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Multi-objective powertrain cost and autonomy optimization dedicated to electric vehicles

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Abstract— **weak autonomy and high manufacturing cost are the main restrictions of Electric Vehicles (EVs). To solve these problems, several research studies try to improve the electric vehicle performance.**

This paper is about providing a multi-objective optimization algorithm combined with analytical model of electric vehicle. Permanent Magnet Synchronous Machine (PMSM) is chosen as the power train engine. The motor mathematical modelling is first described and the genetic algorithm is then detailed. This study aims to find best design parameters of motor-converter that provide optimal autonomy with an acceptable cost.

Keywords— **powertrain; autonomy optimization; cost optimization; genetic algorithm; multi-objective optimization; PMSM; weighted sum method**

I. INTRODUCTION

Nowadays, different types of electric vehicles are increasingly designed because they represent an ideal substitute to solve pollution problems and provide a big contribution in reducing carbon and greenhouse gases.

Nevertheless, the major drawbacks of electric vehicles are their weak autonomy, which is directly bound to the low-level storage capacity of batteries, and their high cost. [1][2]
This fact prevents their introduction in the consumer market in important numbers.

The electric vehicle (EV) system includes two subsystems: the electric machine and the vehicle platform (electrical energy source, control system and a power converter) [1] [3]

In this context, choosing the best motor configuration and finding its optimum design parameters are an important task for an acceptable autonomy and affordable cost.

The permanent magnet synchronous motor (PMSM) with radial flux is chosen in this study. It does not require an external power source for excitation and demonstrate high efficiency ratios compared with induction motors. [4][5]

This paper is organized as follow: First, the structure of the powertrain is briefly introduced. Then, the PMSM model is detailed. Next, we formulate the multi-optimization problem by fixing the objective function and the technological and geometrical constraints. Simulation results are then presented and discussed.

I. POWERTRAIN MODELLING

The powertrain design is an important step that can highly influence the autonomy and the cost. It's in fact a multidisciplinary task that needs a deep research on different components, their size and composition.
Electrical, mechanical and material knowledge is required to make compromises between all the devises. [6]

As illustrated in fig.1, the powertrain of an EV is composed of: A battery, DC/AC converter, electric motor and mechanical linkage system (differential, reduction gear and wheels) [7] [8].

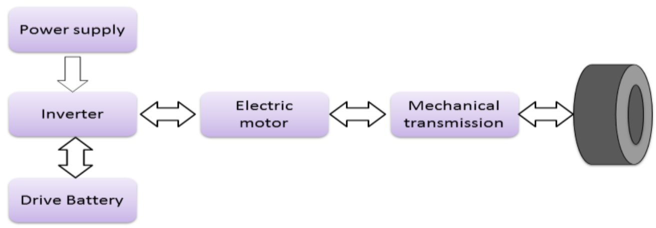

Fig.1 Electric vehicle powertrain structure

A drive system of an electric vehicle should include the following proprieties:
-High robustness facing various operating conditions
-rational cost
-high torque in starting phase and climbing
-regenerative system when braking
-acceptable efficiency

To drive an electric vehicle system, two configurations could be noted: one electric motor or two electric motors each for each wheel.
In this paper, one front drive electric motor is chosen.

II. MATHEMATICAL MODELLING OF PMSM

The permanent magnet synchronous motor is an AC machine composed of three stator windings Y connected and displaced by 120 electrical degrees.
The motor model can be expressed when transformed in the rotor oriented coordinates d-q as follow: [4] [9]

$$u_{sd} = r_s.i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega.\Phi_{sq} \tag{1}$$

$$u_{sq} = r_s.i_{sq} + \frac{d\Phi_{sq}}{dt} - \omega.\Phi_{sd} \tag{2}$$

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$$\Phi_{sd} = L_d.i_{sd} + \Phi_f \quad (3)$$

$$\Phi_{sq} = L_q.i_{sq} \quad (4)$$

$$C_e = \frac{3}{2} p\left[\Phi_f.I_q + \left(L_d - L_q\right).I_d.I_q\right] \quad (5)$$

$$C_e - C_r = J.\frac{d\Omega}{dt} + f.\Omega \quad (6)$$

Where Ω, p, J, f, C_r, C_e, Φf denote: the rotation's speed, the number of pairs of poles, the moment of inertia, the coefficient of viscous friction, the resistive torque, the electromagnetic torque and the flux produced by the permanent magnet.

L_{sd}, L_{sq}, V_{sd}, V_{sq}, r_s are respectively:"d" axis stator inductance, "q" axes stator inductance, "d" axis stator voltage, "q" axis stator voltage and the stator windings resistance.

III. FORMULATION OF COST AND AUTONOMY OPTIMIZATION PROBLEM

The traction motor and the controller are the two main elements of an electric drive system. Therefore, they must be designed to operate with each other as one system.

After defining the powertrain configuration, we explain in this section the optimization problem that focus on the motor-converter mathematical equations to find compromises between higher autonomy and affordable production cost. [2] and [10] present details of modelling equations.

A. Autonomy objective function

The electric vehicle autonomy is expressed for any velocity profile as follow:

$$Au = \frac{W_b \eta}{P_u} V_m \quad (7)$$

Where W_b is the stocked energy in battery, η is the traction chain efficiency, V_m is the average speed and P_u is the average useful power.

V_m is calculated according to the following formula:

$$V_m = \frac{1}{n}\sum_{k=1}^{n} V\left(k\right) \quad (8)$$

The autonomy is directly related to the powertrain efficiency. Minimizing the autonomy is therefore minimizing the powertrain efficiency which is expressed as:

$$\eta = \frac{P_u}{P_u + P_c + P_i + P_m + P_r + P_{cond}} \quad (9)$$

$P_u, P_c, P_i, P_m, P_r, P_{cond}$ are respectively: average useful power, copper losses, iron losses, mechanical losses, reducer losses and converter losses.

They are given by the following expressions:

$$P_u = \frac{C_{wm} V_m}{R_w} \quad (10)$$

where C_{wm} is the average torque should be developed by motor wheels.

$$P_i = q.f^{1.5}.(\mathrm{M_{sy}.B_{cs}}^2 + \mathrm{M_{st}.B_g}^2) \quad (11)$$

$$P_o = 3.R.(\frac{I}{\sqrt{2}})^2 \quad (12)$$

We define R as the motor phase resistance and expressed as follow:

$$R = \rho.\frac{\frac{ntc}{3}.L_{sp}}{\frac{I}{\sqrt{2}}}.\delta \quad (13)$$

and I motor average current on the circulation mission:

$$I = \frac{2}{3}.\frac{C_d}{r_g.K_e} \quad (14)$$

$$K_e = \frac{8}{\pi}.N_{sph}.D_o.D_i.B_g.\sin\left(\frac{\pi}{2}.\beta\right).\sin\left(\frac{\pi}{2}.\beta.\alpha\right) \quad (15)$$

$$P_m = \frac{C_{wm}.\frac{V_m}{R_w}}{\left(1 - K_m\right).\left(1 - K\right)}.K_m \quad (16)$$

$$P_r = K.\left(\frac{C_{wm}.\frac{V_m}{R_w}}{1 - K}\right) \quad (17)$$

$$P_c = a.I_m^2 + b.I_m + c \quad (18)$$

After defining the losses equations, we have noticed that the autonomy depends directly on the following design parameters: R_w, r_g, Di, D_o, B_g, δ, B_{cs}, B_{cr} and N_{sph}

R_w : Wheel radius

r_g : Gear reduction ratio

Di : Motor inner diameter

D_o : Motor outer diameter

B_g : Air-gap induction

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δ : Acceptable current density in coils

B_{cs} : Magnetic induction in stator yoke

B_{cr} : Magnetic induction in rotor yoke

N_{sph} : Number of spires per phase

As a result, the autonomy is function of:

$$A_u = f\left(R_w, r_g, D_i, D_o, B_g, \delta, B_{cs}, B_{cr}, N_{sph}\right) \quad (19)$$

B. Cost objective function

To minimize the EV cost, we have focused in this work on the motor-converter set since they are the main parts of a powertrain.

The cost objective function is expressed as follow: [3] [11]

$$Cost = C_m.M_m + C_c.M_c + \left(M_{sy} + M_{st} + M_{ry}\right).\left(C_i + C_{fab}\right) + C_{conv}.U_{dc}.I_{\max} \quad (20)$$

Mass equations are given by: [10]

$$M_{sy} = \pi.\left[\left(\frac{D_o + e}{2} + H_{tooth} + H_{sy}\right)^2 - \left(\frac{D_o + e}{2} + H_{tooth}\right)^2\right].D_i.M_{vt} \quad (21)$$

$$M_{st} = \frac{A_t}{2}.Nt.\left[\left(\frac{D_o}{2} + \frac{e}{2} + H_{tooth}\right)^2 - \left(\frac{D_o}{2} + \frac{e}{2}\right)^2\right].D_i.M_{vt} \quad (22)$$

$$M_{ry} = \pi.\left[\left(\frac{D_o - e}{2} - H_m\right)^2 - \left(\frac{D_o - e}{2} - H_m - H_{ry}\right)^2\right].D_i.M_{vt} \quad (23)$$

$$M_m = M_w.p.\left[\left(\frac{D_o - e}{2}\right)^2 - \left(\frac{D_o - e}{2} - H_m\right)^2\right].D_i.D_m \quad (24)$$

$$M_c = 3.\left[2.D_o + 4.a_{enc}.\left(\frac{D_o}{2} + \frac{e}{2} + \frac{H_{tooth}}{2}\right)\right].\frac{N_{sph}.I.M_{vc}}{\sqrt{2}.\Delta} \quad (25)$$

$$I_m = \frac{2}{3}.\frac{R_w.M_v}{r_g.K_e}.\left[\frac{V_b}{t_d} + 9.8.\sin\left(A_d.\frac{\pi}{180}\right)\right] \quad (26)$$

We define:

C_m : Cost of a kilogram of magnet

C_c : Cost of a kilogram of copper

C_i : Cost of a kilogram of iron

C_{fab} : Motor cost fabrication/Kg

C_{conv} : Converter cost per KW

M_m : Magnet mass

M_c : Copper mass

M_{sy} : Stator yoke mass

M_{st} : Stator teeth mass

M_{ry} : Rotor yoke mass

U_{dc} : DC bus voltage

After fixing all the mass equations we can conclude that the cost is function of:

$$\cos t = f\left(R_w, r_g, D_i, D_o, B_g, e, U_{dc}\right) \quad (27)$$

"e" represents the gab thickness.

C. Problem constraints

To establish the different constraints of autonomy-cost problem, we have considered physical, technological and expert properties.

1) Geometrical constraints:

$100mm \le D_o \le 250mm$

$90mm \le D_i \le 140mm$

$1mm \le e \le 8mm$

2) Technological constraints

$0.25m \le R_w \le 0.35m$

$3 \le r_g \le 8$

$2 \le \delta \le 7$

$20 \le N_{sph} \le 400$

3) Magnetic constraint

$0.1T \le B_g \le 1.04T$

$0.2T \le B_{cs} \le 1.6T$

$0.2T \le B_{cr} \le 1.6T$

IV. MULTIOBJECTIVE OPTIMIZATION

A. PRINCIPLE

A multi-objective optimization is a mathematical optimization problem that involves minimizing or maximizing more than one objective function. It has been applied in different fields especially engineering and economics.

It has in general the following form: [10][12]

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Minimise/Maximise: $F(X)= (F_1(x), F_2(x),\ldots F_n(x))$ (28)

With :

$$\begin{cases} g_j(X)=0, & j=1,\ldots m \\ h_k(X)\leq 0, & k=1,\ldots k \end{cases} \tag{29}$$

n: Number of objective functions

m: Number of equality constraints

k: Number of inequality constraints

In this study, increasing the power train autonomy will highly increase its cost.

In this context, the challenge of a multi-objective optimization problem is to find optimal solutions despite the presence of conflicting objective functions.

A. *Weighted sum method*

To solve the multiple objectives optimization problem, combining all the objectives into a single one is the solution.

The weighted sum is the simplest method to make decision in a multi-criteria problem. [10] [13]

We define:

$$F\left(F_1,F_2\right)=F\left(w_1,w_2\right)=w_1F_1+w_2F_2 \tag{30}$$

F is the function to maximize.

w_1 and w_2 are weighting values.

The objective function can be divided by a positive number without changing the solution. [11]

When dividing (30) by w_1, we can define w as:

$$w=\frac{w_2}{w_1} \tag{31}$$

Then (30) takes the following form:

$$F(w)=F_1(X)+wF_2(X) \tag{32}$$

The cost minimization problem is transformed into a maximization problem to have a homogenous function. Therefore, our cost and autonomy optimization problem consists in maximizing F function taking into account to keep $\mathrm{Im}\succ Id$ and $\eta\geq 0.95$

$$F=Au+a.\left(Cm-Cost\right) \tag{33}$$

Cm is a pre-defined maximum cost of the motor-converter

To conclude, the optimization problem can be expressed as follow:

$$\begin{cases} \text{Maximize F} \\ I_m\geq I_d \\ \eta\geq 0.95 \\ 0.1\leq \mathrm{B_g}\leq 1.04 \\ 250\leq R_w\leq 350 \\ 3\leq r_g\leq 8 \\ 90\leq D_i\leq 140 \\ 100\leq D_o\leq 250 \\ 1\leq e\leq 8 \\ 2\leq \delta\leq 7 \\ 0.2\leq \mathrm{B_{cs}}\leq 1.6 \\ 0.2\leq \mathrm{B_{cr}}\leq 1.6 \\ 20\leq \mathrm{N_{sph}}\leq 400 \\ 200\leq \mathrm{U_{dc}}\leq 400 \end{cases} \tag{34}$$

V. SIMULATION AND RESULTS

The genetic algorithm method was used in this study to solve the optimization problem [14].

The figure 2 describes the steps of the optimization process.

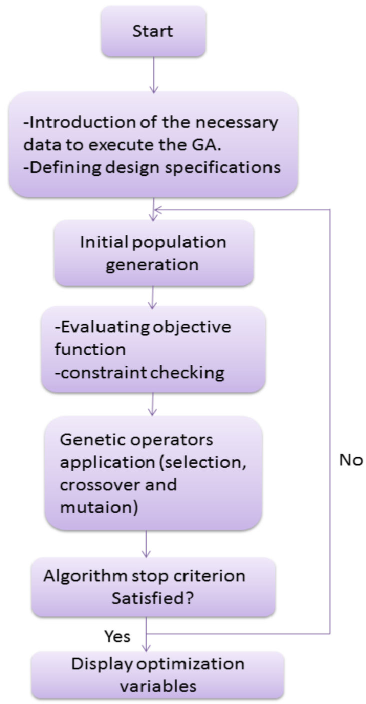

Fig.2 Cost and autonomy multi-objective algorithm

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The Genetic Algorithm (GA) was coded with Matlab using the parameters summarized in the table below:

TABLE I

GENETIC ALGORITHM CODE PARAMETERS

Parameter	Value
Population size	1022
Mutation probablity	0.01
Crossover probability	0.85
Generations number	100

The following table resumes the EV simulation parameters:

TABLE II
EV SIMULATION PARAMETERS

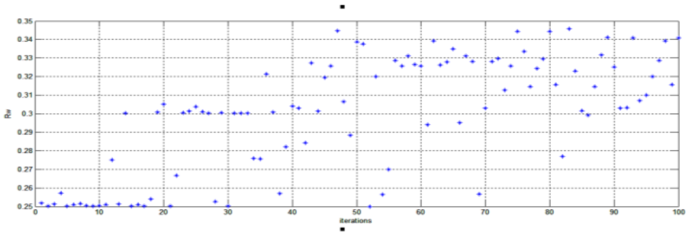
Parameter	Value
Vehicle mass	800Kg
Maximal speed of the EV	100Km/h
Vehicle front area	1.4m^2
Rolling resistance coefficient	0.013

After 100 iterations, the optimal values of objectives function for a maximal autonomy and minimal motor-converter cost are given in the following table.

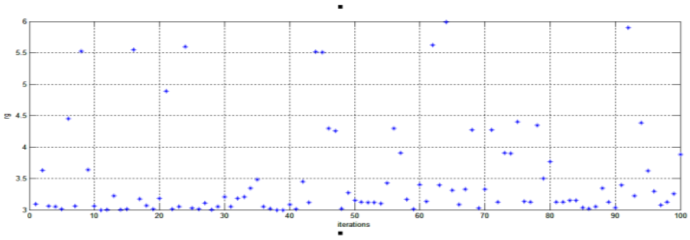
TABLE III

OPTIMAL SOLUTIONS

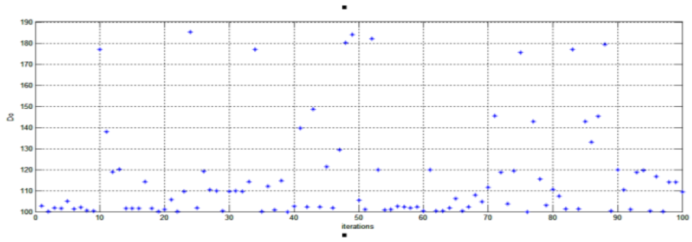
Parameters	Optimal solutions
B_g	0.1175T
R_w	0.2519m
r_g	3.0929
D_i	90.9286mm
D_o	102.7859mm
e	1.0929mm
δ	2.0929
B_{cs}	0.226T
B_{cr}	0.226T
N_{sph}	27.0577
U_{dc}	201.8573V
Optimal value of autonomy function	211.111 Km/h
Optimal value of cost function	1724.333 $



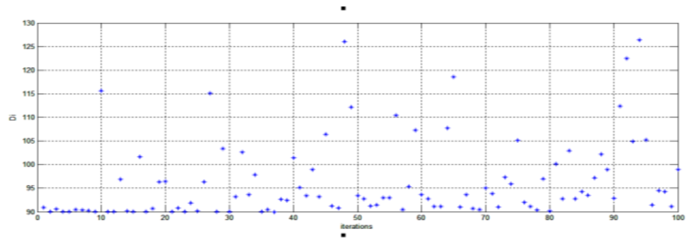
(a) Wheel radius



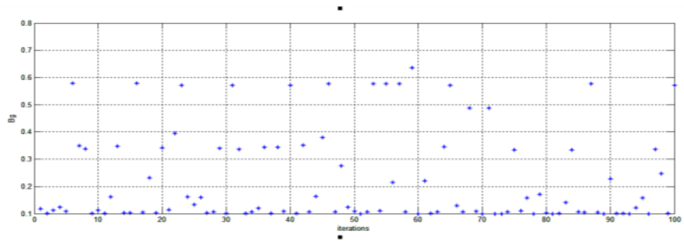
(b) Gear reduction ratio



(c) Outer diameter



(d) Inner diameter



(e) Air-gab induction

Fig. 3 Evolution of some optimization parameters function of iterations

The figure 3 illustrates the evolution of the wheel radius, the gear reduction ratio, the outer and inner diameter and the air-gab induction in function of iterations.

We can notice that some values are quite far from the optimal result. This fact is due to mutations.

The obtained results of optimal solutions conforms the constraints we have previously fixed.

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Optimal autonomy and cost values are acceptable witch demonstrates that the proposed approach to solve the multi-objective problem is satisfying.

Conclusions

In this paper, we have developed a multi-objective optimization approach using the weighted sum method.

The developed problem aims to find the optimal configuration that maximizes the overall powertrain efficiency with a minimum possible cost of the motor-converter.
The optimum results obtained respect the fixed constraints witch shows the efficiency of the proposed algorithm.

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