Innovative Optimization Software for Electric Motor Design

Gianni Di Pillo

ACTOR SRL
Spinoff of Sapienza University of Rome , Italy

Coiltech 2018 - World Magnetic Conference (WMC)
Pordenone, September 26-27, 2018

Joint work with

- Andrea Credo
  University of L'Aquila, Italy
- Stefano Lucidi
  Sapienza University of Rome, Italy
- Marco Villani
  University of L'Aquila, Italy
- R13Technology
  Spinoff of University of L'Aquila, Italy

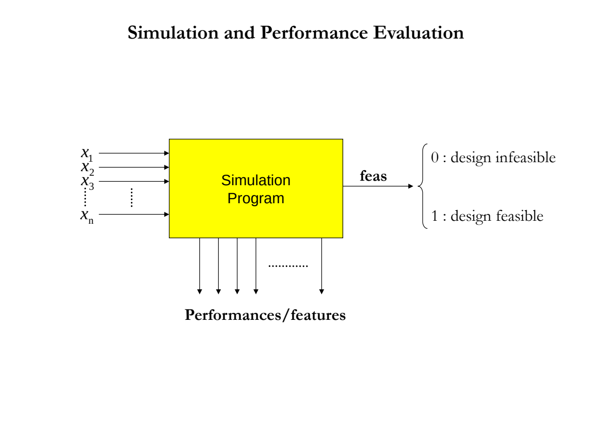
Outline

- In this talk we describe an approach to the optimal design of electric motors, based on an innovative optimization software
- The innovations rely on:
  - considering the design variables as discrete rather than continuous
  - considering the optimization problem as bi-level rather that single-level
- We claim that the optimization software described in this talk is by far the most advanced tool for the optimal design of electric motors
- A friendly graphical user interface (GUI) enriches the optimization software, thus providing an interactive environment for the optimal design

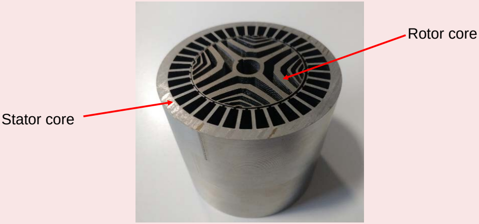
Outline

- As examples we will consider:
  - the design of a Synchronous Reluctance Motor for maximum electromagnetic torque
  - the design of a Brushless Motor for minimum material cost
- Of course any other kind of electrical motor, for any other kind of objective function, can be designed by the optimization software

The black-box approach for optimal design



The Synchronous Reluctance Motor has been used as test case to drive the developments of the optimization algorithm towards better performances



Problem Variables

$x(1) =$ outlet stator radius

$x(2) =$ Inner stator radius

$x(3) =$ slot heigth

$x(4) =$ position of the first barrier

$x(5) =$ position of the second barrier

$x(6) =$ position of the third barrier

$x(7) =$ position of the fourth barrier

$x(8) =$ the width of the first barrier

$x(9) =$ width of the second barrier

$x(10) =$ width of the third barrier

$x(11) =$ width of the fourth barrier

$x(12) =$ width of the fifth barrier

$x(13) =$ length stack

$x(14) =$ tooth width

Problem Constraints

$g_1(x) =$ maximum phase voltage - θ_1 $(\theta_1 = 360\,V)$

$g_2(x) =$ maximum current density - θ_2 $(\theta_2 = 10A/(mm^2))$

$g_3(x) = \theta_3$ - minimum electromagnetic torque $(\theta_3 = 200N \cdot m)$

Objective Function

$f(x) =$ - electromagnetic torque

The standard mathematical optimization problem

$$\begin{aligned} \min_{x} \quad & f(x) \\ s.t. \quad & g_i(x) \leq 0, \quad i = 1, \ldots, m \\ & l \leq x \leq u \end{aligned} \tag{1}$$

- $x, l, u \in \mathbb{R}^n$
- $f(x)$ and $g_i(x)$ are continuous functions
- values of $f(x)$ and $g_i(x)$ obtained by simulation
- derivatives of f and g_i are not available

Electric motor experts of University of L'Aquila solved this problem for the optimal design of the Synchronous Reluctance Motor using a standard derivative free optimization algorithm [Brachetti, Di Pillo, Lucidi, 1996]

$\Downarrow$

They got

objective function $f(x^*) = -0.4257$

constraints violation $viol(x^*) = \sum_{i=1}^{3} \max\{0, g_i(x^*)\} = 1.48610^{-3}$

Our aim is to get improved results by exploiting a better understanding of the properties of the electrical motor design problem

Technological limits impose that all variables vary only in a discrete way

$$\Downarrow$$

computed	$f(x^*) = -0.4257$	$viol(x^*) = 1.48610^{-3}$
actual	$f(\hat{x}) = -0.4286$	$viol(\hat{x}) = 1.42710^{-3}$

Discrete Variables Mathematical Optimization Problem

$$
\begin{aligned}
\min_{x} \quad & f(x) \\
s.t. \quad & g_i(x) \leq 0, \quad i = 1, \ldots, m \\
& l \leq x \leq u, \\
& x \in \mathbb{Z}^n,
\end{aligned}
\tag{2}
$$

The optimization algorithm DVBB-OptAlg by [Liuzzi, Lucidi, Rinaldi, 2018]

- uses function values only, no derivatives
- accounts for discrete variables

very hard requirements for optimization algorithms

- starting point $f(x^*) = -0.4257 \qquad viol(x^*) = 1.48610^{-3}$
- max number of function evaluations =500
- objective function $f(x^*) = -0.67670 \qquad viol(x^*) = 0.d0$
- max number of function evaluations =5000
- objective function $f(x^*) = -0.7050 \qquad viol(x^*) = 0.00$

The variables have different effects on the resulting design

$\Downarrow$

- $x(1), x(2), x(3)$ strongly affect the physics of the design
- the variables $x(4), \ldots, x(14)$ must be adapted to the values of $x(1), x(2), x(3)$

$$f(x) = f(x_u, x_l)$$
$$g_i(x) = g_i(x_u, x_l), \qquad i = 1, \ldots, m.$$

where $x_u \in \mathbb{R}^{n_u}$, $x_l \in \mathbb{R}^{n_l}$, $n = n_u + n_l$

$$\Downarrow$$

the sensitivities of f and g_i are very different with respect to x_u or x_l

Bilevel optimization problem

$$
\begin{aligned}
\min_{x_u, x_l} \quad & f(x_u, x_l) \\
s.t. \quad & g(x_u, x_l) \leq 0 \\
& l_u \leq x_u \leq u_u, \quad x_u \in \mathbb{Z}^{n_u} \\
& x_l \in \mathcal{S}(x_u),
\end{aligned}
\qquad \text{(Upper Level)}
$$

where

$$
\begin{aligned}
\mathcal{S}(x_u) = \arg\min_{x_l} \quad & f(x_u, x_l) \\
s.t. \quad & g(x_u, x_l) \leq 0 \\
& l_l \leq x_l \leq u_l, \quad x_l \in \mathbb{Z}^{n_l}
\end{aligned}
\qquad \text{(Lower Level}(x_u))
$$

Bilevel optimization algorithm

For the previuos bilevel optimization algorithm, it possible to define BDVBB-OptAlg by using:

- DVBB-OptAlg for the Upper Problem
- DVBB-OptAlg for the Lower Problem

Single level algorithm DVBB-OptAlg

- max f.e. = 500 $f(x^*) = -0.6767$ $viol(x^*) = 0.00$
- max f.e. = 5000 $f(x^*) = -0.7050$ $viol(x^*) = 0.00$

Bilevel algorithm BDVBB-OptAlg

- max f.e. Upp.Prob.= 24, max f.e. Low.Prob. = 22 (total $\approx$ 500)

  $f(x^*) = -0.7060$ $viol(x^*) = 0.00$
- max f.e. Upp.Prob.= 75, max f.e. Low.Prob. n =66 (total $\approx$ 5000)

  $f(x^*) = -0.7100$ $viol(x^*) = 0.00$

The Optimization Environment

It is composed by 3 items:

- the optimization software
- the simulation software
- the graphical user interface

The Simulation Software

- At present the optimization software is interfaced with Ansys Mechanical APDL performing a finite element analysis
- In the future different software will be linked, like Ansys Electronic Desktop and Altair Flux

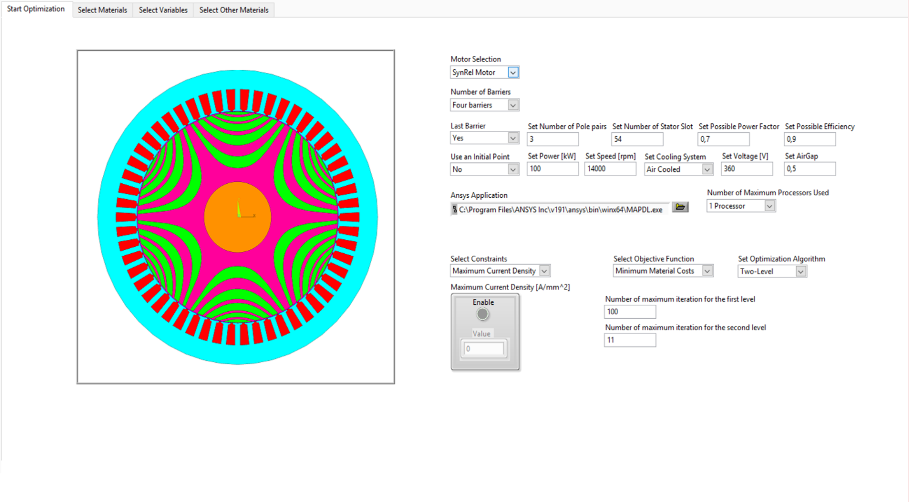
GUI main features 1

- The GUI doesn’t require more than one hour to start your first optimization
- By the GUI it is possible to see the preliminary design of the motor and change it
- All geometry variables are described with very simple image and a shortcut get all information for the users
- Possible user errors are highlighted and it is simple to correct them

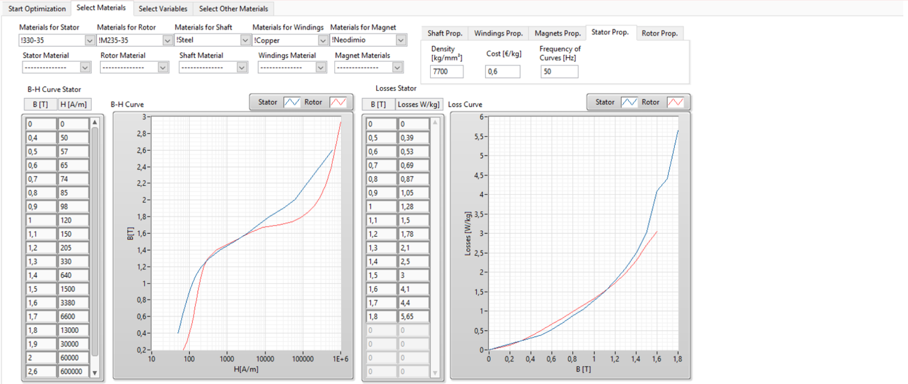
GUI main features 2

- It is possible to set motor parameters and requirements to get a preliminary design by an analytical procedure
- It is possible to choose materials from a default material library or create custom ones
- It is simple to choose the variables to be optimized from a list
- One can choose the objective function and the constraints from a pre-defined list

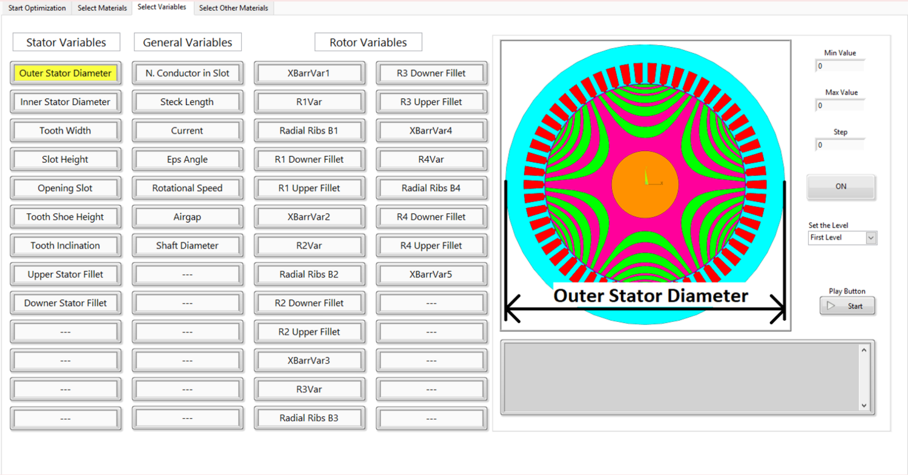
View of the workbench



Materials selection



Design variables selection



Optimal design of a Brushless Motor

The optimal design of brushless motor is now considered to show the GUI mode of operation. In particular:

- the GUI window displays all the best projects calculated from the initial one
- the design, all performances, flux density and the mechanical stress can be analyzed.
- it is possible to see the "evolution" of the design variables, of the objective function, and constraints violation while the optimization procedure progresses

Problem Variables

- x(1) = inner stator radius
- x(2)= slot height
- x(3) = length stack
- x(4) = tooth width
- x(5) = current
- x(6) = position of the first barrier
- x(7) = position of the second barrier
- x(8) = position of the third barrier
- x(9) = position of the fourth barrier
- x(10) = the width of the first barrier
- x(11) = width of the second barrier
- x(12) = width of the third barrier
- x(13) = width of the fourth barrier
- x(14) = width of the fifth barrier

Problem Constraints

$g_1(x) =$ maximum phase voltage - θ_1 $\quad (\theta_1 = 240\,V)$

$g_2(x) =$ maximum current density - θ_2 $\quad (\theta_2 = 7A/(mm^2))$

$g_3(x) = \theta_3$ - minimum electromagnetic torque $\quad (\theta_3 = 70N \cdot m)$

$g_4(x) = \theta_4$ - maximum torque ripple $\quad (\theta_4 = 25\%)$

Objective Function

$f(x) =$ material cost

Preliminary design

Start Optimization | Select Materials | Select Variables | Select Other Materials

Stator Variables

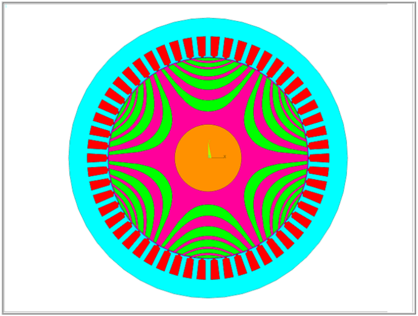
Outer Stator Diameter	250
Inner Stator Diameter	180
Tooth Width	4,5
Slot Height	17
Opening Slot	2
Tooth Shoe Height	0,8
Tooth Inclination	0,7
Upper Stator Fillet	0,01
Downer Stator Fillet	0,01

General Variables

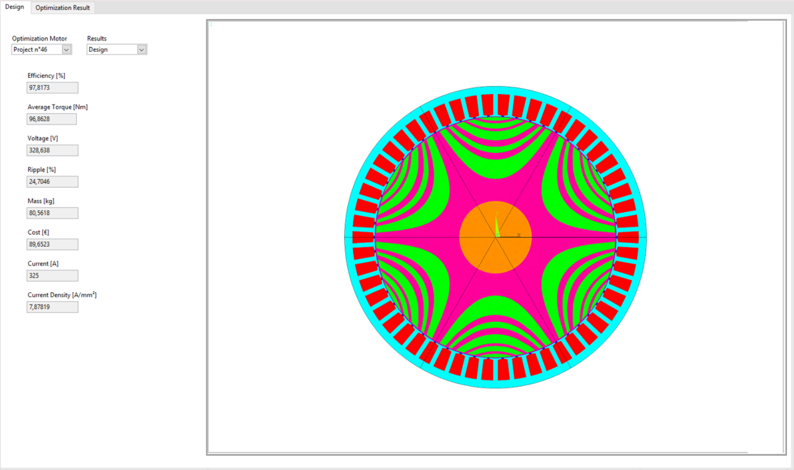
N. Conductor in Slot	2
Steck Length	200
Current	330
Eps Angle	84
Rotational Speed	14000
Airgap	0,5
Shaft Diameter	60

Rotor Variables

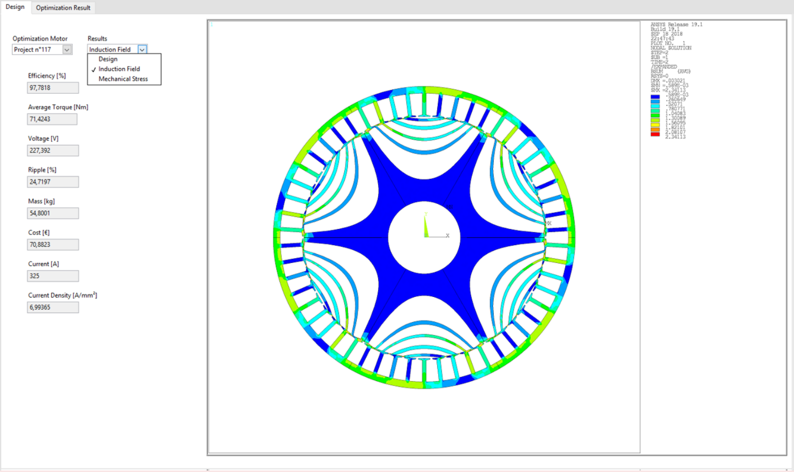
XBarrVar1	0
R1Var	0
Radial Ribs B1	0,5
R1 Downer Fillet	0,05
R1 Upper Fillet	0,05
XBarrVar2	0
R2Var	0
Radial Ribs B2	0,5
R2 Downer Fillet	0,05
R2 Upper Fillet	0,05
XBarrVar3	0
R3Var	0
Radial Ribs B3	0,5
R3 Downer Fillet	0,05
R3 Upper Fillet	0,05
XBarrVar4	0
R4Var	0
Radial Ribs B4	0,5
R4 Downer Fillet	0,05
R4 Upper Fillet	0,05
XBarrVar5	0



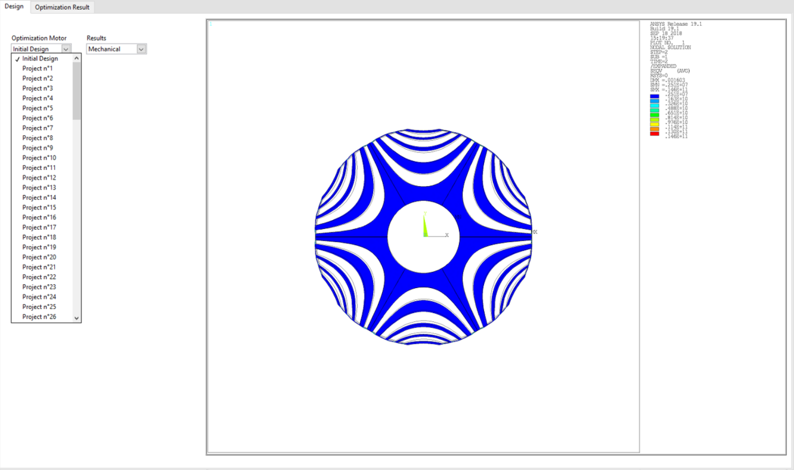
Output: evolution of the optimized design



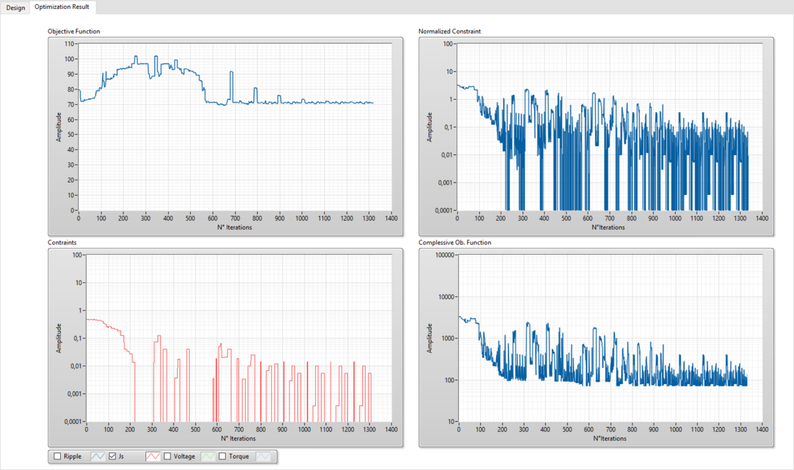
Output: evolution of the flux density



Output: evolution of mechanical stress



Output: trend of objective and constraint functions



Design evolution

Initial and final designs

Example – SynRel 6pole, 54slots, 4barr

Parameters	Constraints	Initial Design	Final Optimized Design
Efficiency	> 97.0 %	97.6 %	97.78 %
Torque	> 72 Nm	166 Nm	71.42 Nm
Voltage	< 230	400 V	227 V
Ripple	< 25%	60 %	24.72 %
Mass	< 60kg	78.7 kg	54.8 kg
Current	< 350 A	330 A	325 A
Current Density	< 7 A/mm^2	10.4 A/mm^2	6.99 A/mm^2

Material Cost	Objective Function	79.6 €	70.9 €

We have described an innovative software environment for the optimal design of electric motors, that takes account of the following features:

- discrete, rather than continuous, design variables
- possible bi-level, as well as single-level, optimization design
- friendly graphical user interface for interactive design

The design of a two electric motors have been considered as examples:

- a Synchronous Reluctance Motors for the analytic developments
- a Brushless Motor for the GUI presentation

Of course other classes of electrical motor design can be optimized

Further develoments of the optimization environment will concern:

- multi-objective optimal design
- robust optimal design

Many thanks for your attention !!!