Sliding Mode Propulsion System Control for Two wheels Electric Vehicle Drive

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Abstract: In this paper novel propulsion system control stability is presented. The present work introduces multi-converter multi-machine systems (MMS), the proposed propelling system consists of two induction motors (IM) that ensure the drive of the two back driving wheels. The proposed control structure called independent machines- for speed control permit the achievement of an electronic differential. The electronic differential system ensures the robust control of the vehicle behaviour on the road it also allows controlling independently every driving wheel to turn at different speeds in any curve. Our electric vehicle sliding mode control’s simulated in Matlab SIMULINK environment, the results obtained present the efficiency of the proposed control with no overshoot, the rising time is perfected with good disturbances rejections comparing with the classical control law.

Key words: Electric vehicle, Electronic differential, induction machine, propulsion system, sliding mode control.

I. INTRODUCTION

Electric vehicles (EVs) are developing fast during this decade due to drastic issues on the protection of environment and the shortage of energy sources. While commercial hybrid cars have been rapidly exposed on the market, fuel-cell-powered vehicles are also announced to appear in 5–10 years. Researches on the power propulsion system of EVs have drawn significant attention in the automobile industry and among academics. EVs can be classified into various categories according to their configurations, functions or power sources. Pure EVs do not use petroleum, while hybrid cars take advantages of energy management between gas and electricity [1].

Indirectly driven EVs are powered by electric motors through transmission and differential gears, while directly driven vehicles are propelled by in-wheel or, simply, wheel motors [2]. The basic vehicle configuration of this research has two directly driven wheel motors installed and operated inside the driving wheels on a pure EV. These wheel motors can be controlled independently and have so quick and accurate response to the command that the vehicle chassis control or motion control becomes more stable and robust, compared to indirectly driven EVs. Like most research on the torque distribution control of wheel motor, wheel motors [3] proposed a dynamic optimal tractive force distribution control for an EV driven by four wheel motors, thereby improving vehicle handling and stability.

The researchers assumed that wheel motors were all identical with the same torque constant; neglecting motor dynamics the output torque was simply proportional to the input current with a prescribed torque constant.

In this paper, a sliding mode decoupling controller for electric vehicle control is proposed. The reminder of this paper is organized as follows:

Section II reviews the principle components of the Electric traction chain modeling .Section III shows the indirect field-oriented control (IFOC) of induction motor. Section IV shows the development of sliding mode controllers design for Electric vehicle. The proposed structure of the studied propulsion system is given in the section V. Section VI gives some simulation results of different studied cases. Finally, the conclusion is drawn in section VII.

II. ELECTRIC TRACTION SYSTEM ELEMENTS MODELLING

A. Energy source

The battery considered in this paper is of the Lithium-Ion accumulator’s battery for which a simple model is assumed. Therefore, a simplified version of the complex battery model reported in [9] is used

B. Static converter

In this electric traction system, we use an inverter to obtain three balanced alternating current phases with variable frequency from the current battery.

\[
\begin{align*}
\mathbf{v}_{an} &= U_{dc} \begin{bmatrix} 2 & -1 & -1 \end{bmatrix} S_a \\
\mathbf{v}_{be} &= U_{dc} \begin{bmatrix} -1 & 2 & -1 \end{bmatrix} S_b \\
\mathbf{v}_{ce} &= U_{dc} \begin{bmatrix} -1 & -1 & 2 \end{bmatrix} S_c \\
\end{align*}
\]

The logic \( S_j \) of the switches are obtained by comparing the control inverter signals with the modulation’s signal.

C. Traction motor

The used motor is a three phase induction motor type (IM)
supplied by an inverter voltage controlled with Pulse Modulation Width (PWM) techniques. A model based on circuit equivalent equations is generally sufficient in order to make control synthesis. The dynamic model of three-phase, Y-connected induction motor can be expressed in the d-q synchronously rotating frame as [6, 7]:

\[
\frac{d\phi_r}{dt} = -\frac{1}{\sigma L_s} \left( R_s + \left( \frac{L_m}{L_s} \right) R_r + \sigma L_s \omega_s i_q + \frac{L_m}{L_r} \phi_q + \frac{L_m}{L_s} \phi_d \right)
\]

\[
\frac{d\omega_s}{dt} = -\frac{1}{\sigma L_s} \left( \frac{L_m}{L_s} \phi_q - \frac{L_m}{L_r} \phi_d + \omega_s \left( \omega_s - \omega_r \right) \right)
\]

\[
\frac{d\phi_d}{dt} = -\frac{1}{\sigma L_s} \left( \frac{L_m}{L_s} \phi_q - \frac{L_m}{L_r} \phi_d + \frac{L_m}{L_s} \phi_q - \frac{L_m}{L_s} \phi_d \right)
\]

Where \( \sigma \) is the coefficient of dispersion and is given by (2):

\[
\sigma = 1 - \frac{L_m^2}{L_s L_r}
\]  

(3)

\( L_s, L_r, L_m \) stator, rotor and mutual inductances;
\( R_s, R_r \) stator and rotor resistances;
\( \omega_s, \omega_r \) electrical and rotor angular frequency;
\( \omega_s \) slip frequency \( (\omega_s - \omega_r) \);
\( \tau_r \) rotor time constant \( (L_s / R_s) \);
\( P \) pole pairs

D. Mechanical part.

The developed globally traction chain model based on the data uses from the Leroy-Somer Society, [4] is shown in figure 2:

![Electromechanical structure](image)

Fig.2: Electromechanical structure

1. The vehicle as load

The vehicle's considered as a load is characterized by many torques which are mostly considered as resistive torques [4, 5, 12, 13, 16, 17]. The different torques includes:

1. The vehicle inertia torque is defined by the following relationship:

\[
T_v = J_v \frac{dv_o}{dt}
\]  

(4)

2. The aerodynamics torque is:

\[
T_{aero} = \frac{1}{2} \rho S C_w \rho_r^2
\]  

(5)

3. The slope torque is given as:

\[
T_{slope} = M g \sin \alpha
\]  

(6)

4. The maximal torque of the tire which can be opposed to the motion has the following expression:

\[
T_{max} = M g f_r R_r
\]  

(7)

We obtain finally the total resistive torque:

\[
T_v = T_{slope} + T_{inve} + T_{aero}
\]  

(8)

2. Gear

The speed gear ensures the transmission of the motor torque to the driving wheels. The gear is modelled by the gear ratio, the transmission efficiency and its inertia.

The mechanical equation is given by:

\[
J_e \frac{d\omega_m}{dt} + f\omega_m = p(T_{em} - T_r)
\]  

(9)

With:

\[
T_v = \frac{1}{\eta_{kov}} T_r
\]  

(10)

\[
J_e = J + \frac{J_v}{\eta_{kov}}
\]  

(11)

The modelling of the traction system allows the implementation of some controls such as the vector control and the speed control in order to ensure the globally system stability.

III. VECTOR CONTROL

The main objective of the vector control of induction motors is, to control independently the flux and he torque as DC machines, this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector [6, 7, 15]. In ideally field-oriented control, the rotor flux linkage axis is forced to align with the d-axes, and it follows that [6, 7, 15]:

\[
\phi_q = \frac{d\phi_q}{dt} = 0
\]  

(12)

\[
\phi_d = \phi = \text{const} \tan t
\]  

(13)

Applying the result of (12) and (13), namely the indirect field-oriented control, the torque equation become analogous to the DC machine and can be described as follows:

\[
T_v = \frac{3}{2} p \frac{L_m}{L_r} \phi_d i_q
\]  

(14)

And the slip frequency can be given as follow:

\[
\omega_s = \frac{1}{\tau_r} \frac{i_q^m}{i_q^d}
\]  

(15)
Consequently, the dynamic equations (1) yield:
\[
\begin{align*}
\frac{d\phi_r}{dt} &= \frac{L_m}{\tau_r} i_{ds} - \frac{1}{\tau_r} \phi_r \\
\frac{d\omega_e}{dt} &= \frac{3}{2} \frac{P^2 L_m}{J L_r} i_{qs} \phi_{rd} - \frac{f_r}{J} \omega_e - \frac{P}{J} T_l
\end{align*}
\] (16) (17)

The decoupling control method with compensation is to obtain the inverter output voltages such that [10]:
\[
\begin{align*}
V_{ds}^* &= \left( K_p + K_i \frac{1}{s} \right) \left( i_{qs}^* - i_{ds} \right) - \omega_e \sigma L_r i_{qs} \\
V_{qs}^* &= \left( K_p + K_i \frac{1}{s} \right) \left( i_{qs}^* - i_{qs} \right) + \omega_e \sigma L_r i_{qs}^* + \omega_e \frac{L_m}{L_r} \phi_{rd}
\end{align*}
\] (20) (21)

According to the above analysis, the indirect field-oriented control (IFOC) [6, 7, 15] of induction motor with current-regulated with PWM inverter control system can reasonably be presented by the block diagram shown in Fig. 3. In this step we use the classical regulator for IFOC tuning control parameter.

![IFOC strategy for an EV induction motor](image_url)

**Fig. 3: IFOC strategy for an EV induction motor.**

### IV. SLIDING MODE CONTROL

Sliding modes is phenomenon may appear in a dynamic system governed by ordinary differential equations with discontinuous right-hand sides. It may happen that the control as a function of the system state switches at high frequency, this motion is called sliding mode. It may be enforced in the simplest tracking relay system with the state variable \(x(t)\) [7, 8, 9, 10, 11]:
\[
\frac{\partial x}{\partial t} = f(x) + u
\] (22)

With the bounded function \(f(x)\)
\[
|f(x)| < f_0; \quad f_0 \text{ is constant and the control as a relay function of the tracking error } e = r(t) - \dot{x}/\partial t; \quad r(t) \text{ is the reference input and } u \text{ is given by:}
\]
\[
u = \begin{cases} 
    +u_0, & \text{if } e > 0 \\
    -u_0, & \text{if } e < 0
\end{cases}
\] (23)

Or: \(u = u_0 \text{sign}(e); \quad u \text{ is constant.}

Figure 4 shows the relay control scheme:

![Relay control scheme](image_url)

**Fig. 4: relay control**

The values of \(e\) and \(\dot{e}/\partial t = e - r - f(x) - u_0 \text{sign}(e)\)

According to Lyapunov stability criteria the system's stable if it does verify the following condition: \(e \cdot e < 0\)

By means that we have the different signs if \(u_0 > f_0 + |r|\).

And finally \(u_0\) must be positive constant.

### IV.1. Design of sliding mode speed and current controller

The speed error is defined by [8, 9, 10, 11]:
\[
\begin{align*}
    e &= \omega_{ref} - \omega_e \\
    \dot{e} &= f(x) + u
\end{align*}
\] (24)

The derivative of the sliding surface can be given as:
\[
\dot{s}(\omega) = \dot{\omega} \cdot - \dot{\omega}_e
\] (25)

From the equation (24) and (2), we can obtain:
\[
\dot{s}(\omega) = \dot{\omega}_e = \frac{3}{2} \frac{P^2 L_m}{J L_r} i_{qs} \phi_{rd} - \frac{f_r}{J} \dot{\omega}_e - \frac{P}{J} T_l
\] (26)

The current control is given by:
\[
i_{qs}^* = i_{qs}^* + k_{iqs} \cdot saf(s(\omega)/\phi_{ds})
\] (27)

To avoid the chattering phenomenon produced by the \(\text{Signs}\) function we use the Saturation function \(\text{Sat}\) in the discontinuous control defined as follows:
\[
saf\left(\frac{S}{\phi}\right) = \begin{cases} 
    \frac{S}{\phi}, & \text{if } \frac{S}{\phi} < 1 \\
    \text{Sign}\left(\frac{S}{\phi}\right), & \text{if } \frac{S}{\phi} > 1
\end{cases}
\]

Where \(\phi\) is the boundary layer thickness.

The discontinuous current control can be written as:
\[
i_{qs}^* = k_{iqs} \cdot \text{sgn}(s(\omega)/\phi_{ds})
\] (28)

\(k_{iqs}\): Positive constant.

The current control is defined by:
\[
i_{qs}^* = \frac{2}{3} \frac{P L_m}{\phi_{rd}} \left( \dot{\omega}_e + \frac{f_r}{J} \omega_e + \frac{P}{J} T_l \right)
\] (29)
The figure 5 shows the SMC control strategy scheme for the electric traction chain.

![SMC control strategy scheme](image)

**Fig.5:** the SMC control strategy scheme

For the IFOC tuning parameters we need two surfaces $S_1$ and $S_2$ the first for the $i_d$ regulator and the second for $i_{qs}$ regulator respectively where:

$$s_1 = i_d^* - i_d$$

$$s_2 = i_{qs}^* - i_{qs}$$

(30)

(31)

The derivative of $S_1$ can be given as:

$$s_1 = i_d - i_d^*$$

from equation (2) and (30) we can obtain:

$$s_1 = i_d - i_d^* = \left[ \frac{R_i}{\sigma L_i} + \frac{1-\sigma}{\sigma} \right] \left[ i_d + \omega_l i_{qs} + \frac{L_m}{\sigma L_i \tau_s} \phi_{rd} + \frac{1}{\sigma L_i} V_{ds} \right]$$

The virtual voltage controller $V_{ds}$ is given by:

$$V_{ds} = V_{ds}^{eq} + V_{ds}^n$$

(32)

The voltage discontinuous control $V_{ds}^n$ is defined as:

$$V_{ds}^n = k_s \cdot \text{sat}(s_1 / \phi_1)$$

(33)

According to Lyapunov stability criteria [10] our speed loop system’s sable if: $s_1, s_2 < 0$ by means that $K_1$ is positive constant.

The equivalent control $V_{ds}^{eq}$ is given as:

$$V_{ds}^{eq} = \alpha L_i \left[ i_d^* + \frac{1-\sigma}{\sigma} \left( R_i + R_L \right) \frac{L_m}{\sigma L_i \tau_s} \phi_{rd} + \frac{1}{\sigma L_i} \phi_{qs} \right]$$

(32)

The derivative of $S_2$ can be given as:

$$s_2 = i_{qs} - i_{qs}^*$$

From equation (2) and (31) we can obtain:

$$s_2 = i_{qs} - i_{qs}^* = \left[ \frac{R_i}{\sigma L_i} + \frac{1-\sigma}{\sigma} \right] \left[ i_{qs} + \omega_l i_d + \phi_{rd} + \frac{1}{\sigma L_i} V_{qs} \right]$$

The virtual voltage controller $V_{qs}$ is given by:

$$V_{qs} = V_{qs}^{eq} + V_{qs}^n$$

(33)

The $V_{qs}^{eq}$ equivalent control actions defined as:

$$V_{qs}^{eq} = \alpha L_i \left[ i_{qs}^* + \frac{1-\sigma}{\sigma} \left( R_i + R_L \right) \frac{L_m}{\sigma L_i \tau_s} \phi_{rd} + \frac{1}{\sigma L_i} \phi_{qs} \right]$$

(34)

The voltage discontinuous control $V_{qs}^n$ is defined as:

$$V_{qs}^n = k_2 \cdot \text{sat}(s_2 / \phi_2)$$

(35)

For the same reason condition of $K_1$:

$K_2$ is positives constant.

V. Structure of the studied system

The general scheme of the driving wheels control is represented by figure 7. It’s an electric vehicle, which the back vehicle wheels are controlled independently by two IM.

The reference blocks must provide the speed references of each motor taking into consideration informations from the different sensors.

V.1. Speed references computation.

It is possible to determine the speed references versus the requirements of the driver. When the vehicle arrives at the beginning of a curve, the driver applies a curve angle on each driving wheels [13,16,17]. The electronic differential acts immediately on the two motors reducing the driving wheel speed situated inside the curve, and increases the speed of the driving wheel situated outside the curve. The driving wheels angular speeds are:

$$w_{dh} = \frac{V_h}{R_r} + k_d \Delta w$$

(36)

$$w_{dl} = \frac{V_h}{R_r} - k_d \Delta w$$

(37)

with $k_d = +1$ corresponding to a choice of the direction of the wheel, (-1) for the right turn, and (+1) for the left turn. The driving wheels speed variation is imposed by the trajectory desired by the driver and it’s given by:

$$\Delta w = \frac{d_w \sin (\delta + \beta)}{2} \frac{V_h}{l_w \cos \delta - R_r}$$

(38)

The relation between $\alpha$ which is the curve angle given by the driver wheel and $\delta$ of the real curve angle of the wheels is given by:

$$\delta = \frac{\alpha}{k_d}$$

(39)

The figure 6 shows the vehicle geometry of the studied system.

![Vehicle geometry](image)
The speeds references of the two motors are:

\[ w_{mR}^* = N_{red} \cdot w_{rR} \]  
\[ w_{mL}^* = N_{red} \cdot w_{rL} \]  

Fig. 7: The driving wheels control of the studied propulsion system.

VI. SIMULATION RESULTS

In order to characterise the driving wheel system behaviour, simulations were carried using the model of figure. 7. They show vehicle speed variation for PI and the Sliding mode controllers.

We can summaries the results of the two control laws in the table given bellow:

<table>
<thead>
<tr>
<th>Results</th>
<th>Rising time [Sec]</th>
<th>Overtaking [%]</th>
<th>Steady state error [%]</th>
<th>Disturbance application time (slope torque)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.8895</td>
<td>11.6666</td>
<td>0</td>
<td>At 3 Sec</td>
</tr>
<tr>
<td>SMC</td>
<td>0.7932</td>
<td>0</td>
<td>0</td>
<td>At 3 Sec</td>
</tr>
</tbody>
</table>

From the figure.8 and the table we can say that: the effect of the disturbance is neglected in the case of the sliding mode control. It appears clearly that the classical control with PI controller is easy to apply. However the control with sliding mode controllers offers better performances in both of the overshoot control and the tracking error.

In addition to these dynamic performances, it respects the imposed constraints by the driving system such as the robustness of parameter variations

A. Case of straight way

- Flat road with 10% slope at 60km/h speed

In this test, the system is submitted to the same speed law control in two cases, figure.8 shows the system response.
The driving wheels speeds stay always the same and the road slope does not affect the control of the wheel and the sliding mode control act immediately on the speed loop’s and rejects the disturbance and give’s more and more efficiency to the electronic differential output references. Only a change of the developed motor torque is noticed. We can say the slope effect results in a high improvement in the electromagnetic motor torque left and right of each motor and it’s sensitize the motorization to develop efforts in order to satisfy the electric traction chain demand. The system behaviour of theses speeds is illustrated by figures 9.1, 9.2, figures 9.5. and 9.4 describe the electromagnetic left and right variations. The resistant torques are shown in figures 9.3.

We can summaries the results o the straight way driven wheels in the following tables:

| Table 2: Performances of the PI & SMC controllers in vehicle speed loop |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| **Results**                 | \( \Delta \omega \) | \( \omega_{refL} \) | \( \omega_{refR} \) | \( \alpha \) |
| PI                          | 0               | 60              | 60              | 0               | 60             | 60.87          | 60.87          |
| SMC                         | 0               | 60              | 60              | 0               | 60             | 60             | 60             |

All vehicle torques variation results are illustrated in this table:

<table>
<thead>
<tr>
<th>Table 3: Performances of the SMC controller</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Results</strong></td>
</tr>
<tr>
<td>Maximum value [Nm]</td>
</tr>
<tr>
<td>Time application [Sec]</td>
</tr>
</tbody>
</table>

B. Case of curved way

-Curved road at right side with speed of 60km/h
The vehicle is driving on a curved road on the right side with 60km/h speed. The assumption is that the two motors are not disturbed. In this case the driving wheels follow different paths, and they turn in the same direction but with different speeds.
Also we can summaries our curved way response results

Table 4: Performances of the SMC controller in the vehicle speed loop

<table>
<thead>
<tr>
<th>Results</th>
<th>PI</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta v )</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( V_{refL} )</td>
<td>65.74</td>
<td>65</td>
</tr>
<tr>
<td>( V_{refR} )</td>
<td>54.26</td>
<td>55</td>
</tr>
<tr>
<td>Time curve</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Curve angle ( \phi )</td>
<td>5.81</td>
<td>5.81</td>
</tr>
<tr>
<td>( V_h )</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>( V_{wL} )</td>
<td>65.6</td>
<td>65</td>
</tr>
<tr>
<td>( V_{wR} )</td>
<td>54.15</td>
<td>55</td>
</tr>
</tbody>
</table>

The electronic differential acts on the two motor speeds by decreasing the speed of the driving wheel on the right side situated inside the curve, and on the other hand by increasing the wheel motor speed in the external side of the curve. The sliding mode control ensure the stability of the propulsing system by maintaining the motorization error speed equal zeros and gives a good rising time and no over tracking error too. The behaviour of these speeds is given by figure 10.3, figure 10.4 shows the electric vehicle resistant torques and figures 10.1 and 10.2 shows the electromagnetic torques.

VII. CONCLUSION

The research outlined in this paper has demonstrate the feasibility of an improved vehicle stability which uses two independent back drive wheels for motion by using the sliding mode control. The proposed ‘independent machine’ control approach structure applied to a propulsing system by the sliding mode speed control ensure the disturbance rejection. The results obtained by simulation show that this structure permits the realization of an robust control loop speed based on Lyapunov switching surface with a good dynamic and static performances of electric traction chain. The proposed sliding mode model controls the driving wheels speeds with high accuracy either in flat roads or curved ones in each case. The disturbances do not affect the performances of the driving motor wheels stability.

Appendix

Table 6: Electric vehicle Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_e )</td>
<td>247 Nm</td>
</tr>
<tr>
<td>( J_e )</td>
<td>7.07Kgm²</td>
</tr>
<tr>
<td>( R_w )</td>
<td>0.36m</td>
</tr>
<tr>
<td>( a )</td>
<td>10.0</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.93</td>
</tr>
<tr>
<td>( M )</td>
<td>3904Kg</td>
</tr>
<tr>
<td>( f_b )</td>
<td>0.001</td>
</tr>
<tr>
<td>( K_v )</td>
<td>0.46</td>
</tr>
<tr>
<td>( A )</td>
<td>3.48 m²</td>
</tr>
<tr>
<td>( f_v )</td>
<td>0.01</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.8</td>
</tr>
<tr>
<td>( L_w )</td>
<td>2.5m</td>
</tr>
<tr>
<td>( d_w )</td>
<td>1.5m</td>
</tr>
</tbody>
</table>
Table 7: Induction Motors Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rr</td>
<td>0.003 Ω</td>
</tr>
<tr>
<td>Rs</td>
<td>0.0044 Ω</td>
</tr>
<tr>
<td>Le</td>
<td>16.1 μH</td>
</tr>
<tr>
<td>Lea</td>
<td>482 μH</td>
</tr>
<tr>
<td>Le</td>
<td>12.9 μH</td>
</tr>
<tr>
<td>Fr</td>
<td>0.0014</td>
</tr>
<tr>
<td>P</td>
<td>4</td>
</tr>
<tr>
<td>N</td>
<td>2885 rpm</td>
</tr>
<tr>
<td>Rated power</td>
<td>100 hp</td>
</tr>
</tbody>
</table>

Table 8: Symbols, Designation and Units.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nomenclature</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rr</td>
<td>Rotor resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>Rs</td>
<td>Stator resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>P</td>
<td>Pole pairs</td>
<td></td>
</tr>
<tr>
<td>Ls</td>
<td>Stator inductance</td>
<td>μH</td>
</tr>
<tr>
<td>Lr</td>
<td>Rotor inductance</td>
<td>μH</td>
</tr>
<tr>
<td>Lm</td>
<td>Mutual inductance</td>
<td>μH</td>
</tr>
<tr>
<td>J</td>
<td>Rotor inertia</td>
<td>Kg.m²</td>
</tr>
<tr>
<td>Jg</td>
<td>Moment of inertia</td>
<td>Kg.m²</td>
</tr>
<tr>
<td>Jl</td>
<td>Vehicle inertia</td>
<td>Kg.m²</td>
</tr>
<tr>
<td>Tm</td>
<td>Electromagnetic torque</td>
<td>Nm</td>
</tr>
<tr>
<td>Tsa</td>
<td>Vehicle torque</td>
<td>Nm</td>
</tr>
<tr>
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<td>Distance between two wheels</td>
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