

## TWO-DIMENSIONAL WORKING-OPTIMISATION OF A WOUND-ROTOR-SYNCHRONOUS MOTOR FOR EV DRIVE-TRAIN

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**Abstract** - Energy saving is becoming more and more important today, particularly for electric vehicle application where the range is limited by batteries. In order to have a high performance drive-train, motor control must take into account this energy constraint. The wound-rotor-synchronous motor seems to be a good solution for electric drive-train thanks to its high Power/weight and Power/volume ratios. However, its energy optimisation is complex because of the supplementary degree of freedom due to the setting of the field current. In this paper we will present a method to make a two-dimensional optimisation of this kind of motor and we will highlight, by E.V simulation, the advantage of this method compared to uni-dimensional ones.

**Keywords** : Synchronous motor, electric vehicle (E.V), energy optimisation.

### 1. INTRODUCTION

The Laboratory of Transportation and Environment (LTE) of INRETS has been involved in the simulation of electric and hybrid vehicle drive-trains for 7 years [1]. A software was developed to simulate electric and series hybrid vehicles. It enables us to determine the following elements :

- working conditions of the drive-line (speed and torque of the electric motor and transaxel) which are calculated from recorded actual use schedules (real urban, suburban, highway driving schedules) using a vehicle and road laws model.
- Current, voltage and losses in the electric motor and its control.
- distribution of energy fluxes and losses in the drive-line
- electric and fuel consumption, pollutant emissions of the internal combustion engine
- dynamic performances of the vehicle
- Relevance of the various control laws for optimising vehicle performance in hybrid mode.

Since 1991, several versions of this software have been formulated in co-operation with car, bus and component manufacturers such as Peugeot S.A [2,3], Renault V.I [4], ALSTOM, and universities (GREEN INPL, LEEP, CEGELY) [5].

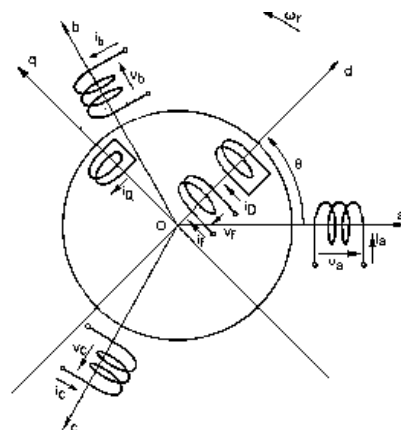
Nowadays, accurate models, validated on test benches, of three kind of electric motor (DC, AC induction and synchronous motor) are available in the software library [6,7]. They may be integrated in any electric or hybrid vehicle architecture for simulation on actual use

conditions (actual use schedules recorded and classified by INRETS).

This paper deals with the synchronous motor as an economic solution for future automotive application and especially the wound rotor motor. We will mainly discuss a global method for energy saving by using a two-dimensional optimisation which is possible with this kind of motor [8].

### 2. SYNCHRONOUS MOTOR MODEL

We will consider a classical electric model for a wound rotor synchronous motor expressed in Park co-ordinates (d,q) figure 1. However, we added the magnetic saturation effect and core losses after identifying them on a test bench.



**Figure 1.** Electric motor model and the transformation of co-ordinates

Electric equations in Park coordinates can be written as follows :

$$\begin{cases} v_d = R_s i_d + \frac{d\Phi_d}{dt} - p\omega_r \Phi_q \\ v_q = R_s i_q + \frac{d\Phi_q}{dt} + p\omega_r \Phi_d \\ v_f = R_f i_f + \frac{d\Phi_f}{dt} \end{cases} \quad (I)$$

where  $p$  is the number of pair of poles.

And flux equations :

$$\begin{cases} \Phi_d = L_d i_d + M_f i_f \\ \Phi_q = L_q i_q \\ \Phi_f = L_f i_f + M_f i_d \end{cases} \quad (II)$$

With the electromagnetic torque :

$$T = p(\Phi_d i_q - \Phi_q i_d) \quad (III)$$

Previous studies have shown that for electric vehicle applications, we can not neglect the magnetic saturation effect unless we tolerate considerable error in current and energy calculation [6]. In our case, this effect is included in the model by considering  $M_f$  variations with  $i_f$  (figure. 2) and  $L_d$  variations with  $I_s$  (rms stator current) measured on a test bench.

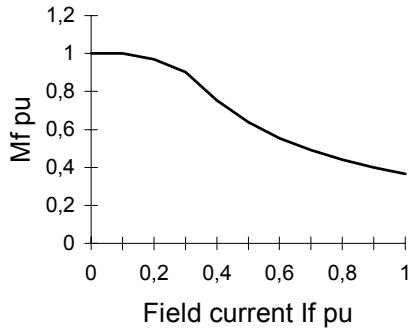


Figure 2. Saturation effect on Mutual  $M_f$

This allows us to improve the model accuracy even if we do not take into account the cross saturation phenomenon.

### 3. WORKING OPTIMISATION METHODS

For optimisation calculation, the electric equations are considered only on steady state mode. Optimisation during transient mode is not taken into account because of resolution difficulties.

Both for calculation or for actual vector control, there are three parameters to set ( $i_d$ ,  $i_q$ ,  $i_f$ ) in order to reach a desired mechanical working point of a wound rotor-synchronous motor. Only one relationship between these parameters must be assured (torque equation III). So there are 2 degrees of freedom which should be fixed by including working criteria and/or constraints. In what follows, we consider  $i_d$  and  $i_f$  as the 2 degrees of freedom to set when  $i_q$  is fixed by the torque equation. Several method can be used.

#### 3.1 Uni-dimensional optimisation : method 1

In this method,  $i_f$  is fixed according to a data table for example, usually to work at maximum  $i_f$  up to the maximum voltage, and then remains the maximum voltage. For our motor we will take a current  $i_f$  variation with speed according to the curve shown on figure 3.

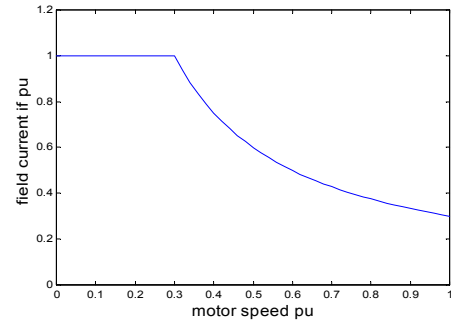
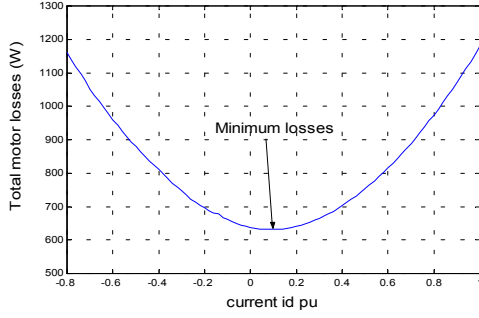


Figure 3.  $i_f$  variation with motor speed.

As  $i_f$  is fixed, the remaining degree of freedom allows a uni-dimensional optimisation (of total motor losses for example) by choosing the appropriate  $i_d$  stator current component (figure 4). For the  $i_q$  component, it is fixed by the torque equation.



**Figure 4.** Motor losses variation with  $i_d$  at constant  $i_f$ .

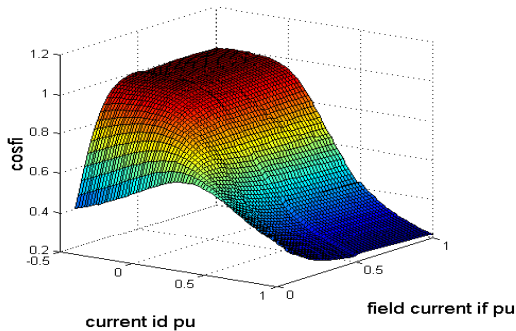
The optimum current  $i_d$  corresponds to the minimum losses.

### 3.2 Two-dimensionnal optimisation with constraint (here $\cos\varphi = 1$ ) : method 2

This method gives two equations to solve and one equation to minimise in order to find the three parameters ( $i_d$ ,  $i_q$ ,  $i_f$ ). For the case where the constraint is  $\cos\varphi = 1$ , this can be expressed by the following system :

$$\begin{cases} i_q = T(i_d, i_f) \\ \cos\varphi(i_d, i_f) = 1 \\ \min(\text{Losses}(i_d, i_f)) \end{cases}$$

If we draw the  $\cos\varphi$  variation with  $i_d$  and  $i_f$  for a working point (Figure 5), we can see that the domain where  $\cos\varphi = 1$  is small, and this reduces the margin of loss minimisation considerably.



**Figure 5.**  $\cos\varphi$  variation with  $i_d$  and  $i_f$

### 3.3 Two-dimensionnal optimisation without constraints : method 3

Our proposed two-dimensionnal optimisation method enables us to find the 3 optimum parameters ( $i_{dopt}$ ,  $i_{qopt}$ ,

$i_{fopt}$ ) simultaneously, by optimising, an absolute criterion which can be the minimisation of total motor losses for example, and this without fixing constraint other than the torque.

In fact, the total motor losses can be expressed by a multi-variable function  $f$  as follow

$$f(i_d, i_q, i_f) = Rf.i_f^2 + Rs.(i_d^2 + i_q^2) + PF$$

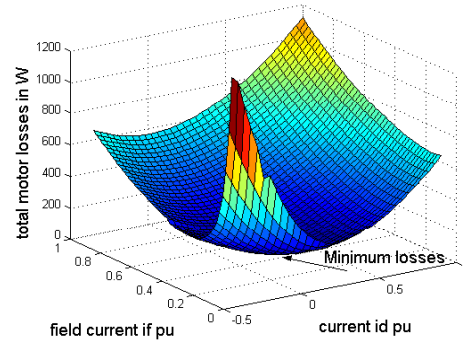
where PF represents the core losses expressed as a function of ( $i_d$ ,  $i_q$ ,  $i_f$ ). using conventional electrical equations and an appropriate core loss model validated with the measurements on the test bench.

In addition, the torque constraint  $g$  is necessary to satisfy the instantaneous torque request :

$$g(i_d, i_q, i_f) = T - p.(Mf.i_f + (Ld - Lq).i_d).i_q = 0$$

As the domain of total losses is assumed to be convex (verified even with saturation effect), we can apply the Simplexe algorithm [9] to find the 3 optimum parameters ( $i_{dopt}$ ,  $i_{qopt}$ ,  $i_{fopt}$ ) by searching the global minimum of the function  $f$  while satisfying the constraint  $g$ .

The existence of a global minimum of total losses corresponding to an optimum current  $i_{dopt}$  and an optimum field current  $i_{fopt}$  is illustrated by figure 6. The optimum current  $i_{qopt}$  verifies the torque constraint.



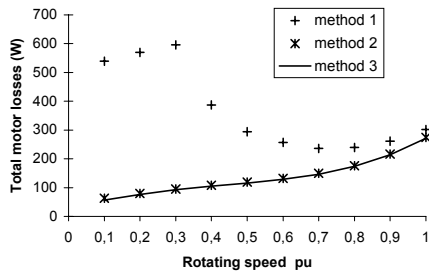
**Figure 6.** Total motor losses variation with  $i_d$  and  $i_f$

## 4. SIMULATION RESULTS

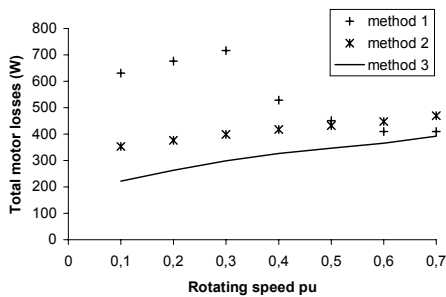
### 4-1 Comparison of the 3 methods on several working points

#### Loss comparison

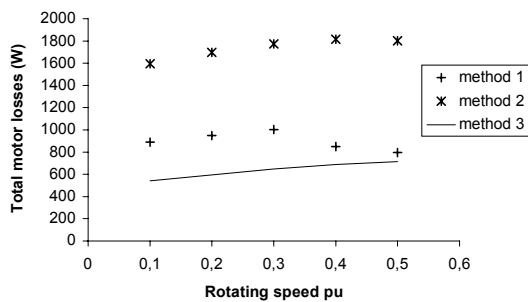
Considering three values of torque : low, mean and high, we have calculated total motor losses variation with the motor rotating speed for each one of the three optimisation methods. Results are shown on figures 7, 8 and 9.



**Figure 7.** Total motor losses against speed at low torque for the 3 optimisation methods



**Figure 8.** Total motor losses against speed at mean torque for the 3 optimisation methods



**Figure 9.** Total motor losses against speed at high torque for the 3 optimisation methods

For low torque (figure 7), method 1 gives the highest losses because field losses are considerable and mainly at low speed. At high speeds, field current reduction makes the differences lower between the three optimisation methods. We can also note that method 2 shows total losses very close to those of method 1 because, at this torque range, the  $\cos\varphi = 1$  domain is near the minimum loss point.

For mean torque (figure 8), we find the same conclusions as above except for the losses corresponding to method 2 which become distinctly higher than those of method 1. This phenomenon amplifies at high torque range (figure 9) because the  $\cos\varphi = 1$  domain moves away from the minimum loss point. At this range of torque, method 2 becomes the least energy efficient, when method 1 gives lower relative differences as compared to method 3, especially at high speeds.

In every case, the lowest losses are obtained using method 3, which comes up to our expectations.

#### Maximum range comparison

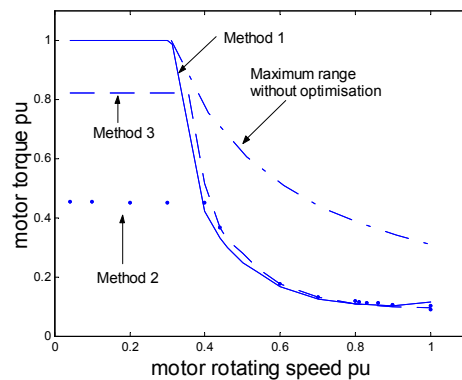
In E.V application, there are several constraints for choosing electric motor, we can list :

- good Power/weight ratio.
- good Power/volume ratio.
- not very high DC voltage.

Several studies showed that, according to actual vehicle use, it is better to choose smaller motor which can be transiently over-loaded in order to raise momentarily the ratios listed above [5]. We talk about 5 minutes Power and permanent Power.

Consequently it is important to study the E.V motor at its maximum range and the limits introduced by the optimisation methods when considering a maximum stator current  $I_{s \max}$ , a maximum DC voltage  $V_{cc \max}$  and a maximum field current  $i_{f \max}$ .  $I_{s \max}$  can be variable with cooling method and time range during which we maintain this maximum value.

The following figure presents torque and speed maximum ranges for the 3 previously described methods at the same electric parameter limits of our motor.



**Figure 10.** Maximum torque/speed domain for different optimisation method

We can see the influence of stator current limit before 0.3 pu speed value, and the maximum voltage influence after it. The voltage constraint limits considerably the maximum torque developed at mean and high speed and this when using any method of optimisation. For low speeds, method 1 presents the highest torque because it

operates at the maximum field. However method 2 shows a maximum torque considerably low because, as we noted it above, the  $\cos\varphi = 1$  domain gives very high stator current at this speed and torque range.

#### 4-2 Simulation of E.V on actual driving schedules using methods 1 and 3.

##### Simulation conditions

As the torque range of method 2 is not large enough to carry out the driving schedules, we consider vehicle simulation using only method 1 and 3. At the present algorithm state, we do not allow the optimisation method to change during a driving schedule. This option should be available in the next versions of the software

Using the described motor model and the LTE software for vehicle simulation, we consider a 1tonne E.V, simulated on actual use driving schedules.

In fact, since 1987, INRETS has recorded and classified different kind of vehicle trips in actual use by equipping cars with sensors and a data system registerer [10]. Figure 11 shows an example of vehicle speed against time curve registered in these studies.

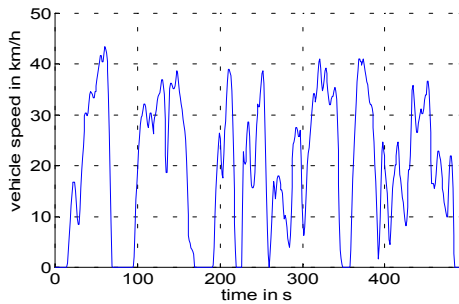


Figure 11. Sequence of an urban driving schedule.

For the vehicle simulation, 3 of these registered schedules are considered: a slow urban one (UL), a fast urban one (UF) and an extra urban one (R). The following table summarizes the characteristics of each driving schedule.

	Mean speed (km/h)	Maximum speed (km/h)	Maximum Acceleration (m/s <sup>2</sup> )
UL	7.4	22.5	1.82
UF	19.2	45.2	2.58
R	31.2	68.9	2.54

Table 1. INRETS's driving schedules characteristics

##### Simulation results

If we examine the different kind of losses, we can see from figure 12 to 14 that method 3 reduces core losses, and more significantly, field losses. However stator copper losses are lower if using method 1. This distribution is due to the field magnitude which raises field and core losses when it is high and reduces stator copper losses for the same torque.

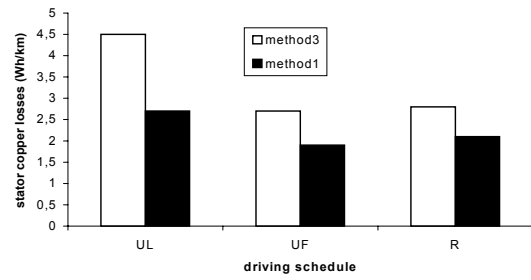


Figure 12. Stator copper losses per km during the driving schedules

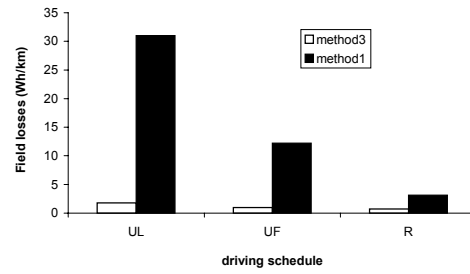


Figure 13. Field losses per km during the driving schedules

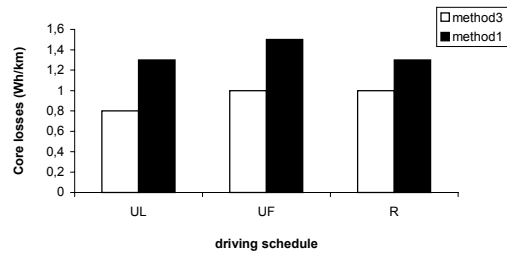


Figure 14. Core losses per km during the driving schedules

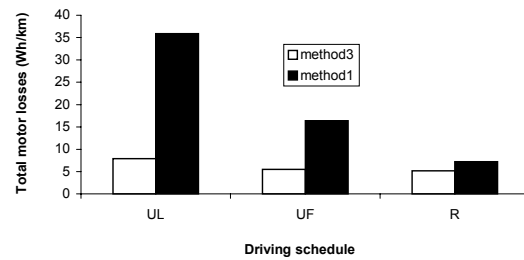


Figure 15. Total losses per km during the driving schedules

The total losses shown on figure 15 corroborate the previous conclusion concerning the performance of method 3. Nevertheless, The advantage of this method decreases with the mean speed of the driving schedule. For high speed schedules, the gain is not significant.

In order to show the influence of the optimisation method on battery consumption using the 2 methods and the energy gain allowed by method 3, the following table summarises the main results obtained for the three selected driving schedules. We distinguish traction and regeneration mode because this later depends on braking regulation. Here, we give the value of all the battery

energy potentially recoverable from the mechanical inertia.

		UL	UF	R
Cons Wh/km Method 1	T*	176.1	154.8	184.6
	R**	-5.4	-41.3	-76.0
Cons Wh/km Method 3	T	146.9	144.5	183.4
	R	-25.4	-46.9	-78.1
Gain in %	T	16.5	6.6	0.6
	R	11.3	3.6	1.1

\*T : Traction mode

\*\*R : Regeneration mode

**Table 2.** Battery energy consumption according to driving schedule, and method 3 relative gain

We can note that the energy gain in traction mode, using method 3 compared to method 1, can reach 16 % of the total energy consumption, and this on slow urban conditions. Besides, if we assume that braking control allows the recovering of all the regenerated energy, the global gain becomes higher (about 30 %). However, the same conclusion as above concerning high speed schedules is valid.

## 5. CONCLUSION

The use of Wound-rotor-synchronous motor in the E.V. applications can be advantageous if it is well controlled. This kind of motor presents 2 electric degrees of freedom for a mechanical working point, so that optimisation using functioning criteria is possible. 3 energy optimisation methods are studied in this paper using a model validated on test bench equipped with a motor dedicated to electric drive-trains. The best calculation results are obtained by using a two-dimensional optimisation method without supplementary constraints. When simulated with the INRETS electric vehicle software on actual driving schedules, this method shows considerable energy gain for slow urban trips. However, this gain decreases with velocity of the schedules and the difference between different optimisation methods becomes insignificant.

In the future, a test bench will be mounted at INRETS with a wound-rotor-synchronous motor and an advanced Digital Signal Processor for its control. In order to implement optimisation methods in the real time process, and especially the two-dimensional method, we should study how to reduce the calculation time.

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