

Multi-objective powertrain optimization of cost and autonomy for electric vehicles

Mariem BEN AMOR^{#1}, Souhir TOUNSI^{#2}

^{#1,2} *Laboratory of advanced Electronic Systems and Sustainable Energy
 Sfax, Tunisia*

¹ mariembenamor11@gmail.com

² souhir.tounsi@enetcom.rnu.tn

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

INTRODUCTION

Different types of electric vehicles are increasingly designed because they represent an ideal substitute to solve pollution problems caused by the gasoline-powered engines emissions.

Nevertheless, the major drawbacks of electric vehicles are their weak autonomy and their high cost. [1][2]

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 axial 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 devices. [9]

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) [6] [7]

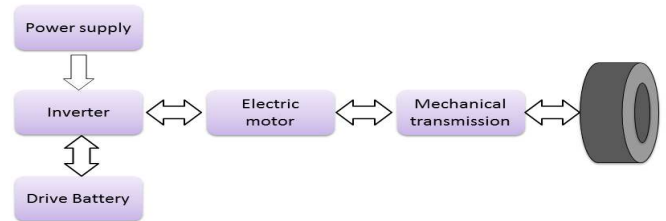


Fig.1 Electric vehicle powertrain structure

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] [8]

$$u_{sd} = r_s \cdot i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega \cdot \Phi_{sq} \quad (1)$$

$$u_{sq} = r_s \cdot i_{sq} + \frac{d\Phi_{sq}}{dt} - \omega \cdot \Phi_{sd} \quad (2)$$

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

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

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

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

Where Ω , p , J , f , C_r , C_e , Φf , L_{sd} , L_{sq} , V_{sd} , V_{sq} , r_s are respectively: 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, the flux produced by the permanent magnet, "d" axis stator inductance, "q" axes stator inductance, "d" axis stator voltage, "q" axis stator voltage and the stator windings resistance.

III. COST AND AUTONOMY OPTIMIZATION PROBLEM

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], [8] 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:

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

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.

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

R_w : Wheel radius

r_g : Gear reduction ratio

Di : Motor inner diameter

Do : Motor outer diameter

B_g : Air-gap induction

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:

$$A_u = f(R_w, r_g, Di, Do, B_g, \delta, B_{cs}, B_{cr}, N_{sph}) \quad (10)$$

B. Cost objective function

To minimize the EV cost, we 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]

$$Cost = C_m M_m + C_c M_c + (M_{sy} + M_{st} + M_{ry}) \cdot (C_i + C_{fab}) + C_{conv} U_{dc} I_{max} \quad (11)$$

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

All the motor mass expressions are detailed in [3] and [8].

When defining all the mass equations we can conclude that the cost is function of:

$$cost = f(R_w, r_g, Di, Do, B_g, e, U_{dc}) \quad (12)$$

"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.

We define:

1) Geometrical constraints:

$$100mm \leq D_o \leq 250mm$$

$$90mm \leq D_i \leq 140mm$$

$$1mm \leq e \leq 8mm$$

2) Technological constraints

$$0.25m \leq R_w \leq 0.35m$$

$$3 \leq r_g \leq 8$$

$$2 \leq \delta \leq 7$$

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

3) Magnetic constraint

$$0.1T \leq B_g \leq 1.04T$$

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

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

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: [8][12]

$$\text{Minimise/Maximise: } F(X) = (F_1(x), F_2(x), \dots, F_n(x)) \quad (13)$$

With :

$$\left\{ \begin{array}{l} g_j(X) = 0, \quad j = 1, \dots, m \\ h_k(X) \leq 0, \quad k = 1, \dots, k \end{array} \right. \quad (14)$$

n: Number of objective functions

m: Number of equality constraints

K: NUMBER OF INEQUALITY CONSTRAINTS

B. 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. [8] [13]

We define:

$$F(F_1, F_2) = F(w_1, w_2) = w_1 F_1 + w_2 F_2 \quad (15)$$

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 (15) by w_1 , we can define w as:

$$w = \frac{w_2}{w_1} \quad (16)$$

Then (15) takes the following form:

$$F(w) = F_1(X) + w F_2(X) \quad (17)$$

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 $Im \succ Id$ and $\eta \geq 0.95$

$$F = Au + a.(Cm - Cost) \quad (18)$$

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

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

$$\left. \begin{array}{l} \text{Maximize } F \\ I_m \geq I_d \\ \eta \geq 0.95 \\ 0.1 \leq B_g \leq 1.04 \\ 250 \leq R_w \leq 350 \\ 3 \leq r_g \leq 8 \\ 90 \leq D_i \leq 140 \\ 100 \leq D_o \leq 250 \\ 1 \leq e \leq 8 \\ 2 \leq \delta \leq 7 \\ 0.2 \leq B_{cs} \leq 1.6 \\ 0.2 \leq B_{cr} \leq 1.6 \\ 20 \leq N_{sph} \leq 400 \\ 200 \leq U_{dc} \leq 400 \end{array} \right\} \quad (19)$$

V. SIMULATION AND RESULTS

We have used the genetic algorithm method to solve the optimization problem. [14]

The Genetic Algorithm (GA) was coded using Matlab and the used parameters are shown in the table below:

TABLE I
 GENETIC ALGORITHM CODE PARAMETERS

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

The EV simulation parameters are summarized in the following table:

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 \$

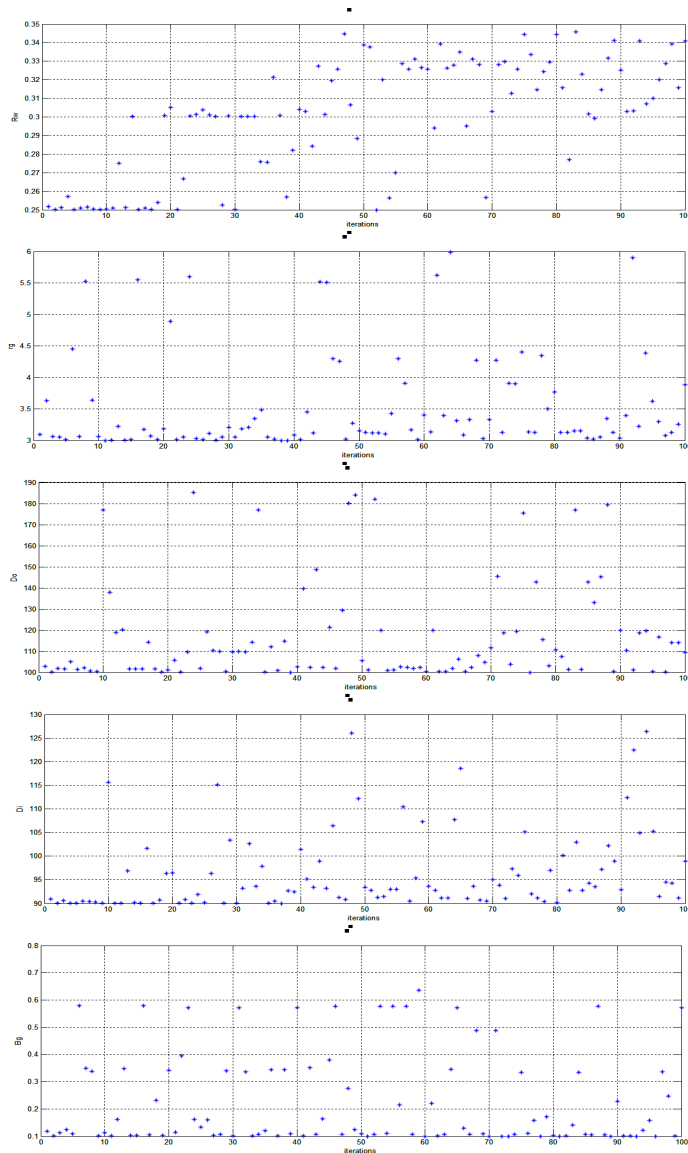


FIG. 2 EVOLUTION OF SOME OPTIMIZATION PARAMETERS FUNCTION OF ITERATIONS

The figure 2 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.

Optimal autonomy and cost values are acceptable so 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 which shows the efficiency of the proposed algorithm.

REFERENCES

- [1] S. Bradai, M.Ghariani, A.Guermazi, "Study of the traction chains of different models of electric vehicles with the ADVISOR tool", IEEE, 2016.
- [2] S. Tounsi, N. Ben Hadj, R. Neji and F. Sellami, "Optimization of electric motor design parameters maximizing the autonomy of electric vehicles", International Review of Electrical Engineering, vol. 2, pp.118-126, 2007.
- [3] S. Tounsi, "Modélisation et optimisation de la motorisation et de l'autonomie d'un véhicule électrique", Doctoral thesis report, ENIS, 2006.
- [4] B. Bossoufi, M. Karim, S. Ionita and A. Lagrioui, "The optimal direct torque control of a PMSM drive: FPGA-Based implementation with MATLAB & SIMULINK simulation", Journal of theoretical and applied information technology, Vol. 38, No 2, pp. 63-72, 2011.
- [5] Fu-Long Xin, L. Qian, H. Du and W. Li, "Multi-objective robust optimization design for powertrain mount system of electric vehicles", Journal of Low Frequency Noise, Vibration and Active Control, Vol. 36, pp 243-260, 2017.
- [6] M. Hadj Kasem, S. Tounsi and R. Neji, "Design of an electrical vehicle power train," 6th International Renewable Energy Congress (IREC), 2015.
- [7] P. Caillard, F. Gillon, M. Hecquet, S.A. Randi and N. Janiaud, "An optimization methodology to pre design an electric vehicle powertrain", IEEE, 2014.
- [8] N. Ben hadj, S. Tounsi, R. Neji and F. Sellami, "Use of evolutionary approach for multiobjective optimization of losses and mass in permanent magnet motor", Journal of Electrical Systems, vol. 4, pp. 277-292, 2008.
- [9] M. Hadj Kacem, S. Tounsi and R. Neji, "Dimensionnement de la chaîne de traction d'un véhicule électrique", International conference on Green Energy and Environmental Engineering (GEEE-2014), Sousse-Tunisia, 2014.
- [10] A. Haddoun, M. El Hechmi Benbouzid, D. Diallo, R. Abdessemed, J. Gouili, and K. Srairi, "A loss-minimization DCT scheme for EV induction motor," IEEE transaction on vehicular technology, vol. 56, NO.1, January 2007.
- [11] G. Domingues, A. Reinap and M. Alaküla, "Design and cost optimization of electrified automotive powertrain", IEEE, 2016.
- [12] R. T. Marler and J. S. Arora, "The weighted sum method for multi-objective optimization: new insights", Struct Multidisc Optim, Vol. 41, pp.853-862, 2010.
- [13] A. Elkamel, M. Mathew and M. Fowler, "Optimization of a Battery Pack in Plug-In Hybrid Electric Vehicles", Proceedings of the 2016 International Conference on Industrial Engineering and Operations Management, Kuala Lumpur, Malaysia, March 8-10, 2016.
- [14] J. Nellen, B. Wolters, L. Netz, S. Geulen and E. Àbrahàm, "A Genetic Algorithm based Control Strategy for the Energy Management Problem in PHEVs", GCAI 2015. Global Conference on Artificial Intelligence, Volume 36, pp 196-214, 2015.