Metamodel-Based Electric Vehicle Powertrain Optimization : A Drive Cycle Approach

Claude Marchand, Mehdi Djami, Maya Hage-Hassan, Guillaume Krebs, Philippe Dessante, Lamya Belhaj

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Claude Marchand
Université Paris Saclay, CNRS, Centralesupelec, Laboratoire de Génie Electrique et Electronique de Paris
Gif-sur-Yvette, France
Sorbonne Université,CNRS,Laboratoire de Génie Electrique et Electronique de Paris
Paris, France
claude.marchand@centralesupelec.fr

Mehdi Djami
Université Paris Saclay, CNRS, Centralesupelec, Laboratoire de Génie Electrique et Electronique de Paris
Gif-sur-Yvette, France
Sorbonne Université,CNRS,Laboratoire de Génie Electrique et Electronique de Paris
Paris, France

Stellantis, Centre Technique de Carrières-sous-Poissy,212 Boulevard Pelletier
Carrières-sous-Poissy, France.
mehdi.djami@stellantis.com

Maya Hage Hassan
Université Paris Saclay, CNRS, Centralesupelec, Laboratoire de Génie Electrique et Electronique de Paris
Gif-sur-Yvette, France
Sorbonne Université,CNRS,Laboratoire de Génie Electrique et Electronique de Paris
Paris, France
Maya.Hage-Hassan@centralesupelec.fr

Guillaume Krebs
Université Paris Saclay, CNRS, Centralesupelec, Laboratoire de Génie Electrique et Electronique de Paris
Gif-sur-Yvette, France
Sorbonne Université,CNRS,Laboratoire de Génie Electrique et Electronique de Paris
Paris, France
guillaume.krebs@centralesupelec.fr

Lamya Belhaj
Stellantis, Centre Technique de Carrières-sous-Poissy,212 Boulevard Pelletier
Carrières-sous-Poissy, France.
lamya.belhaj@stellantis.com

Philippe Dessante
Université Paris Saclay, CNRS, Centralesupelec, Laboratoire de Génie Electrique et Electronique de Paris
Gif-sur-Yvette, France
Sorbonne Université,CNRS,Laboratoire de Génie Electrique et Electronique de Paris
Paris, France
philippe.dessante@centralesupelec.fr

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***Abstract*— Components selection and mutualizing for different segments are needed to improve electric vehicle powertrains and limit costs. This paper proposes a first accelerated approach to model and design the electric vehicle powertrain. The optimization scope includes relevant electric powertrain components such as the inverter, the electrical machine, and the reducer. This methodology applies metamodeling techniques for estimating losses in the machine and analytical models for calculating the inverter and the reducer power losses. The driving cycle is considered through the k-means method to reduce the number of operating points considered. The multi-objective optimization is applied to a case study for the WLTC drive cycle and multiple component combinations to investigate modularity.**

Keywords—electric powertrain, drive cycle, metamodeling, multi-objective optimization.

I. Introduction

Low energy consumption, good range, and acceptable driving performances while limiting costs are the keys for car manufacturers to stay attractive in the automotive market [1]. These characteristics depend mainly on the choices of the inverter, the electrical machine, and the gearbox [2][3].

Setting up energy-efficient powertrains requires fast models in terms of computation time, depending on the precision of the model [4]. For example, in the case of electric motor design, FEA is widely used for modeling because of its precision but generally presents a long execution time [5]. The complete design of the powertrain can therefore be particularly long and complex. A solution is replacing time-consuming models with substitution ones, called "metamodels" to reduce calculation time. Application of metamodels in electrical engineering is wide. As an example, it is used for the evaluation of electromagnetic performances [6] or the sizing of an electric machine for automotive application in [7] and [4]. This paper proposes an approach based on metamodeling and analytical modelling to evaluate electric powertrain losses on a drive cycle. The proposed method quickly identifies the best tradeoff between different objectives while considering different system performance requirements.

The first part of this paper is devoted to modeling the powertrain components. Then, the optimization is carried out, considering existing components for the reducer and inverter. The proposed solutions for the electric machine are adapted to every combination of the three components. This methodology is applied to the WLTC cycle for a B-segment vehicle. The optimization algorithm considers the same constraints for all the combinations, thus permitting the use of modularity in choosing the best trade-off between different solutions.

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II. Electric Powertrain Modeling

A. Electric Machine Metamodeling

The electrical machine modeling used is based on [4], which presents an optimization procedure for rapidly evaluating electric machine performances on a driving cycle using kriging metamodel. This method is fast and much less expensive in calculation time compared to classical modeling techniques like FEA, allowing the designer to evaluate the machine performances on the entire drive cycle quickly.

The detailed workflow of the metamodel creation is in [4] and [8]. The steps of the construction of a metamodel are summarized as follows [8]:

- Sampling: The sampling points should be well distributed to have a good estimation everywhere in the design space. Many sampling methods exist such as Latin hypercube sampling (LHS), Sobol sampling, etc.

- Database creation: This is done by evaluating the exact responses at the sampling points using the original calculation method, FEA in our case.
- Metamodel construction: The internal parameters of the metamodel, known as hyper-parameters, are determined and optimized to give a robust metamodel.
- Convergence test: This is done by comparing the exact and predicted responses at a set of test points.

The selected machine for this study is a synchronous machine with buried permanent magnets with 48 slots and eight poles, developed under Ansys Motor-CAD. The materials and machine performances are detailed in [9]. Some parameters do not vary during the process, these are determined from the preliminary design stage, including the slot and pole number, the winding configuration, and the materials' properties. Table I defines the optimization variables and their respective lower and upper bounds. The design space should be large enough not to miss potential solutions but relatively narrow to give an accurate prediction in a reasonable simulation time [7]. Note that the variables are geometry based, as detailed below:

- Slot width ratio = Slot width / Slot pitch
- Slot depth ratio = Slot depth / (Slot depth + Stator yoke)
- Stator diameter
- Magnet thickness
- Machine length
- Split ratio = Bore diameter / Stator outer diameter

Using dimensionless variables prevents producing infeasible designs and gives more flexibility to define the design space boundaries. Fig. 1 shows the geometric parametrization on one-quarter of the machine's radial cross-section.

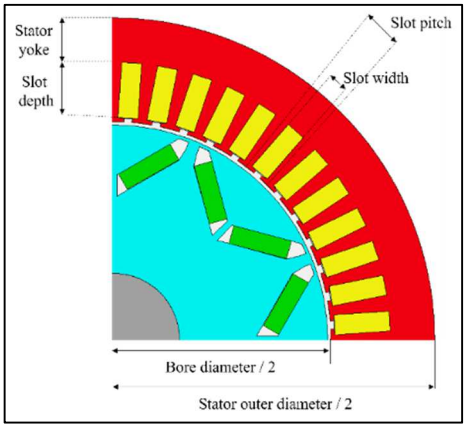

Fig. 1. Design parameterization in Motor-CAD

TABLE I. VARIATION RANGE FOR THE DIFFERENT VARIABLES OF THE METAMODEL

Variable	Range	Unit
x_1 : slot width ratio	[0.7 - 0.8]	-
x_2 : slot depth ratio	[0.7 - 0.8]	-
x_3 : stator outer diameter	[150 - 210]	mm
x_4 : magnet thikness	[4.5 – 6.5]	mm
x_5 : machine length	[130 - 210]	mm
x_6 : split ratio	[0.7 - 0.75]	-

To reduce the computation time, we propose evaluating the performances of the electrical machines on a reduced number of operating points. The k-means data partitioning method is one of the most accurate methods to perform such a task [10] [11]. The method consists in grouping operating points into "clusters" that are entirely characterized by a centroid and a weight (given by the number of points in the cluster) [7]. This method is applied to the WLTC driving cycle with 6 clusters, as shown in Fig. 2.

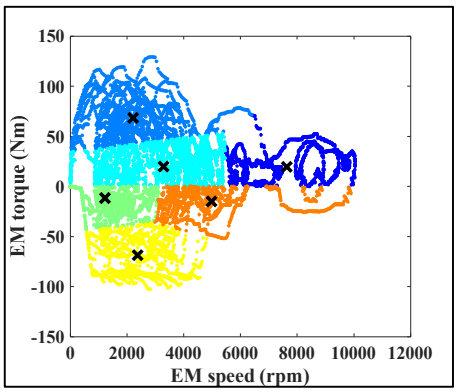

Fig. 2. WLTC drive cycle operating points clustering

The design space is covered using Sobol sampling [12], with 400 samples containing the six variables. The database needed to create the metamodels is then obtained by performing FEA calculations for the centroids obtained by k-means, in addition to two operating points representing the driving cycle maximum torque and speed, to ensure the respect of the torque and speed constraints of the driving cycle. The analysis was completed in about 36 hours using only one instance of Motor-CAD.

Metamodels for predicting total losses on the different centroids are created, then validated by comparing exact and predicted responses at a set of 50 test samples. The comparison shows good accuracy of the different metamodels. An example is illustrated in Fig. 3 and Fig. 4 for two centroids. Calculation time for these 50 test samples with FE method is 5 hours while it takes less than one minute to be evaluated by metamodels.

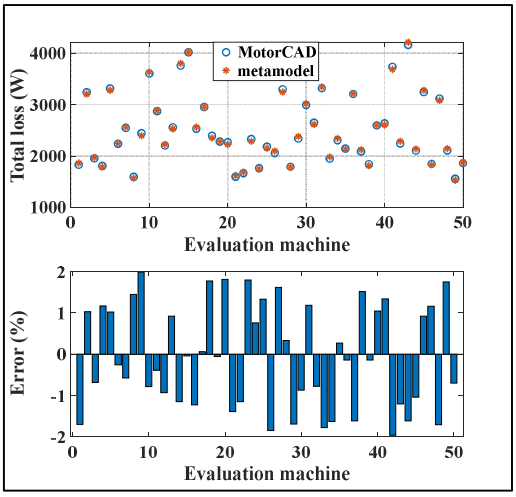

Fig. 3. Evaluation of the precision of total losses metamodel for centroid 1

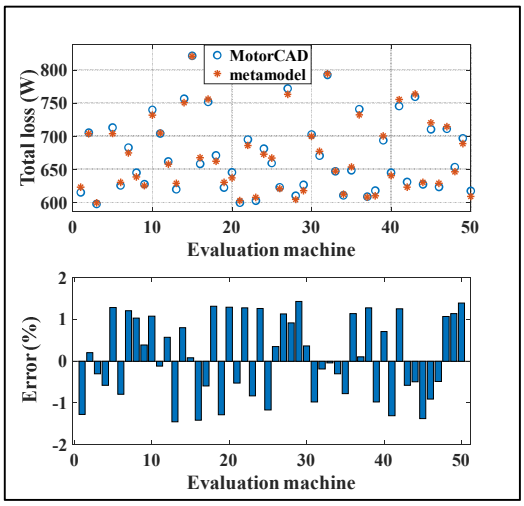

Fig. 4. Evaluation of the precision of total losses metamodel for centroid 2

B. Power Converter Modeling

The next component in powertrain modeling is the inverter. In this work, we will consider an IGBT converter, largely used in industrial applications, for its low cost compared to other technologies [2]. IGBT and diode power losses can be divided into conduction and switching losses. The inverter losses are calculated by multiple methods like physical modeling, which simulates the dynamic characteristics of the IGBT [13], and analytical calculation methods, including curve fitting and mathematical modeling [14]. In our case, an analytical model is privileged for calculating inverter losses. The total inverter losses are given by (1) and (2):

$$P_{\text{IGBT}} = V_{\text{T0}}.\frac{I_S\sqrt{2}}{2\pi}\left[1 + \text{r}.\frac{\pi}{4}\cos\phi\right] + R_{\text{T0}}.2.\text{I}_S^2.\left[\frac{1}{8} + \frac{r}{3\pi}.\cos\phi\right] + F_d\left(\frac{a_T}{4}.\hat{\text{I}}_s^2 + \frac{b_T}{\pi}.\hat{\text{I}}_s + \frac{c_T}{2}\right).\frac{E}{V_{\text{ref}}} \quad (1)$$

$$P_{\text{DIODE}} = V_{\text{D0}}.\frac{I_S\sqrt{2}}{2\pi}\left[1 - \text{r}.\frac{\pi}{4}\cos\phi\right] + R_{\text{D0}}.2.\text{I}_S^2.\left[\frac{1}{8} - \frac{r}{3\pi}.\cos\phi\right] + F_d\left(\frac{a_D}{4}.\hat{\text{I}}_s^2 + \frac{b_D}{\pi}.\hat{\text{I}}_s + \frac{c_D}{2}\right).\frac{E}{V_{\text{ref}}} \quad (2)$$

Where $E = 400\,V$, is the DC bus voltage, V_{ref} is the test voltage specified in the manufacturer's documentation, F_d is the switching frequency, V_{T0}, R_{T0}, V_{D0}, R_{D0} are obtained from the manufacturer's datasheet, and coefficients a_T, b_T, c_T, a_D, b_D, c_D consider the evolution of the switching energies as a function of the switched current.

C. Transmission Modeling

The last component of the powertrain is the reducer, which connects the electric machine directly to the vehicle's wheels and adapts the torque and speed required. In this work, a single stage reducer is considered for calculating the reducer losses; these losses are due to different effects in each reducer component. An analytical model is used to generate efficiency and loss maps of the reducer over its operating range. This model considers different parameters related to the bearings, geometry, and oil used to reduce friction during the operation. In the optimization process, the reducer will be considered directly by the drive cycle operating points, then the reducer losses are calculated separately using the losses map.

III. Optimization Procedure

A. Optimization Workflow

The optimization problem is solved using the NSGA-II algorithm [15]. We seek to minimize the powertrain's total losses on the drive cycle (f_1) and the electrical machine volume (f_2). For this, we look for the best solution for the electrical machine with different combinations of the inverter and the reducer. For this purpose, we chose nine (9) IGBT power modules from 3 suppliers; these choices were made considering the requirements for maximum current and voltage for our application; Table II gives the different power modules' characteristics. In addition, three reducers are selected with different gear ratios, directly impacting the electrical machine's torque and speed demand. Table III gives the maximum torque and speed required for the example of the WLTC driving cycle in the case of an electric vehicle of the B-segment. The problem formulation is given in (3). The optimization variables represented by vector X are detailed in Table I.

$$Minimize\ F(X) = [f_1(X) \quad f_2(X)]$$

Under constraints:

$$T_m \leq T_{max}, \quad \Omega_m \leq \Omega_{max} \quad (3)$$

$$f_1 = \sum_{j=1}^{nb\ cluster} Losses_{mot} + Losses_{inv} + Losses_{red}$$

Where T_m and Ω_m are, respectively, the maximum torque and speed of the machine. The constraints on the maximum torque (T_{max}) and speed (Ω_{max}) are identical for all three reducers, to guarantee that an optimal solution for one reducer can be applied to the others without encountering any issues related to achieving the desired levels of torque or speed.

TABLE II. INVERTERS SELECTED FOR THE STUDY

Inverter	Specifications
Inverter 1	650 V/ 400 A
Inverter 2	1200 V/ 600 A
Inverter 3	650 V/ 450 A
Inverter 4	650 V/ 600 A
Inverter 5	1200 V/ 600 A
Inverter 6	700 V/ 400 A
Inverter 7	650 V/ 400 A
Inverter 8	750 V/ 660 A
Inverter 9	750V/ 900A

TABLE III. REDUCERS SELECTED FOR THE STUDY

Reducer	Gear ratio	Maximum torque requested (N.m)	Maximum speed requested (rpm)
RED_1	7.9	157	8230
RED_2	9.7	131	10035
RED_3	11.9	108	12390

B. Optimization Results

The optimization procedure described above was applied to design a B-segment vehicle on a WLTC drive cycle. Fig. 2, Fig.3, and Fig.4 illustrate the Pareto fronts obtained for the powertrain energy loss and electric machine volume (p.u) minimization, for respectively reducers RED_1, RED_2 and RED_3.

The optimization results were obtained in less than eight minutes for each reducer. This reduced time is achieved by using metamodels, which shows interest in using such models, especially for the early stages of conception.

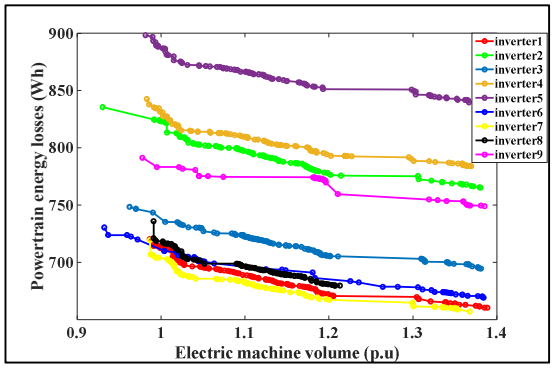

Fig. 5. Optimization results for RED_1

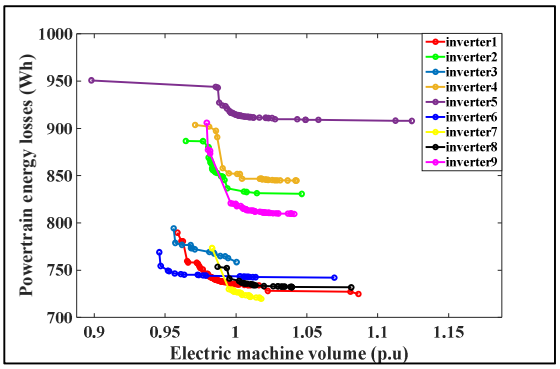

Fig. 6. Optimization results for RED_2

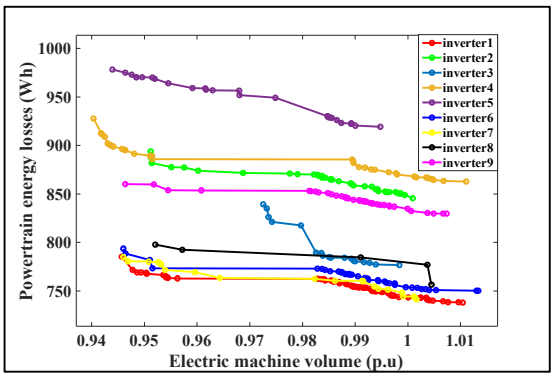

Fig. 7. Optimization results for RED_3

For the same reducer, powertrains with inverters 1 and 7 have similar curves and represent the lowest losses on the WLTC drive cycle; this is predictable since their power modules possess the same characteristics. The volume of the electric machine in the case of reducer RED_1 reaches a value of 1.4 (p.u) due to its high torque, resulting in larger machines capable of handling such torque values. Additionally, powertrains equipped with inverter 5 exhibit the highest losses, due to the inverter being over-dimensioned in voltage for our application, as indicated in Table II.

To see the difference between the optimization results for the three reducers, we compare in Table IV a solution of the same volume (p.u) and for the same inverter, here we choose inverter 4.

TABLE IV. OPTIMIZATION PARAMETERS VARIATION

Reducer	x_1	x_2	x_3	x_4	x_5	x_6
RED_1	0.702	0.7	200.7	4.57	154.3	0.704
RED_2	0.7	0.71	175.4	5.23	175	0.7
RED_3	0.715	0.72	177	5.5	171.5	0.74

Table IV shows that the resulting electric machines are not the same for all reducers, mainly because they will not see the same operating points depending on the reducer used. This will be investigated in future works to see the possibility of modularity between the different optimal powertrains chosen for each case.

IV. CONCLUSION

This paper presented a methodology for optimizing an electric vehicle powertrain over a driving cycle, using a combination of analytical models and metamodels to estimate the losses of each component. The proposed workflow provides a fast and robust method for the design space exploration and optimization of electric powertrains. The methodology is very useful for design engineers in the early steps of conception.

The present study investigated a WLTC driving cycle application for a B-segment electric vehicle with a V-buried magnet synchronous machine and different reducer and inverter technologies to find the best compromise between the available components. In future work, a generalized approach will be developed for designing a multirange powertrain; it will consider more design variables for the motor, more components' technologies, and finally, more drive cycles and vehicle profiles. The goal is to propose an approach that aims to optimize the electric powertrain components considering modularity in the design, with a wide variety of vehicles and usages, while ensuring a limited computation time.

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BIOGRAPHIES

M. Djami is currently working towards a PhD degree in electrical engineering at the Group of Electrical Engineering of Paris (GeePs laboratory) in collaboration with Stellantis. He received the Engineering degree in Electrical Engineering from Ecole Nationale Polytechnique d'Alger in 2019, and the Master's degree from Université Paris Saclay in 2020. His current research interests include design and optimization of electric powertrains over drive cycle.

C. Marchand graduated from the Ecole Normale Supérieure de Cachan, France. He received the Ph.D. and the HDR degrees from the Université Paris-Sud, Paris, France in 1991 and 1999 respectively. He joined the Université Paris-Sud as an Assistant Professor in 1994 and became a Full Professor in 2000. Since 1988, he has been a researcher at the Laboratoire de Génie Electrique de Paris (LGEP) where his research interests are in eddy current nondestructive testing and in the design and control of electrical actuators. Since 2015, he is head of the Group of Electrical Engineering of Paris (GeePs laboratory).

M. Hage Hassan received her B.S. degree in mechanical engineering from the faculty of engineering, Lebanon, Masters in Product Design and Development from Ecole Centrale de Nantes in 2010 and a Ph.D. degree in electrical engineering from University Paris-Saclay in 2014. She is now an Associate Professor at CentraleSupelec. Her current research interests include design and optimization of electric machines and drives.

G. Krebs received his Ph.D. degree and Habilitation for Direction of Research respectively in 2006 and 2017, both from Paris Saclay University, France. He is now an Associate Professor at Paris-Saclay University since 2008. His current research interests include design, optimization and finite element analysis of electric machines and drives.

P. Dessante received the Ph.D. degree in applied mathematics and physics from Versailles University, Versailles, France, in 2000, and the HDR (Accreditation to Supervise Research) degree from the University of Paris-Sud (Paris-Saclay), Paris, France, in 2012. He is currently a Professor with CentraleSupélec, Gif-sur-Yvette, France, and a Researcher with the Group of Electrical Engineering of Paris (GeePs laboratory). His current research interests include the simulation and optimization of electrotechnical systems (drive systems and electrical discharges).

L. A. Belhaj was born in Morocco in 1979. She received the electrical engineering degree in 2001 from Polytech Nantes, France. Her PhD: Dynamic modelling and control of coupled alternators in embarked electrical network has been presented in the University of Nantes in 2006. She developed the IE2 asynchronous machines range in Leroy Somer and worked on the alternators refurbishment and control in Jeumont Electric Maintenance in France. Since 2017, she has been working on the design of electrical machines for traction in Groupe PSA, France and is currently the electrical machine expert in Stellantis group.