is simulated and the operation of the system is studied. The simulation results show that ED ensures both reliability and good path tracking.

KEYWORDS: Ackerman principle, Electric differential, Electric vehicle, Fictitious master, Synchronization strategy.

1. INTRODUCTION

In recent decades, transportation investigations have emphasized the development of high efficiency, clean, and safe transportation, therefore Electric Vehicles (EVs) have been typically proposed to replace with conventional vehicles in the future. EVs use energy storage elements, such as batteries, to generate electric energy and transform it into mechanical energy by electrical motors to yield a required driving power.

Now the multi-motor and in-wheel-motor applications have a very attractive field in industrial applications, due to better stability and reducing the traditional mechanical coupling [1,2]. Therefore, they have less tailpipe emission and less fuel consumption.

The use of an Electric Differential (ED) instead of a Mechanical Differential (MD) constitutes a technological advance in vehicle design along the concept of multi-motor applications. The ED is characterized by the features as, no mechanical link between the drive wheels; the separately traction power to each wheel, the applied less power to the inner wheel during a turn and finally the ED act as a differential lock while the wheels of vehicle are driving straight paths. However, despite its long reported advantages, the application of the ED has been limited, mainly due to a number of problems in practical implementations, for instance, an increment of control loops and an increase of computational effort [3]. The fictitious master technique for synchronization of an electric differential for an electric vehicle with two independently driven motors has been presented in [3]. The control strategy has the advantage of being linear and, therefore, easy to implement. However, despite its many advantages, the synchronization strategy has a problem when the vehicle moves straight path.

The ED operation needs to solve two technological problems, wheel synchronization and

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computation of the relative wheel speed as a function of the turn angle. Usually, a synchronization structure such as master–slave, cross coupling, sliding mode, fuzzy or neural network control has been applied to control the relative speed during pathway in the ED [4]. In this reference, to obtain adaptive performance of ED a neural network based control method has been presented. But low reliability of neural network controllers is disadvantageous of the proposed method.

The inner and outer wheel velocity relationship in a corner has usually been described by the use of the Ackerman steering principle. This principle computes the relative speed difference in the wheels by using the data of the turn (steering) angle [5].

Electric differentials, could be classified in two categories. First involves EDs for EVs with two Wheels Drive (2WD) ability [5,6]. In this case, two rear or front wheels of EV are equipped with independent motors and ED system distributes traction power between them, adjusts wheels speed [7-11]. In second one, ED is designed for EV with four Wheels Drive (4WD) ability. In this case, all EV wheels are equipped with electrical motors [12]. In 4WD condition, the traction power divide between four motors, so the required motor sizes are small. Therefore, the chassis level of EV is lower and a part of aerodynamic problem is resolved. Also, EV has better weight distribution, could be helpful for stability of EV. These EDs have been developed for EVs with two Wheels Steering (2WS) [13] or Four Wheels Steering (4WS) ability [14]. However, the complex controller is the main disadvantage of the mentioned references.

Three types of ED have been proposed for in wheel drive EVs in [13], to reduce controller complexity and expensive sensors. But in the proposed methods, because of uncertainty in the estimated speed, can lead the overall performance to become unstable in hard driving conditions. It seems that generally the ED designs with only two in-wheel drive motors, separated from the steering wheels, are studied in the papers.

In the present paper, an electric differential for an electric vehicle with four independent driven motors is proposed. This ED has been developed for four wheels steering vehicles. The method of four wheels steering can steer front wheels and rear wheels at once to least the side slip angle. So this method can increase the yaw response time of vehicle to the steering handle input and rotating performance by decreasing a radius of rotation.

The Ackerman principle is used to compute an adaptive desired wheel speed, and the synchronization action is achieved by using an improved fictitious master technique. The control strategy ensures both reliability and good path tracking for both curve and straight paths, and has the additional advantage of being easy to implement due to its linear nature. So it hasn’t the problems of previous EDs.

The proposed ED is simulated and the operation of the system is studied. The simulation results show that ED ensures both reliability and good path tracking.

2. MODELLING AND CONTROL STRATEGY

In this section, the proposed electric differential system for an electric vehicle with 4WD and 4WS ability is described. The four wheels of EV are equipped with four IMs that each of them directly linked to each wheel by virtue of a fixed gear. IMs have the ability to direct control of torque and speed. The kinematic and dynamic models of the system are derived, and the synchronization strategy is presented for the 4WD/4WS vehicle.

2.1. Wheels speed computation

Ackerman principle is used to compute wheels speed. Rudolf Ackerman discovered and defined this principle early in the 19th century. The principle of Ackerman Steering is the relationship between the front inside tire and front outside tire in a corner or curve. The Ackerman steering principle defines the geometry that is applied to all vehicles, whatever they are 2WS or 4WS to enable the correct turning angle of the steering wheels to be generated when negotiating a corner or a curve [15].

To create the proper geometry, the steering arms are angled to turn the inside wheel at a sharper angle than the outside wheel. This allows the inside wheel to follow a smaller radius circle than the outside wheel and prevents scrubbing of the steer tires while turning.

The Ackerman concept is to have all four wheels rolling around a common point during a turn. This can greatly improve cornering ability and performance. Turning of 4WD/4WS vehicle, according to Ackerman principle is shown in Fig. 1.

The ideal turning angles on the front and rear wheels are established by the geometry seen in the Fig. 1, and define the steering angles for the turn.

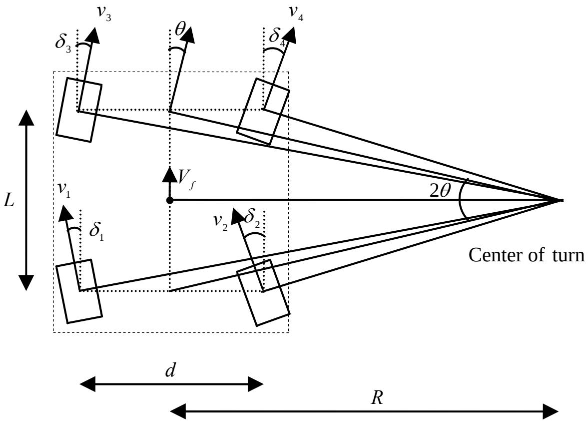

Fig.1. Turning of 4WD/4WS vehicle, according to Ackerman principle [16]

For proper geometry in the turn, the steer angles are given by below equations [16]:

$$\tan(\delta_1) = \frac{L/2}{R + d/2} \tag{1}$$

$$\tan(\delta_2) = \frac{L/2}{R - d/2} \tag{2}$$

$$\tan(\delta_3) = \frac{L/2}{R + d/2} \tag{3}$$

$$\tan(\delta_4) = \frac{L/2}{R - d/2} \tag{4}$$

where d and L are car's width and longitude, respectively, and R is the turn radius which is obtained with (5):

$$R = \frac{L}{2\tan(\theta)} \tag{5}$$

where θ is the steering angle of the vehicle.

The kinematic model of the car when tracking a curve path is given by the Ackerman equations. Such equations describe the relationship between the car angular velocity, ω_f, and the inner and outer wheels velocities using basic trigonometry. So, the linear speed of each wheel for 4WD/4WS vehicle can be expressed in terms of the angular vehicle speed ω_f and the turn radius R (see Fig. 1), *i.e.*:

$$v_1 = \omega_f \sqrt{\left(R + \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{6}$$

$$v_2 = \omega_f \sqrt{\left(R - \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{7}$$

$$v_3 = v_1 = \omega_f \sqrt{\left(R + \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{8}$$

$$v_4 = v_2 = \omega_f \sqrt{\left(R - \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{9}$$

Substituting (5) in (6) - (9), the angular speed of each wheel can be determined as follows:

$$\omega_1 = \frac{v_1}{r} = \frac{\omega_f}{r} \sqrt{\left(\frac{L}{2\tan(\theta)} + \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{10}$$

$$\omega_2 = \frac{v_2}{r} = \frac{\omega_f}{r} \sqrt{\left(\frac{L}{2\tan(\theta)} - \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{11}$$

$$\omega_3 = \frac{v_3}{r} = \frac{\omega_f}{r} \sqrt{\left(\frac{L}{2\tan(\theta)} + \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{12}$$

$$\omega_4 = \frac{v_4}{r} = \frac{\omega_f}{r} \sqrt{\left(\frac{L}{2\tan(\theta)} - \frac{d}{2}\right)^2 + \frac{L^2}{4}} \tag{13}$$

where r is the each wheel radius.

The angular velocity of each wheel can be acquired in term of vehicle linear velocity, V_f, with definition of it as follow:

$$V_f = R\omega_f \tag{14}$$

So:

$$\omega_f = \frac{V_f}{R} = V_f \frac{2\tan(\theta)}{L} \tag{15}$$

Substituting (15) in (10) - (13), the angular speed of each wheel in term of the vehicle linear speed can be determined as follows:

$$\omega_1 = \frac{V_f}{r} \sqrt{1 + \frac{2d}{L}\tan(\theta) + \left(1 + \frac{d^2}{L^2}\right)\tan^2(\theta)} \tag{16}$$

$$\omega_2 = \frac{V_f}{r} \sqrt{1 - \frac{2d}{L}\tan(\theta) + \left(1 + \frac{d^2}{L^2}\right)\tan^2(\theta)} \tag{17}$$

$$\omega_3 = \omega_1 = \frac{V_f}{r} \sqrt{1 + \frac{2d}{L}\tan(\theta) + \left(1 + \frac{d^2}{L^2}\right)\tan^2(\theta)} \tag{18}$$

$$\omega_4 = \omega_2 = \frac{V_f}{r} \sqrt{1 - \frac{2d}{L}\tan(\theta) + \left(1 + \frac{d^2}{L^2}\right)\tan^2(\theta)} \tag{19}$$

2.2. Dynamic model and synchronization strategy

By considering a four-wheeled vehicle subjected to the action of four electric motors situated on the all wheels, the equation of motion of the car is given as follows:

$$M\frac{dV_f}{dt} = -Mgf_r\cos(\alpha) - Mg\sin(\alpha) - \frac{1}{2}\rho A C_D V_f^2 + \frac{1}{r}\left(\sum_{i=1}^{4} u_i\right) \tag{20}$$

where M is the vehicle mass, g is the gravity constant, f_r is the rolling friction coefficient, α is the terrain inclination, ρ is the air density, A is the effective area of the aerodynamic resistance of the vehicle, C_D is the aerodynamic drag coefficient, and u_i ($i = 1, 2, 3, 4$) is the produced torque by each motor. Moreover, consider four induction motors with perfect field orientation (e.g., motors under indirect field-oriented control (IFOC) without field weakening), then the actuated wheel dynamics can be shown to be equivalent to:

$$\frac{\omega_i(s)}{u_i(s)} \approx \frac{1}{J_i s + b_i} \tag{21}$$

where *s* is the differentiator operator, and J_i and b_i are the moment of inertia and friction coefficient of each motor, respectively.

However, since the motors are attached to the vehicle, dynamics of vehicle and motors are coupled, and every perturbation on the vehicle will be reflected to the motors. In this way, we can rewrite the wheel dynamics in the embedded system as:

$$J_i\frac{d\omega_i}{dt} = -b_i\omega_i - T_{Li} + u_i - d_f r\left(Mgf_r\cos(\alpha) + Mg\sin(\alpha) + \frac{1}{2}\rho A C_D V_f^2\right) \tag{22}$$

where T_{Li} shows external perturbations at wheel *i*. Notice that since the vehicle and wheels velocity are related by the Ackerman equation, the whole vehicle–motor system can be described using only four differential equations, which are related to the vehicle plus three wheels dynamics or, alternately, all wheels dynamics, as follows:

The next step in the description of the proposed strategy for the electric differential system is to use the traction model of (22) – (26) to construct the synchronization scheme. In this paper, the used synchronization strategy is Improved Fictitious Master technique.

$$J_1\frac{d\omega_1}{dt} = -b_1\omega_1 - T_{L1} + u_1 - d_f r\left(Mgf_r\cos(\alpha) + Mg\sin(\alpha) + \frac{1}{2}\rho A C_D V_f^2\right) \tag{23}$$

$$J_2\frac{d\omega_2}{dt} = -b_2\omega_2 - T_{L2} + u_2 - d_f r\left(Mgf_r\cos(\alpha) + Mg\sin(\alpha) + \frac{1}{2}\rho A C_D V_f^2\right) \tag{24}$$

$$J_3\frac{d\omega_3}{dt} = -b_3\omega_3 - T_{L3} + u_3 - d_f r\left(Mgf_r\cos(\alpha) + Mg\sin(\alpha) + \frac{1}{2}\rho A C_D V_f^2\right) \tag{25}$$

$$J_4\frac{d\omega_4}{dt} = -b_4\omega_4 - T_{L4} + u_4 - d_f r\left(Mgf_r\cos(\alpha) + Mg\sin(\alpha) + \frac{1}{2}\rho A C_D V_f^2\right) \tag{26}$$

Reference [3] presented fictitious master technique to synchronization of an electric differential for an electric vehicle with two independently driven motors. The control strategy has the advantage of being linear and, therefore, easy to implement. However, despite its many advantages, the synchronization strategy has a problem when the vehicle moves straight path.

In this section, the fictitious master technique for the synchronization of electric differential system for a 4WD/4WS electric vehicle is presented and a basic block diagram of the synchronization controller is shown in Fig. 2. The blocks which are named "motor system 1" to "motor system 4" are related to the traction systems in (22)-(26). With this technique, the reference speed of each wheel is obtained according to Ackerman principle and equations (10)-(13) are used for computation of wheels reference speed.

In Fig. 2, it can be observed that the synchronization scheme is composed of three parts: 1) the fictitious master, 2) a speed controller to each motor (slave system), and 3) a link between them constituted by an average gain K_4 and adaptive references ω_1^*, ω_2^*, ω_3^* and ω_4^*.

Adaptive references $\omega_1^* - \omega_4^*$ are computed based on (10)-(13) using the actual angular velocity of the vehicle (ω_f) rather than the desired reference (ω_f^*). This feature allows the general transient and steady-state response of the overall system to be mainly determined by the fictitious master. In this way, perturbations at the slave stage can be reflected and compensated not only by the slave controller, but also by the virtual master controller, producing new references $\omega_1^* - \omega_4^*$; therefore moderated system responses are obtained even under impulsive perturbations. At this point, it is worthy to notice that perturbation functions T_{Li}, represent environmental or non-controller inputs. In addition, T_{Lf} is a function of system states and has the role of reflecting any control change (due to perturbations or saturations) of the slave controllers to the master controller. Summarizing, the fictitious master controls the torque reflected in each motor without using any torque transducer.

The torque load changes are detected and reflected back to each speed controller inside the IM controllers by using each motor signal u_i. Such signals are added and weighted using gain K_4 and then considered like an external torque command to the Fictitious Master. Once the master detects any load disturbance in any motor (T_{Li}), it produces a new speed reference to each motor controller using the Ackerman principle.

In this way, new references ω_1^* - ω_4^* are computed using (10)-(13). The objective of the proposed scheme is to reflect any disturbance in any wheel into all wheel dynamics via references ω_1^* - ω_4^*; therefore, synchronization is maintained without compromising vehicle stability. In the scheme (see Fig. 2), velocity loops in the wheels constitute slave controllers of a fictitious master controller. By using this procedure, speed synchronization during the speed transient and steady state is maintained, even during high-load impacts. In fact, the Fictitious Master transforms the problem of tracking the turn angle θ into a velocity-tracking problem using the dynamic parameterization from a fictitious system. Observe that this dynamic parameterization is not unique and will vary with the master structure. Different parameters on fictitious dynamics will lead to different vehicle desired velocities. Furthermore, the fictitious master establishes the control objective $\omega_f = \omega_f^*$ as a primary control objective, and wheels can be unsynchronized ($\omega_1^* \neq \omega_2^* \neq \omega_3^* \neq \omega_4^*$) to track ω_f^*. In fact, the only case when $\omega_1^* = \omega_2^* = \omega_3^* = \omega_4^*$ is along an unperturbed straight path. As previously stated, the fictitious master parameterizes the vehicle's velocity based on the designer's choice. Also, the general transient and steady-state response of the overall system is mainly determined by the fictitious master; therefore, it is convenient to properly choose system parameters to obtain good performance.

A slow master dynamics constitutes a conservative choice of dynamics, to depart from a stable configuration, opening the possibility for the designer to use a wide window of tuning gains to obtain a given performance. For example, if the virtual moment of inertia J_f is chosen sufficiently large, big peak current demands can be avoided, thus keeping the inverter current demand in a safety range. In this way, it is suggested to choose the following Fictitious Master parameters [3]:

$$J_f \geq \sum_{i=1}^{4} J_i \tag{27}$$

$$b_f \geq \sum_{i=1}^{4} b_i \tag{28}$$

As previously mentioned, the block diagram of Fictitious Master technique for electric differential of an electric vehicle with 4WD ability is shown in Fig. 2. It can be observed that the angular velocity of the vehicle is given to the system as a reference value. When a vehicle moves straight path with different speeds, its angular speed is always zero. So the election of angular velocity of the vehicle as a reference value causes some problems for the system.

If the linear speed of the vehicle is considered as a reference value, the block diagram of Fig. 2 will be changed into Fig. 3. In this status, the reference values of angular speeds in each wheel (ω_1^* - ω_4^*) are obtained by (16)-(19). By comparison of two block diagrams, it can be observed that the block diagram of Fig. 3 has the same structure of Fig. 2. Because of choosing V_f^* as a reference value for the system and using it to calculation of $\omega_1^* - \omega_4^*$ in this improved Fictitious Master technique, the problems of implementation of it when the vehicle moves a straight path has been removed.

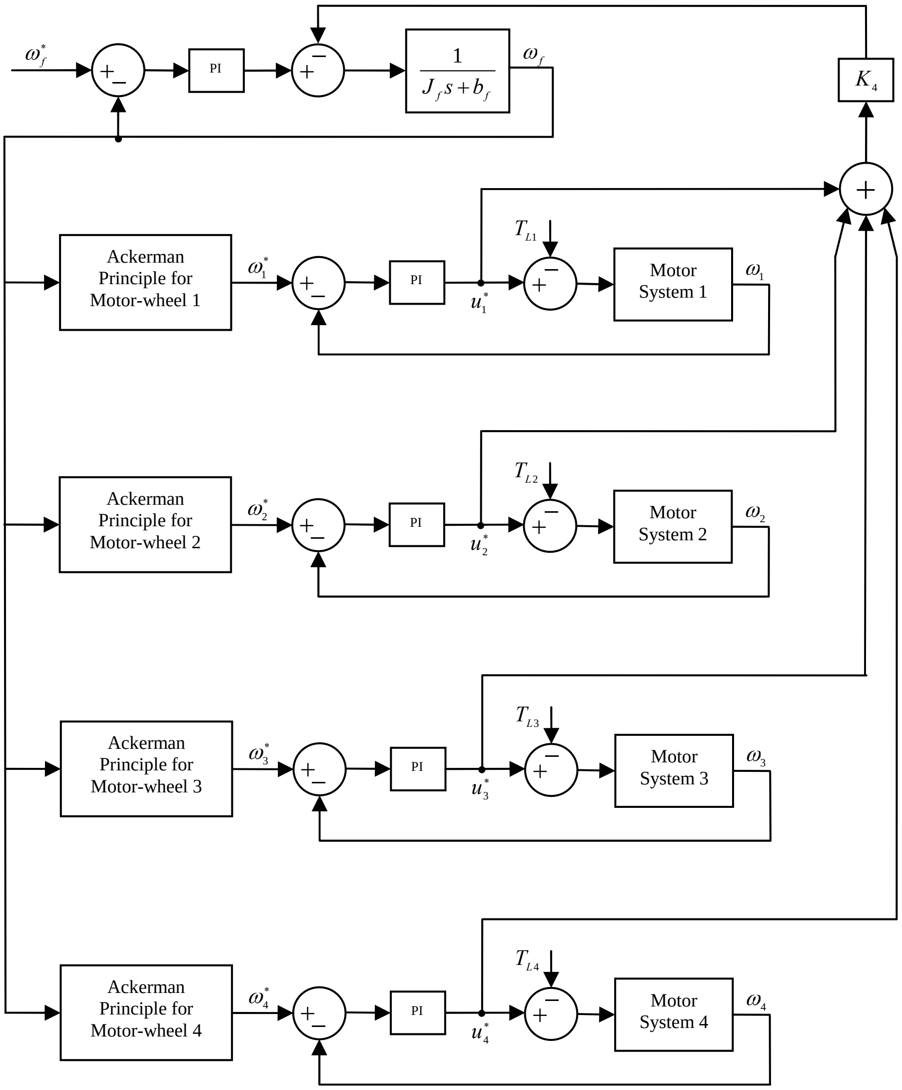

Fig. 2. Block diagram of the fictitious master technique for the synchronization of electric differential system for a 4WD/4WS electric vehicle

3. SIMULATION RESULTS

In this section, performance and robustness of the proposed technique are evaluated during transient and steady state conditions. As previously pointed out, we considered a four driving- wheel EV that places one IM directly linked to each wheel by virtue of a fixed gear. The simulation makes use of rigorous models of vehicle parts to accurately reflect the nonlinear behavior of the overall system. In this way, a complete mechanical model of the vehicle is used to accurately reflect the effect of car load, friction, and aerodynamic forces (parameters can be found in the Appendix).

IFOC is used to move each motor. The IMs work at their constant torque region and provide the full power required by the vehicle. PI compensators are used in DQ controllers. IFOC gains and other parameters can be found in Appendix I. At this point, it is interesting to note that, in contrast to the complexity of the model used; the control structure is simple, constituted by linear controllers, making the implementation task easier.

The transient and steady-state response of the overall system is controlled by the improved

Fictitious Master, which, in this case, is tuned using the biggest moment of inertia of the overall system with the aim to avoid a big peak current demand and to keep the inverter current demand in a safety range. The K_4 gain, which can be seen as an average weight gain, is chosen to be $K_4=1/4$.

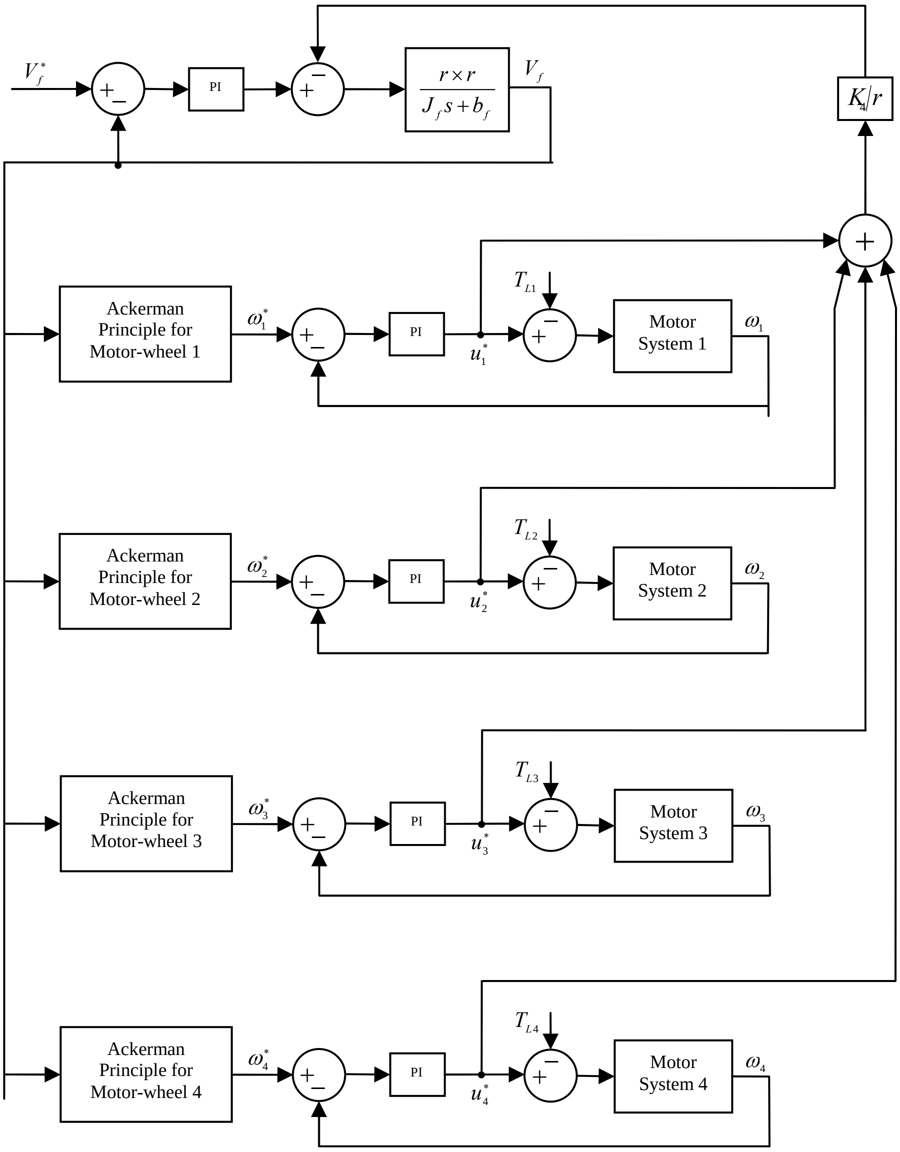

Fig. 3. Block diagram of the improved fictitious master technique for the synchronization of electric differential system for a 4WD/4WS electric vehicle

As a first step, the response of the vehicle during load impacts is evaluated. The system is perturbed while following a straight path with constant speed $V_f^* = 45$ Km/h , with a step-like load change. Fig. 4 shows the applied disturbance torque of motor 1. The simulation results are shown in Figs. 5 and 6. Fig. 6 shows that the produced torque of motor 1 has been increased to provide the applied load torque. Also, it can be seen in Fig. 5 that the speed of this wheel decreases under mentioned condition. If the problem stays in this stage, the synchronization of system has been removed due to the uncoordinated operation of the vehicle wheels. But the electric differential system reflects the disturbance in wheel 1 into all wheels dynamics via producing new references ω_1^* - ω_4^*; then, synchronization is maintained without compromising vehicle stability. So the ED simulates a differential lock while the wheels of vehicle are driving straight paths. Fig. 5

depict that a good degree of speed synchronization during the speed transient and steady state is maintained even during load changes.

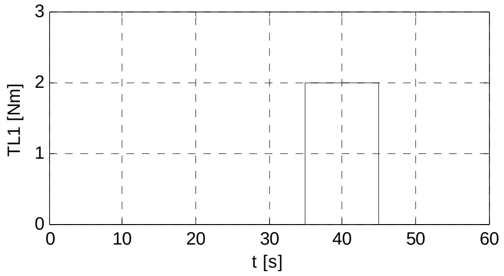

Fig. 4. The applied disturbance torque to motor 1

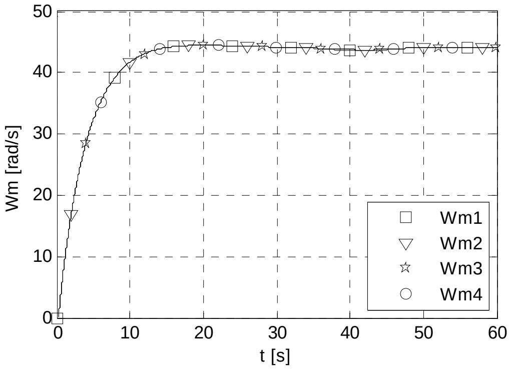

Fig. 5. The angular speeds of vehicle wheels under perturbed condition

On the other hand, to illustrate the performance of the proposed controller while follows curved paths with constant speed, the vehicle is required to follow the curve described by the trapezoidal steering angle in Fig. 7. With this steering angle, the steer angles of the wheels of the vehicle should be such as shown in Fig. 8. In contrast to the case of a straight path, during turns, the wheel velocity is unsynchronized (with respect to each other) for the vehicle to track the virtual reference V_f. That is, during a turn, the outer wheels must be faster than the inner wheels. The simulation results are shown in Figs. 9 and 10. It can be observed that the controller could simulate an electric differential system when the vehicle is turning. The speeds of outer wheels are more than the inner wheels during the turn and the motors produce the proper torque for good path tracking of vehicle.

Fig. 11 shows the curve path that vehicle moves. First, the steering angle of the vehicle is zero and the vehicle moves straight path. With increasing of θ, the vehicle turns and tracks a circular path when θ has its maximum value. With the decreasing of θ, the radius of turning increases and it moves in a straight path when θ becomes zero. The method of 4WS which used in present paper can increase rotating performance by decreasing the radius of rotation. The diameter of turn in recent simulation for the given steering angle is approximately 25m that is obtained from (5) and it can be shown in Fig. 11. If we use the method of 2WS, the diameter of turn in the same steering angle increases to approximately 50 m. It means that by using 4WS method, the vehicle can turn in an easier way.

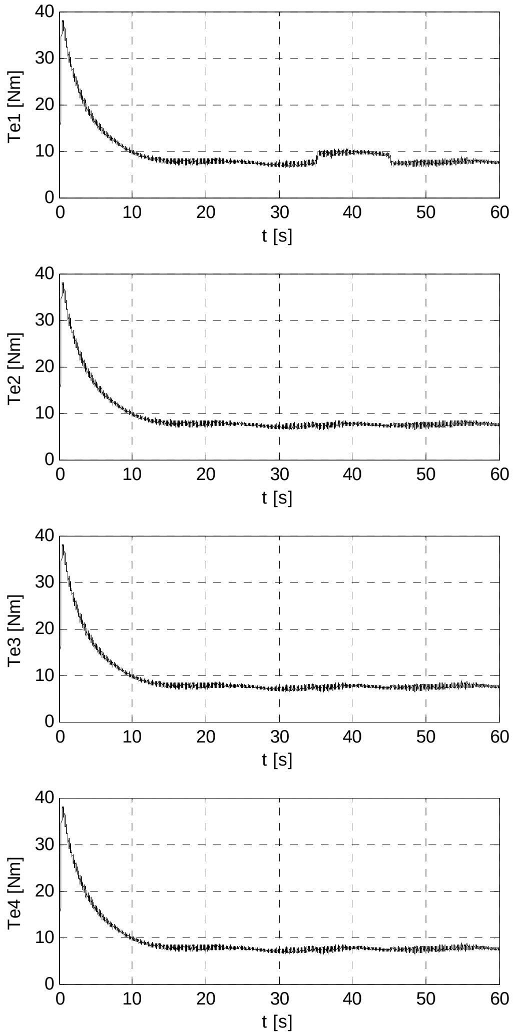

Fig. 6. The torque response of IMs under perturbed condition

It is obvious that by choosing V_f^* as a reference value for the calculation of ω_1^* - ω_4^* in the presented synchronization strategy (improved fictitious master technique), the problems of implementation of ED when the vehicle moves a straight path has been removed. So the system has a good operation even when θ is zero.

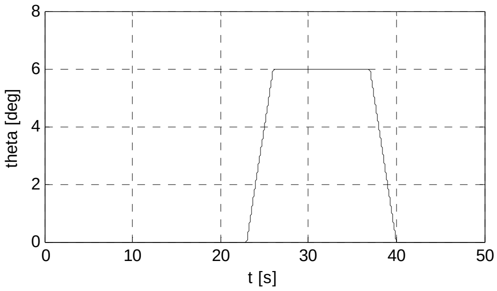

Fig. 7. The steering angle of vehicle

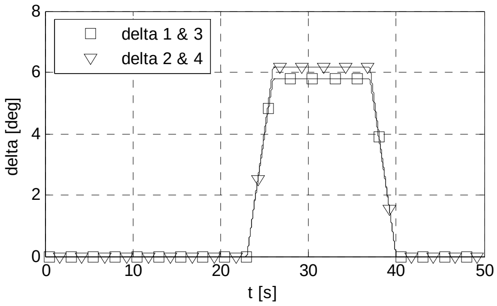

Fig. 8. The steer angles of vehicle wheels

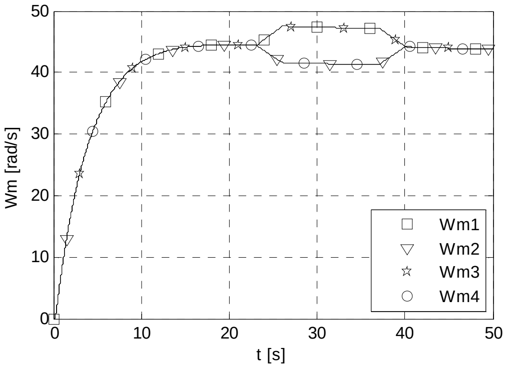

Fig. 9. The angular speeds of vehicle wheels when turning

4. CONCLUSIONS

In this paper, an electric differential for an electric vehicle with four independent driven motors has been proposed. The proposed ED is easy to implement and hasn't the problems of previous EDs. This ED has been developed for four wheels steering vehicles. The method of 4WS can steer both front wheels and rears wheel to minimize the side slip angle. Thus, this method can increase rotating performance by decreasing a radius of rotation.

The synchronization action is achieved by using an improved fictitious master technique, and the Ackerman principle is used to compute an adaptive desired wheel speed. The proposed ED is simulated and the operation of system is studied under perturbed condition, and straight and curved path tracking. The simulation results show that ED ensures both reliability and good path tracking. The study of faulty conditions like motor failure can be performed in the future.

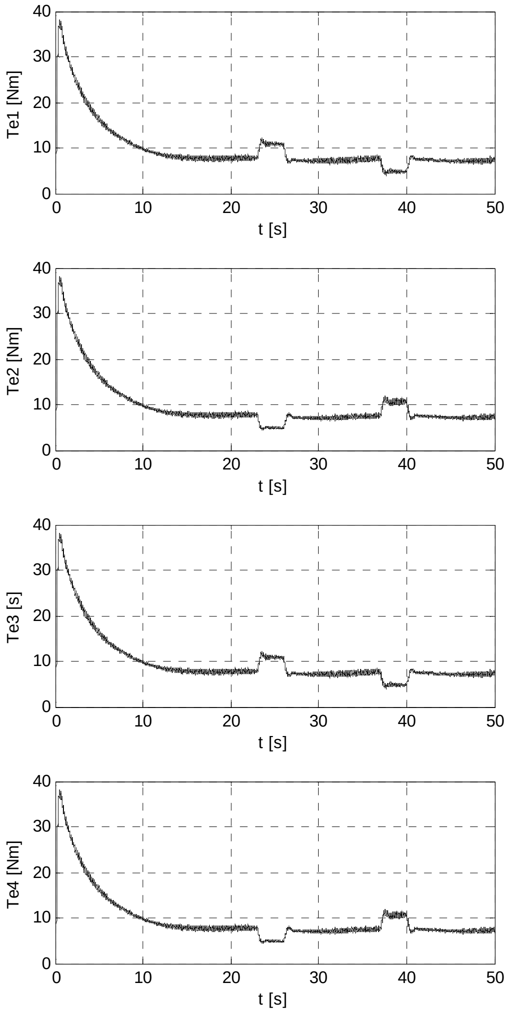

Fig. 10. The torque response of IMs when the vehicle is turning

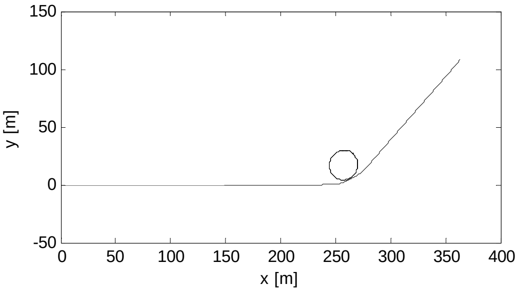

Fig. 11. The curve path that vehicle moves

APPENDIX

For all motors, the following parameters are used: $V_{rated} = 220\mathrm{V}$, $2p = 4$, $L_s = 0.03\mathrm{H}$, $L_r = 0.03\mathrm{H}$, $L_m = 0.44\mathrm{H}$, $R_s = 4\Omega$, $R_r = 2\Omega$, $J = 1.5\mathrm{kg/m^2}$, $b = 0.01\mathrm{Nms/rad}$. The Fictitious Master parameters are: $J_f = 6\mathrm{kg/m^2}$, $b_f = 0.04\mathrm{Nms/rad}$. IFOC controller gains for all motors are: $K_{pd\,IFOC} = 21.779$, $K_{id\,IFOC} = 823.65$, $K_{pq\,IFOC} = 21.779$, $K_{iq\,IFOC} = 823.65$. Other parameters are: $L = 2.7\mathrm{m}$, $d = 1.7\mathrm{m}$, $r = 0.2794\mathrm{m}$, $A = 2\mathrm{m^2}$, $M = 500\mathrm{kg}$, $g = 9.8\mathrm{m/s^2}$, $C_D = 0.25$, $\rho = 1.202\mathrm{kg/m^3}$, $f_r = 0.01$, $d_f = 0.25$.

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