Intelligent Control Of An Electric Vehicle (ICEV)

Taoufik Chaouachi, Kamel Jemaï

Abstract: The electric vehicle allows fast, gentle, quiet and environmentally friendly movements in industrial and urban environments. The automotive industry has seen the opportunity to revive its production by replacing existing vehicles due to the reluctance of oil reserves around the world. In order to greatly reduce countries’ dependence on oil, strategic sectors such as transport must increasingly integrate technologies based primarily on clean and renewable energy. Governments must implement large-scale measures to equip themselves with electric vehicles and build large recharge networks. The traditional system for conversions of conventional vehicles into electric vehicles consists of replacing the internal combustion engine and the gearbox with electrical components (engine and gearbox, or engine and gearbox), retaining the rest of the elements Transmission (transmission shafts, etc.).

Index Terms: Strategy of control, random perturbation method, fuzzy logic, power train vehicle, electric vehicle, Permanent magnetic synchronous motor.

1 INTRODUCTION
Reducing CO emissions represents a challenge for the transport sector. Transportation produces approximately 23 percent of the global CO emissions from fuel combustion. With rapid urbanization in developing countries, energy consumption and CO emissions by urban transport are increasing quickly[18]. Over the last few decades, the environmental impact of oil transport infrastructure, combined with the reluctance of energy resources, has led to renewed interest in an electric transport infrastructure. Electric vehicles differ from fossil fuel vehicles in that the electricity they consume can be produced from a wide range of sources, including fossil fuels, nuclear power and renewable Tidal energy, solar and wind energy or any combination of these. The energy consumption of these electric vehicles varies according to the fuel and the technologies used to produce electricity. Electricity can then be stored in the vehicle using an on-board battery[1], [5]. The electric motors are mechanically simple and often achieve high energy conversion efficiencies over the whole range of speed and power developed and can be controlled with high accuracy. They can also be combined with regenerative braking systems that have the ability to convert motion energy into stored electricity. This can be used to reduce brake system wear and reduce total energy consumption. Electric motors can be finely controlled and provide high starting torque, unlike internal combustion engines, and do not require multiple gears to match power curves. This eliminates the need for gearboxes and torque converters. Electric vehicles offer silent and smooth operation and therefore have less noise and vibration than internal combustion engines. In this work, we have incorporated new strategies for controlling the state variables of an electric vehicle based on fuzzy controllers. We attached particular importance to the mechanical transmission system by means of an appropriate modeling of the symbiosis between the electrical management system and the mechanical management system.

2 FUZZY STRATEGY
2.1 Fuzzy Studied Model
The topology of each fuzzy controller to integrate, was based on an interaction between two input variables, characterized successively by an error $\varepsilon \times Mi$ and an instantaneous variation of the error $\varepsilon \times Mi/\partial t$, to synthesize a fuzzy vector $K_{xMi}$ [6], [7], [8].

A surface $S_{R_k}$ swept by the control vector for a rule $R_k$ is given by: $K_{x_i}$
\[
S_{R_k} = \pi_{R_k} \cdot mfunc_{\epsilon_k}
\]  
(2)

Indeed, we have implemented a matrix of fuzzy inferences through a number of membership functions \(MF_i\), both for the error \(E_x(N_{\epsilon_x} = 11)\), that for its variation \(\frac{\partial E_x}{\partial t}(N_{\epsilon_x} = 11)\) and for the control vector \(U_f(N_{U_f} = 11)\). [15].

Thus, the total number of fuzzy inferences is given by:

\[
N_{règles} = N_{E_x} \cdot N_{\frac{\partial E_x}{\partial t}} = 121
\]  
(3)

These membership functions are specified in the following table:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Membership functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(MF_1 \Rightarrow MF_{NTG})</td>
</tr>
<tr>
<td>2</td>
<td>(MF_2 \Rightarrow MF_{NG})</td>
</tr>
<tr>
<td>3</td>
<td>(MF_3 \Rightarrow MF_{N})</td>
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<tr>
<td>4</td>
<td>(MF_4 \Rightarrow MF_{NM})</td>
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<tr>
<td>5</td>
<td>(MF_5 \Rightarrow MF_{NP})</td>
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<td>6</td>
<td>(MF_6 \Rightarrow MF_{ZE})</td>
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<tr>
<td>7</td>
<td>(MF_7 \Rightarrow MF_{PP})</td>
</tr>
<tr>
<td>8</td>
<td>(MF_8 \Rightarrow MF_{PM})</td>
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<tr>
<td>9</td>
<td>(MF_9 \Rightarrow MF_{P})</td>
</tr>
<tr>
<td>10</td>
<td>(MF_{10} \Rightarrow MF_{PG})</td>
</tr>
<tr>
<td>11</td>
<td>(MF_{11} \Rightarrow MF_{PTG})</td>
</tr>
</tbody>
</table>

Fig. 3. Surface related to rule \(R_k\)

The overall area swept by the fuzzy vector \(K_{x_i}\) after use of all the rules is formulated as follows:

\[
S_{K_{x_i}} = \frac{\sum_k S_{R_k}}{N_{R_k}}
\]  
(4)

With \(N_{R_k}\) number of rules that are used. Thus, the fuzzy vector \(K_{x_i}\) is none other than the abscissa of the center of gravity of the overall surface \(S_{K_{x_i}}\) swept by the control vector \(K_{x_i}\) and deduced in accordance with the relationship.

\[
K_{x_i}^{nf} = \frac{\int_{x_i}^{x_{i+2}} \int_{t_{i-1}}^{t_i} \pi_{R_k} \cdot mfunc_{\epsilon_k}(K_{x_i})K_{x_i} \cdot \partial K_{x_i}}{\sum S_{x_i}}
\]  
(5)

Where \(K_{x_i}^{nf}\) is an un-fuzzy vector.

2.2 New Rescaling Technique

A new technique of scaling will be of great importance for the magnitudes of the state variables that may possibly exceed the extreme limits quoted. In other words, all sizes to be treated \(x_i\) giving rise to an error \(\epsilon_x\) and a variation of...
error $\frac{\partial e}{\partial t}$. Must undergo a transfer at the base of fuzzy variables evidenced by the interval [-1,1] to generate the fuzzy input required for processing by the designated controller in accordance with the following system of equations [9]:

$$\left\{\begin{array}{l}
\dot{e}_1 = B_1 e_1 + [1 - B_1 ] \\
\frac{\partial e}{\partial t} = B_2 \frac{\partial e}{\partial t} + [1 - B_2 ] \\
B_1 = \frac{G_{max}(mfunc,e_1) - G_{max}(mfunc,e_2)}{2} \\
B_2 = \frac{G_{max}(mfunc,e_2) - G_{max}(mfunc,e_1)}{2}
\end{array}\right.$$  \hspace{1cm} (6)

Where:

$$\begin{align*}
G_{max}(mfunc,e) & = \max \left\{ \frac{1}{\sigma_e \sqrt{2\pi}} \exp \left[ -\frac{(e - \mu_e)^2}{2\sigma_e^2} \right] \right\} \\
G_{min}(mfunc,e) & = \min \left\{ \frac{1}{\sigma_e \sqrt{2\pi}} \exp \left[ -\frac{(e - \mu_e)^2}{2\sigma_e^2} \right] \right\}
\end{align*}$$  \hspace{1cm} (7)

Where $\mu_e, \sigma_e$ denote respectively the mean and standard deviation of the error and variation of error $e_1$ and $e_2$.

Similarly, the control vector $K$ must undergo a transfer to the basic quantities studied, rescaled, to assign the value $K_{out}$ and this means the system of equations:

$$\left\{\begin{array}{l}
K_{out} = B_{K_e} K_e + [1 - B_{K_e}] \\
B_{K_e} = \frac{G_{max}(mfunc,K_e) - G_{max}(mfunc,K_e)}{2}
\end{array}\right.$$  \hspace{1cm} (8)

Where:

$$\begin{align*}
G_{max}(mfunc,K_e) & = \max \left\{ \frac{1}{\sigma_{K_e} \sqrt{2\pi}} \exp \left[ -\frac{(K_e - \mu_{K_e})^2}{2\sigma_{K_e}^2} \right] \right\} \\
G_{min}(mfunc,K_e) & = \min \left\{ \frac{1}{\sigma_{K_e} \sqrt{2\pi}} \exp \left[ -\frac{(K_e - \mu_{K_e})^2}{2\sigma_{K_e}^2} \right] \right\}
\end{align*}$$  \hspace{1cm} (9)

Through this new technique of rescaling, we assigned a dynamic behavior to the fuzzy controller in order to ensure better tracking of the variable to control [9].

3 ELECTRIC VEHICLE MODEL
The model of the electric vehicle studied is illustrated in figure 2. We focus mainly on the components of the power system that provide electric traction namely[11, [14]:

- The photovoltaic panel,
- The buck converter,
- The battery,
- The DC-Link,
- The DC/AC converter,
- The filter,
- The permanent magnet synchronous machine (PMSM).

![Fig.5. Model of the studied electric vehicle](image)

4 PHOTOVOLTAIC GENERATOR
We start with a reminder of the electrical equations of the integrated photovoltaic generator. We highlight the model of the basic component of this generator, namely the photovoltaic cell with a real model.

4.1 Real Model of a Photovoltaic Cell
In order to highlight the physical phenomena that occur in the photovoltaic cell, we must consider:

- The leaks resulting from the edge effects of the junction PN and this by the integration of a shunt resistor $R_s$ in the equivalent scheme of the cell,
- The losses due to the contacts and the connections and which will be modeled, in the equivalent diagram, by a series resistance $R_s$.

![Fig.6. Real model of a photovoltaic cell](image)
The current supplied by the photovoltaic cell is then:

\[
I_p = I_{ph} - I_s \left[ e^{\frac{V_p + R_s I_p}{R_{sh}}} - 1 \right] - \frac{V_p + R_s I_p}{R_{sh}} \tag{10}
\]

The current \(I_{cc}\) supplied by the photovoltaic cell when the latter has a zero voltage to these terminals (\(V_p = 0V\)):

\[
I_{cc} = I_{ph} - I_s \left[ e^{\frac{R_s I_{cc}}{R_{sh}}} - 1 \right] - \frac{R_s I_{cc}}{R_{sh}} \tag{11}
\]

The voltage \(V_{cc}\) delivered by the photovoltaic cell when the latter does not discharge any current (\(I_p = 0A\)) is:

\[
V_{cc} = V_r \cdot Ln \left( \frac{I_{ph}}{I_s} - \frac{V_{cc}}{R_{sh} I_s} + 1 \right) \tag{12}
\]

The optimum power \(P_{op}\) delivered by the photovoltaic cell is defined when it delivers an optimum current \(I_{op}\) under an optimum voltage \(V_{op}\):

\[
P_{op} = V_{op} \cdot I_{op} \tag{13}
\]

The photovoltaic generator then delivers energy to the rest of the power circuit of the electric vehicle as shown in figure 9.

4.2 Model Of A Photovoltaic Generator

We present in the following the developed scheme of the model of a photovoltaic generator, figure 8.

5 BUCK CONVERTER

In order to ensure a conditioned transfer of the energy supplied by the photovoltaic generator (\(V_p, I_p\)) to the rest
of the power system of the electric vehicle, we have integrated a buck converter. In fact, by checking the duty cycle \( \alpha_{buc} \) of this converter, according to the requirement of the PMSM motor, we identify the level of the requested power of the photovoltaic (PV) generator. Let \( T_{buc} \) be the commutation cycle of the buck converter. From 0 to \( \alpha_{buc} T_{buc} \) we have:

\[
V_p = L_{buc} \frac{dI_p}{dt} + V_{soc} \tag{17}
\]

From \( \alpha_{buc} T_{buc} \) to \( T_{buc} \) we have:

\[
0 = L_{buc} \frac{dI_p}{dt} + V_{soc} \tag{18}
\]

And thus:

\[
I_p = -\frac{V_{soc}}{L_{buc}} (t - T_{buc}) + I_{p-min} \tag{19}
\]

On the other hand:

\[
I_{p-max} = -\frac{V_{soc}}{L_{buc}} (\alpha_{buc} - 1) T_{buc} + I_{p-min} \tag{20}
\]

The current \( I_p \) ripple noted \( \Delta I_p \) is evaluated through the relationship:

\[
\Delta I_p = I_{p-max} - I_{p-min} = \frac{1 - \alpha_{buc}}{L_{buc} \cdot f_{buc}} V_{soc} \tag{21}
\]

Where:

\[
f_{buc} = \frac{1}{T_{buc}}
\]

Thus, we conclude that the average value of the voltage at the terminals of the storage battery \( V_{soc} \) is expressed as a function of the voltage applied by the photovoltaic generator \( V_p \) in accordance with the following relation:

\[
\langle V_{soc} \rangle = \alpha_{buc} V_p \tag{22}
\]

6 BATTERY MODEL

The charge separation that takes place in each battery cell give rise to a cell voltage, or Open Circuit Voltage, OCV. As soon as the terminal ends are closed in an electrical circuit, chemical reactions start to take place in the cell, causing the flow of a current. However, due to the charge transport in the electrolyte, and the chemical reactions at the surface of the plates and the current in the plates, there is a resistance to the current, which is called the battery’s internal resistance, \( R \). A simple circuit model of a battery is depicted in Figure 10, where the OCV is depending on the SOC, and the resistance is constant. There are, however, a number of factors that are not included in this simple model, such as the charge accumulation at the plates, which gives capacitive contributions to the resistance, SOC and temperature dependence of all parameters (OCV, \( R \) and \( C \)), and finally a self-discharge of the battery, that can be modeled as a shunt resistance to the OCV.

7 BOOST CONVERTER MODEL

The energy delivered by the storage battery \((V_b, I_b)\) must meet the requirements imposed instantly, namely:

- Maintain a DC link voltage level \( V_{dc} \) required by the operating point of the PMSM motor,
- Determine the level of desired reference voltages \( V^*_{dc}, V^*_{q_c} \) that the converter \( C_{PMSM} \) must supply.
For these and other reasons, we have integrated a boost (step-up) converter with a duty cycle $\alpha_{boc}$ and a commutation cycle $T_{boc}$.

Referring to the figure 11, we write:

$$V_{dc} = \frac{1}{1 - \alpha_{boc}} V_b \quad (23)$$

As already reported, any operating point of the PMSM motor automatically imposes a DC-Link voltage level $V_{dc}$. Therefore, we relied on the control of the duty cycle $\alpha_{boc}$. For this purpose, a fuzzy controller evaluates an instantaneous reference of this duty cycle $\alpha_{boc}^*$ as a function of a desired level of the voltage reference level $V_{dc}^*$, figure 12.

![Fuzzy Controller](image)

**Fig.12. Fuzzy control of the DC link voltage**

Referring to the above figure, the reference voltage $V_b^*$ that the battery must supply is given by:

$$V_b^* = (1 - \alpha_{boc}^*) V_{dc} \quad (24)$$

Under these conditions, the level of the charge voltage $V_{soc}$ of the battery is given by:

$$\begin{align*}
V_{soc} & = R_b \cdot I_b + V_b^* \\
V_{soc} & = \alpha_{buc} \cdot V_p
\end{align*} \quad (25)$$

We thus go back in order to estimate the duty cycle $\alpha_{soc}$ of the buck converter as shown in figure 13, [15].

![Model of duty cycle $\alpha_{buc}$ control](image)

**Fig.13. Model of duty cycle $\alpha_{buc}$ control**

In figure 13, the DC-Link voltage level $V_{dc}$ is evaluated by taking into account the transit powers $P_{boc}$ and $P_m$:

$$V_{dc} = \sqrt{\frac{2}{C_{dc}} \cdot \int_{t}^{t+\Delta t} (P_{boc} - P_m) dt} \quad (26)$$

Where $\Delta t$ is the step of calculation.

8 PERMANENT MAGNET SYNCHRONOUS MACHINE (PMSM) MODEL

The topology of the permanent magnet synchronous machine (PMSM) is illustrated in figure 14. By performing the transform Park to stator windings with respect to a reference associated with the rotor of the machine, we obtain a bipolar fictitious machine with axes $(d, q)$, [14], [17].

![Permanent magnet synchronous machine (PMSM) relating to $(d, q)$ axes.](image)

**Fig.14. Permanent magnet synchronous machine (PMSM) relating to $(d, q)$ axes.**

The magnetic flux $\phi_f$ created by the permanent magnet at the rotor is oriented along the d-axis. Thus, the components of the voltage at the terminals of the stator of the PMSM machine are given by the following system:

$$\begin{align*}
v_{dm} & = R_s i_{dcm} + \frac{d\phi_{dm}}{dt} - \omega \phi_{qm} \\
v_{qm} & = R_s i_{qcm} + \frac{d\phi_{qm}}{dt} + \omega \phi_{dm}
\end{align*} \quad (27)$$

The components of the fluxes along the $(d, q)$ axes are given by the following system:

$$\begin{align*}
\phi_{dm} & = L_d i_{dcm} + \phi_f \\
\phi_{qm} & = L_q i_{qcm}
\end{align*} \quad (28)$$

Taking into account the fluxes equations $\phi_{dm}$ and $\phi_{qm}$, we write:

$$\begin{align*}
v_{dm} & = R_s i_{dcm} + L_q \frac{d\phi_{km}}{dt} - \omega L_d i_{qcm} \\
v_{qm} & = R_s i_{qcm} + L_d \frac{d\phi_{km}}{dt} + \omega (L_d i_{dcm} + \phi_f)
\end{align*} \quad (29)$$
We then obtain two equivalent schemes along the $(d, q)$ axes, figures 15 and 16.

![Fig. 16 Equivalent scheme of the PMSM machine according to the q-axis](image)

![Fig. 16 Equivalent scheme of the PMSM machine according to the d-axis](image)

The active and reactive powers exchanged by the machine are:

$$\begin{aligned}
P_m &= v_{dm} i_{dc} + v_{qm} i_{qm} \\
Q_m &= v_{qm} i_{dc} - v_{dm} i_{qm}
\end{aligned}$$

(30)

We also write:

$$P_m = \frac{\Omega}{p} \left( \phi_{dm} i_{qcm} - \phi_{qm} i_{dc} \right)$$

(31)

Consequently, the electromagnetic torque $T_{em}$ is then:

$$T_{em} = \frac{\phi_{dm} i_{qcm} - \phi_{qm} i_{dc}}{p}$$

(32)

In order to plan the process of numerical integration of the equations of state of the PMSM machine and by referring to the system of equations (33), we write:

$$\begin{aligned}
\frac{d i_{dc}}{dt} &= \frac{v_{dc} - R_i i_{dc} + \omega L_q i_{qcm}}{L_d} \\
\frac{d i_{qcm}}{dt} &= \frac{v_{qm} - R_i i_{qcm} - \omega (L_d i_{dc} + \phi_f)}{L_q}
\end{aligned}$$

(33)

On the other hand, the dynamics of the machine is described by the following model:

$$\begin{aligned}
\frac{d\omega}{dt} &= \frac{T_{em} - T_r - \omega f_r}{J_m} \\
\frac{d\theta}{dt} &= \omega
\end{aligned}$$

(34)

Where: $T_r$ is the resistive torque, $f_r$ coefficient of friction, $J_m$ moment of inertia of the rotating mass and $\theta$ is the angular position. We have adopted the method of Runge Kutta of order 4 to evaluate the components of the current $(i_{dc}, i_{qcm})$ Provided by the converter $C_{PMSM}$.

We write then:

$$\begin{aligned}
i_{qcm}(n+1) &= i_{qcm}(n) + \frac{1}{6} \Delta t \left( R_i i_{qcm} + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) \right) \\
i_{dc}(n+1) &= i_{dc}(n) + \frac{1}{6} \Delta t \left( R_i i_{dc} + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) \right)
\end{aligned}$$

(35)

Therefore:

$$\begin{aligned}
i_{qcm}(n+1) &= i_{qcm}(n) + \frac{1}{6} \Delta t \left( R_i i_{qcm} + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) \right) \\
i_{dc}(n+1) &= i_{dc}(n) + \frac{1}{6} \Delta t \left( R_i i_{dc} + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) \right)
\end{aligned}$$

(36)

With:

$$\begin{aligned}
R_i &= F_{em}(i_{qcm}(n) + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) + 1 \Delta t \left( L_d i_{dc} + \phi_f \right) + R_i) \\
R_i &= F_{em}(i_{dc}(n) + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) + 1 \Delta t \left( L_q i_{qcm} - \phi_f \right) + R_i)
\end{aligned}$$

(37)

And:

$$\begin{aligned}
R_i &= F_{em}(i_{qcm}(n) + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) + 1 \Delta t \left( L_d i_{dc} + \phi_f \right) + R_i) \\
R_i &= F_{em}(i_{dc}(n) + \frac{1}{2} \Delta t \left( L_q i_{qcm} - \phi_f \right) + \frac{1}{2} \Delta t \left( L_d i_{dc} + \phi_f \right) + 1 \Delta t \left( L_q i_{qcm} - \phi_f \right) + R_i)
\end{aligned}$$

(38)

9 QUADRATIC CONTROL OF THE DC LINK VOLTAGE LEVEL

The level of the DC bus voltage is conditioned by the power balance $\Delta P_{dc}$ transited from the boost converter $\Delta P_{boc}$ to the $C_{PMSM}$ converter $\Delta P_m$. We write then:
\[ \Delta P_{dc} = \Delta P_{boc} - \Delta P_m \]  

(39)

knowing that :

\[
\begin{align*}
P_{dc} &= V_{dc} . I_{dc} \\
P_{boc} &= \frac{1}{1 - \alpha_{boc}} V_b . I_{boc}
\end{align*}
\]

(40)

The fluctuations of the power \( P_{dc} \) are evaluated according to the following relation:

\[
\Delta P_{dc} = \frac{\partial P_{dc}}{\partial V_{dc}} \Delta V_{dc} + \frac{\partial P_{dc}}{\partial I_{dc}} (\Delta I_{boc} - \Delta I_m )
\]

(41)

We then find:

\[
\Delta P_{dc} = \frac{\partial P_{dc}}{\partial V_{dc}} \Delta V_{dc} + \frac{\partial P_{dc}}{\partial I_{dc}} (\Delta I_{boc} - m_{cd} i_{dc} - m_{cq} i_{qn})
\]

(42)

Where \( m_{cd}, m_{cq} \) are the index modulations of the \( C_{PMSM} \) converter. The power involved in the DC bus is:

\[
P_{dc} = \frac{1}{2} C_{dc} \cdot \frac{d(V_{dc}^2)}{dt}
\]

(43)

then :

\[
V_{dc}^2 = \frac{2}{C_{dc}} \int_{t}^{t+\text{pas}} P_{dc} \cdot dt
\]

(44)

Which leads to:

\[
V_{dc} = \sqrt{\frac{2}{C_{dc}} \int_{t}^{t+\text{pas}} (P_{boc} - P_m) \cdot dt}
\]

(45)

The notion of quadratic control comes from the fact that we treat the square of the DC bus voltage \( V_{dc} \). Indeed, the control strategy is divided into two blocks namely a calculation block and a control block. In order to attribute to this strategy a better dynamic of pursuit of the desired reference \( V_{dc}^2 \), we have opted for a fuzzy control, figure 17.

**Fig.17. Calculation and control models of the DC-link voltage**

**10 SVPWM STRATEGY APPLIED TO THE C\textsubscript{PMSM} CONVERTER**

In this section, we are interested in developing the space vector pulse width modulation strategy (SVPWM) applied to the \( C_{PMSM} \) converter, figure 18.

**Fig.18. model of the C\textsubscript{PMSM} converter**

The output voltages of the \( C_{PMSM} \) converter are expressed as follow:

\[
\begin{align*}
v_{dcm} &= R_f i_{dcm} + L_f \frac{di_{dcm}}{dt} - \omega L_f i_{qcm} + v_{dm} \\
v_{qcm} &= R_f i_{qcm} + L_f \frac{di_{qcm}}{dt} + \omega L_f i_{dcm} + v_{qm}
\end{align*}
\]

(46)

\( R_f, L_f \) are respectively the resistance and the inductance of the filter.

We write likewise:
\[
\begin{align*}
\dot{v}_{dc} &= m_{cd} V_{dc} \\
\dot{v}_{qc} &= m_{cq} V_{dc}
\end{align*}
\] (47)

Also:
\[
\begin{align*}
I_m &= m_{cd} i_{dc}\ + m_{cq} i_{qc} \\
I_m &= f_{cm}(i_{dc}, i_{qc})
\end{align*}
\] (48)

Current fluctuations \( \Delta I_m \) at the input of the \( C_{PMSM} \) converter are written as follows:
\[
\Delta I_m = \frac{V_{dc}}{V_{dc}} \Delta i_{dc} + \frac{V_{dc}}{V_{dc}} \Delta i_{qc}
\] (49)

Taking into account the Fortescue’s theory based on decomposition into a positive synchronous reference frame (PSRF) and a negative synchronous reference frame (NSRF), figure 19, We implement control loops of currents and voltages.

**Fig.19. Positive and a negative synchronous references frame (PSRF, NSRF)**

The current components \( (i_{dc}, i_{qc}) \) provided by the converter \( C_{PMSM} \) will be decomposed according to the following model.
\[
\begin{align*}
\dot{i}_{dc}^{+} &= i_{dc}^{+} + i_{dc}^{-} \cos(2\theta) + i_{qc}^{+} \sin(2\theta) \\
\dot{i}_{qc}^{+} &= i_{qc}^{+} + i_{qc}^{-} \cos(2\theta) - i_{dc}^{+} \sin(2\theta)
\end{align*}
\] (50)

Where:
- \( x^{+}, x^{-} \) \((d, q)\)-axiscomponents in the PSRF frame,
The vectors \( S_f_{dc,m} \) and \( S_f_{qc,m} \) generated by the fuzzy controllers integrated in the (d, q) axis current control loops are defined as follows:

\[
\begin{align*}
S_f_{dc,m} &= R_s.i_{dc,m} + L_d.i_{dc,m} \\
S_f_{qc,m} &= R_s.i_{qc,m} + L_d.i_{qc,m}
\end{align*}
\]  

(53)

The references of the components \( v_{dc}^* \) and \( v_{qc}^* \) of the voltage at the terminals of the PMSM machine being obtained and taking into account the existence of the \( (R_f, L_f) \) filter of the low-pass type, which completely eliminates all frequencies above the cutoff frequency while passing those below unchanged. We then constitute the components of the reference voltage \( v_{dc}^* \) and \( v_{qc}^* \) that the converter must generate:

\[
\begin{align*}
v_{dc}^* &= R_f.i_{dc}^* - \omega_L.i_{qc}^* + v_{dm}^* \\
v_{qc}^* &= R_f.i_{qc}^* + \omega_L.i_{dc}^* + v_{qm}^*
\end{align*}
\]  

(54)

The components of the reference voltage \( v_{dc}^* \) and \( v_{qc}^* \) are subsequently transferred to a fixed reference frame \( (\alpha, \beta) \) in order to apply the SVPWM technique.

\[
\overline{V}_{\alpha\beta}^* = e^{j.\omega.t}\overline{V}_{d\beta}^*
\]  

(55)

From where:

\[
\begin{align*}
v_{dc}^* &= \cos\theta.(R_f.i_{dc}^* - \omega_L.i_{qc}^* + v_{dm}^*) - \sin\theta.(R_f.i_{dc}^* + \omega_L.i_{qc}^* + v_{dm}^*) \\
v_{qc}^* &= \sin\theta.(R_f.i_{dc}^* - \omega_L.i_{qc}^* + v_{dm}^*) + \cos\theta.(R_f.i_{dc}^* + \omega_L.i_{qc}^* + v_{dm}^*)
\end{align*}
\]  

(56)

It is then necessary to locate the sector of belonging of the desired reference voltage vector \( \overline{V}_{\alpha\beta}^* \) which the \( C_{PMSM} \) converter must supply, figure 21.

With referring to Figure 21, we write:

\[
\gamma = \tan g \left[ \sin \theta(t, R_f.i_{dc}^* - \omega_L.i_{qc}^* + v_{dm}^*) + \cos \theta(t, R_f.i_{dc}^* + \omega_L.i_{qc}^* + v_{dm}^*) \right] \\
\delta = \gamma - \text{angle} \ (\tau_{cl}),
\]

(57)

The distribution of the states of the keys \( K_1, K_2, K_3 \) as well as their application times \( T \), over a modulation period \( T_m \) are illustrated in Figure 22.

\[
\begin{align*}
V_{\alpha\beta} &= \begin{cases} V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \mid V_{\alpha\beta} \\
0 \quad T/2 \quad T/2 \quad T/2 \quad T/2 \quad T/2 \quad T/2 \quad T/2 \quad T/2 \quad T
\end{cases}
\end{align*}
\]

(58)

Fig.22. Distribution of key control times

The keys \( K_1, K_2, K_3 \) application times in a sector \( i \) are defined as follows:

\[
\begin{align*}
T_i &= \sqrt{2} \cdot \frac{V_{\alpha\beta}}{V_{dc}} \cdot T_m \cdot \sin \left[ \frac{i \cdot \pi}{3} - \gamma \right] \\
T_{i+1} &= \sqrt{2} \cdot \frac{V_{\alpha\beta}}{V_{dc}} \cdot T_m \cdot \sin \left[ \gamma - (i - 1) \cdot \frac{\pi}{3} \right]
\end{align*}
\]

Therefore, the average value of the voltage \( \langle \overline{V}_{\alpha\beta} \rangle \) supplied by the \( C_{PMSM} \) converter is:
\[
\left[ \mathbf{v}_{\text{eq}} \right] = \frac{1}{T_e} \left[ I_{\text{eq}} \right] + \frac{1}{T_e} \left[ I_{\text{eq}} \right] e^{j(\omega - j) \frac{2}{3} V_d e^j} + \frac{1}{T_e} \left[ V_d e^j \right] + \frac{1}{T_e} \left[ V_d e^j \right] \right] \tag{59}
\]

Where:

\[
T_0 = \frac{T_H - T_i - T_{i+1}}{4} \tag{60}
\]

This voltage will be transferred to the (d, q) reference frame according to the following relation:

\[
\mathbf{v}_{\text{eq}} = e^{-j\phi} \cdot \frac{1}{T_e} \left[ I_{\text{eq}} \right] + \frac{1}{T_e} \left[ I_{\text{eq}} \right] e^{j(\omega - j) \frac{2}{3} V_d e^j} + \frac{1}{T_e} \left[ V_d e^j \right] + \frac{1}{T_e} \left[ V_d e^j \right] \right] \tag{61}
\]

### 11 Technique de Filtrage

In order to improve the quality of the energy exchanged between the PMSM converter and the PMSM machine, we have integrated a low pass filter \((R_f, L_f)\). The filter cut-off frequency \((f_c)\) is given by:

\[
f_c = \frac{R_f}{2 \pi L_f} \tag{62}
\]

By application of the Laplace transform, the currents at the output of the \((R_f, L_f)\) filter are expressed as follows:

\[
\begin{align*}
I_{\text{dc}} &= \frac{V_{\text{dc}} - V_{\text{dm}} + \omega L_f I_{\text{qm}}}{R_f + p L_f} \\
I_{\text{qm}} &= \frac{V_{\text{dc}} - V_{\text{qm}} - \omega L_f I_{\text{dc}}}{R_f + p L_f}
\end{align*} \tag{63}
\]

Numerically one writes:

\[
\begin{align*}
I_{\text{dc}}(n) &= \frac{I_{\text{dc}}(n) - V_{\text{dc}}(n + 1) - \omega L_f I_{\text{qm}}(n) + V_{\text{dc}}(n)}{R_f + \frac{1}{T_e}} \\
I_{\text{qm}}(n) &= \frac{I_{\text{dc}}(n) - V_{\text{dc}}(n + 1) - \omega L_f I_{\text{qm}}(n) + V_{\text{dc}}(n)}{R_f + \frac{1}{T_e}}
\end{align*} \tag{64}
\]

Or:

\[
\begin{align*}
I_{\text{dc}}(n) &= \frac{I_{\text{dc}}(n) - V_{\text{dc}}(n + 1) - \omega L_f I_{\text{qm}}(n) + V_{\text{dc}}(n)}{R_f + \frac{1}{T_e}} \\
I_{\text{qm}}(n) &= \frac{I_{\text{dc}}(n) - V_{\text{dc}}(n + 1) - \omega L_f I_{\text{qm}}(n) + V_{\text{dc}}(n)}{R_f + \frac{1}{T_e}}
\end{align*} \tag{65}
\]

Where \(T_e\) is the sampling period.

### 12 Phase Locked Loop (PLL)

The transformations of Park, by means of the use of the matrix \([P]\), of axes \((d, q)\) that we have established, were based on arguments perfectly identical to those of the systems of voltages (currents) studied, \((V_{\text{dc}}, I_{\text{dc}})\). The aim of this approach was to reconstitute reference variables, assigned to the control loops, which were extremely precise, and on the other hand to aim at a perfect synchronization of the procedures for digital processing of the various state variables.

On the basis that:

\[
\begin{align*}
v_{dc} &= \frac{3}{\sqrt{2}} V_{\text{max}} \cdot \cos(\arg[P] - \arg(\mathbf{v}_{ic}(t))) \\
v_{qc} &= -\frac{3}{\sqrt{2}} V_{\text{max}} \cdot \sin(\arg[P] - \arg(\mathbf{v}_{ic}(t)))
\end{align*} \tag{66}
\]

In these circumstances, we must ensure that:

\[
\arg[P] = \arg(\mathbf{v}_{ic}(t)) \tag{67}
\]

It then follows:

\[
v_{qc} = -\frac{3}{\sqrt{2}} V_{\text{max}} \cdot (\arg[P] - \arg(\mathbf{v}_{ic}(t))) \tag{68}
\]

Therefore, the phase locked loop (PLL) must guarantee the digital procedure established in figure 23.

### 13 Model of Electric Vehicle Traction (EVT)

The model of the electric vehicle traction that emphasizes the different resistive torques \(T_{\text{frw}}, T_{\text{frw}}, T_{\text{w}}\) opposed to the
electromagnetic torque $T_{em}$ developed by the PMSM motor is illustrated in figure 24.

![Fig.24. Chain of traction](image)

Where:
- $T_{srm}$ is the speed reducer torque of the PMSM side,
- $T_{srw}$ is the speed reducer torque of the wheel side,
- $T_w$ is the wheel torque.

In order to clarify the distribution of these different torques on the electric vehicle's shaft, we have used an analogy with the single-phase electric transformer, figure 25.

![Fig.25. Equivalent model of mechanical torque transfer](image)

By referring to the equivalent model of figure 25, we write:

$$
\begin{align*}
T_{em} &= D_m \cdot \Omega_m + J_m \frac{d\Omega_m}{dt} + T_{srm} \\
T_{srw} &= D_w \cdot \Omega_w + J_w \frac{d\Omega_w}{dt} + T_w
\end{align*}
$$

With:

$$
\begin{align*}
\Omega_w &= r \cdot \Omega_m \\
T_{srm} &= r \cdot T_{srw}
\end{align*}
$$

This leads to:

$$
T_{em} = (D_m + r^2 \cdot D_w) \cdot \Omega_m + (J_m + r^2 \cdot J_w) \frac{d\Omega_m}{dt} + r \cdot T_w
$$

Finally:

$$
T_{em} = D_{tm} \cdot \Omega_m + J_{tm} \frac{d\Omega_m}{dt} + r \cdot T_w
$$

where:

$$
\begin{align*}
D_{tm} &= D_m + r^2 \cdot D_w \\
J_{tm} &= J_m + r^2 \cdot J_w
\end{align*}
$$

The mechanical torque $T_w$ applied to the wheel of the electric vehicle is given by the relation:

$$
T_w = F_r \cdot R_w
$$

$R_w$ The radius of the EV wheel.

$F_r$ The resistive force (N),

On the other hand, the road and the quality of the coating have resistances external to the advance of the vehicle on a longitudinal plane. All the forces at the advancement can be represented by a single force of the second order: Under these conditions, the dynamics of the PMSM machine will be governed by the following mathematical model:

$$
\begin{align*}
\frac{d\Omega_m}{dt} &= \frac{T_{em} - r \cdot T_w - D_{tm} \cdot \Omega_m}{J_{tm}} \\
\frac{d\theta_m}{dt} &= \Omega_m
\end{align*}
$$

With:

$$
\Omega_m = \frac{\omega}{p}, \quad p \text{ is the number of pair poles.}
$$

**14 The Forces Resisting Movement of the Electric Vehicle**

In order to evaluate with great precision the electromagnetic torque which the motor of the electric vehicle (EV) must develop, to overcome the total resisting force $F_r$ opposed to the movement of the vehicle, we must establish the
balance of all the forces \( F_T = \sum F_{ri} \) likely to act during the movement of this vehicle. In effect, a moving vehicle is subjected overall to a force opposed to the penetration into the air \( F_{rap} \), to a force of opposition to the rolling \( F_{rrol} \), and possibly to a force of opposition to the rise in a slope \( F_{rst} \).

### 14.1 Force of penetration into air
This force \( F_{rap} \) is created by the mass of air that the vehicle in motion wishes to pass through.

![Fig.26. Effect of the force of penetration into the air](image)

The force required to penetrate the air \( F_{rap} \) is calculated by applying the relation:

\[
F_{rap} = \frac{1}{2} \cdot \rho_{EV} \cdot S \cdot C_s \cdot V_{EV}^2
\]  
(77)

Where :
- \( \rho_{EV} \) The density of the vehicle,
- \( S \) The surface taken to the wind,
- \( C_s \) Coefficient of penetration into air,
- \( V_{EV} \) Electric vehicle speed.

### 14.2 Rolling resistance force
This force \( F_{rrol} \) is applied to the vehicle as a result of the contact of these wheels with the road followed.

![Fig.27. Effect of the rolling resistance force](image)

The rolling resistance force \( F_{rrol} \) is calculated by applying the relation:

\[
F_{rrol} = M_{EV} \cdot g \cdot (k_{1rol} + k_{2rol} \cdot V_{EV}^2)
\]  
(78)

Where :
- \( M_{EV} \) The mass of the vehicle,
- \( g \) The acceleration of gravity,
- \( k_{1rol}, k_{2rol} \) Coefficients of rolling resistance.

### 14.3 Slope force
This force \( F_{rst} \) is created at times when the vehicle attacks a slope. In fact, it depends on the weight of the vehicle \( P_{EV} \) and the angle of inclination of the road \( \delta_p \) used by the vehicle.

![Fig.28. Effect of the sloping terrain force](image)

The slope force \( F_{rst} \) is calculated by mean of the following relation:

\[
F_{rst} = P_{EV} \cdot \sin(\delta_p)
\]  
(79)

Where \( P_{EV} = M_{EV} \cdot g \).

### 14.4 Centrifugal Force
In Newtonian mechanics centrifugal force \( F_c \) is a force of inertia directed outside the axis of rotation which seems to act on all objects when they are observed in a rotating reference frame. The concept of centrifugal force can be applied to vehicles in rotational motion according to a certain curvature.

![Fig.29. Centrifugal force applied to an electric vehicle](image)
Its intensity is given by the formula:

\[ F_c = \frac{M_{EV} V_{EV}^2}{R_c} \]  

\( R_c \) is the distance from the axis of rotation to the center of gravity of the electric vehicle (EV), i.e. the radius of curvature of the path in meters (m). This reaction force \( F_c \) is sometimes described as a centrifugal inertial reaction [37] [38] that is a force which is centrifuged, which is an equal and opposite reactive force to the centripetal force which is the curvature of the path.

\[ F_{en} = P_{ve} k_{en} \]  
\[ F_{wp} \left( \delta_p \right) = P_{ve} \cdot \sin(\delta_p) \]  
\[ F_{zw} \left( V_{ve}^2 \right) = \left( \frac{1}{2} \rho_{ve} S_{c_e} + P_{ve} k_{zw} + \frac{M_{EV}}{R_c} \right) V_{ve}^2 \]

Therefore, we write the total resistant force opposed to the movement of the vehicle is three-dimensional:

\[ F_r = f_{ve} (P_{ve} , \delta_p , V_{ve}^2) \]  

The dynamics of the electric vehicle brought on the motor shaft then becomes:

\[ \begin{cases} \frac{d\Omega}{dt} = \frac{T_m - r.R_w.f_{ve}(P_{ve}, \delta_p, V_{ve}^2) - D_m.\Omega_m}{J_m} \\ \frac{d\theta}{dt} = \Omega_m \\ \end{cases} \]

Then:

\[ \begin{cases} \frac{d\Omega}{dt} = \frac{T_m - r.R_w.f_{ve}(P_{ve}, \delta_p, V_{ve}^2) - D_m.\Omega_m}{J_m} \\ \frac{d\theta}{dt} = \frac{1}{r.R_w} V_{ve} \end{cases} \]

Taking into account the link between the linear speed of the electric vehicle \( V_{ve} \) and that of the wheels \( \Omega_w \):

\[ \begin{cases} V_{ve} = R_w \cdot \Omega_w \\ \Omega_w = r.\Omega_m \end{cases} \]

We obtain:

\[ F_{zw} \left( \Omega_w^2 \right) = r^2.R_w^2 \left( \frac{1}{2} \rho_{ve} S_{c_e} + P_{ve} k_{zw} + \frac{M_{EV}}{R_c} \right) \Omega_m^2 \]

15 Simulations and Results

We simulated the behavior of an electric vehicle with the following parameters:

\[ \rho_{ve} = 1.3 \text{Kg.m}^{-3} \] The density of the vehicle,

\[ S = 1.2 \text{m}^2 \] The surface taken to the wind,

\[ C_e = 0.29 \] Coefficient of penetration into air,

\[ V_{ve} \] Electric vehicle speed.

\[ M_{VE} = 1400 \text{Kg} \] The mass of the vehicle,

\[ g = 9.81 \text{m.s}^{-2} \] The acceleration of gravity,
Coefficients of rolling resistance:
\[ k_{1,roll} = 12.5 \times 10^{-3}, \quad k_{2,roll} = 32.4 \times 10^{-6} \]

\[ r = 0.92 \] the speed reduction ratio.

\[ R_w = 0.3m \] The radius of the EV wheel.

The parameters of the PMSM motor are:
- stator resistance: \( R_s = 0.4578 \Omega \),
- d-axis inductance: \( L_d = 0.00334 H \),
- q-axis inductance: \( L_q = 0.00334 H \),
- flux: \( \phi_f = 0.171 \text{weber} \),
- inertia: \( J_m = 0.01469 \text{Kg.m}^2 \),
- pair poles: \( p = 4 \),
- nominal torque: \( T_{emn} = 20N.m \),
- friction: \( D_m = 0.00334 N.m \)

We simulated the case where from the instant \( t = 1.2s \) up to \( t = 5s \) the electric vehicle attacks a slope of \( \delta_p = 30^0 \).

\[ \omega_m \]
\[ T_w \]
\[ T_{em} \]

Fig. 31. Rotational speed of the PMSM motor \( \omega_m \)

Fig. 32. Time evolution of electric vehicle speed

Fig. 33. Time evolution of the electromagnetique and resistive torques

During the rise in a slope the variations in the speed of the PMSM are similarly insignificant.

Fig. 34. Time evolution of \( \omega_m \)

Fig. 35. Torque evolution during the rise in a slope of 8%

The electromagnetic torque \( T_{em} \) perfectly compensates for the resistive torque \( T_w \) resulting essentially from the sloping rise \( \delta_p \).
The level of the DC bus voltage $V_{dc}$ remains insensitive to the torque rise of the electric vehicle, which proves that the control strategies adopted have perfectly isolated the engine power system from any abrupt change in the EV vehicle operator mode.

We notice that when the vehicle picks up speed $V_{EV}$ at the beginning of the descent, the regulators engage a braking strategy and we notice that the speed regains its reference value. On the other hand, we observe the engagement of a regenerative braking strategy because the torque becomes negative and the motor returns electrical energy to the battery.

Similarly, during the descent into a ramp, the fuzzy control strategies act in such a way as to attenuate the excesses of certain state variables. We simulated the behavior of the electric vehicle the moment it takes a turn, that is to say when it is subjected to the centrifugal force $F_c$ which pushes it towards the outside of the curve.
During the turning, the control strategies fuzz act to reduce the excess speed and this by an evaluation of new references ensuring an extreme degree of safety.

16 CONCLUSION
In this work, we are interested in the implementation of intelligent strategies based on fuzzy controllers to ensure optimal operation of an electric vehicle. We can say that the design and optimization of the traction chain of an electric vehicle is a multidisciplinary problem that must take into consideration, at a minimum, batteries, mechanical transmission, and electromagnetic powered electronics. The search for a minimal cost is added to the scientific and technological difficulties. The future electric vehicle must be able, with appropriate control, to use the energy stored in the batteries in order to sustain the electricity network during periods of peak consumption or in case of emergency (shutdown of a production plant). The energy stored in the battery of the vehicle could also supply the electrical requirements of the dwelling. This technology requires that the charger embedded in the vehicle as well as the interface between the vehicle and the electrical network are bidirectional. The results obtained are extremely encouraging and prove that the more we refine the electromagnetic model of the electric vehicle the more we obtain a favorable ground for a better implementation of the strategies of control especially the fuzzy strategies.

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