## Innovative Optimization Software for Electric Motor Design

## Gianni Di Pillo

#### ACTOR SRL Spinoff of Sapienza University of Rome , Italy



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# Joint work with

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



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# 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

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# Outline

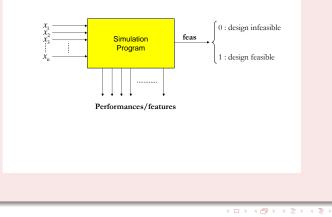
#### As examples we will consider:

- 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

Simulation and Performance Evaluation



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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 - $\theta_1$	$(\theta_1 = 360 V)$
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 $g_2(x) = \text{maximum current density} - \theta_2$   $(\theta_2 = 10A/(mm^2))$ 

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

#### **Objective Function**

$$f(x) =$$
 - electromagnetic torque

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# The standard mathematical optimization problem

$$\begin{array}{ll} \min_{x} & f(x) \\ s.t. & g_{i}(x) \leq 0, \quad i = 1, \dots, m \\ & l \leq x \leq u \end{array}$$

•  $x, l, u \in \mathbb{R}^n$ 

- 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<sub>i</sub> are not available

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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]

#### 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

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

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

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## **Discrete Variables Mathematical Optimization Problem**

$$\begin{array}{ll} \min_{x} & f(x) \\ s.t. & g_{i}(x) \leq 0, \quad i = 1, \dots, m \\ & l \leq x \leq u, \\ & x \in \mathbb{Z}^{n}, \end{array}$$

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

(2)



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



## The variables have different effects on the resulting design

## • x(1), x(2), x(3) strongly affect the physics of the design

# the variables x(4),...,x(14) must be adapted to the values of x(1), x(2), x(3)

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

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

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

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# Bilevel optimization problem

where

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

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# 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

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# 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

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## 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

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## 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

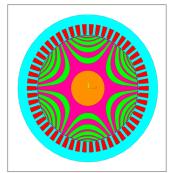
- It is possible to set motor parameters and requirements to get a preliminary design by an analytical procedure
- It is possible to choose materials from a default material library or create custom ones
- It is simple to choose the variables to be optimized from a list
- One can choose the objective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

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## View of the workbench

Start Optimization Select Materials Select Variables Select Other Materials

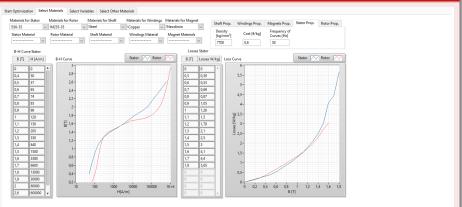


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Use an Initial Point     Set Power (VM)     Set AviGap       100     300     Air Cooling System     Set Voltage VM       100     Air Cooling System     Set Voltage VM       101     Setect Constraints     Setect Objective Function       101     Setect Constraints     Setect Objective Function       101     Minimum Material Costs on Set Optimization Algorithm       101     Number of Instrumm Material Costs on Set Optimization Algorithm       101     Number of Instrumm Material Costs on Set Optimization Algorithm       101     Number of Instrumm Material Costs on Set Optimization Algorithm       101     Number of Instrumm Material Costs on Set Optimization Algorithm	Last Barrier	Set Number of P	ole pairs Set Num	iber of Stator Slot	Set Po	ssible Power Factor	Set Possible Efficiency
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				maximum iterati	on for ti	he second level	



#### Graphical User interface

## Materials selection



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# Design variables selection

rt Optimization Select Materials	Select Variables Select Other N	laterials			
Stator Variables	General Variables	Rotor Va	ariables		Min Value
Outer Stator Diameter	N. Conductor in Slot	XBarrVar1	R3 Downer Fillet	ANULTS.	0
Inner Stator Diameter	Steck Length	R1Var	R3 Upper Fillet		Max Value 0
Tooth Width	Current	Radial Ribs B1	XBarrVar4		Step
Slot Height	Eps Angle	R1 Downer Fillet	R4Var		
Opening Slot	Rotational Speed	R1 Upper Fillet	Radial Ribs B4		ON
Tooth Shoe Height	Airgap	XBarrVar2	R4 Downer Fillet		Set the Level
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Upper Stator Fillet	···· )	Radial Ribs B2	XBarrVar5		
Downer Stator Fillet		R2 Downer Fillet		Outer Stator Diameter	Play Button
]		R2 Upper Fillet			<u></u>
		XBarrVar3			î
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]		Radial Ribs B3		Ų	v [

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#### 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

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## **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 -  $\theta_1$  ( $\theta_1 = 240V$ )

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

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

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

#### **Objective Function**

$$f(x) = material cost$$

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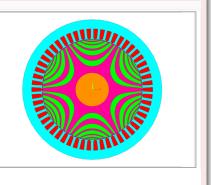


# Preliminary design

Sta	art Optimization Se	lect Materials	Select Variab
	Stator Va	riables	
	Outer Stator Diamet	er 250	
	Inner Stator Diamete	tr 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 Fille	0,01	

s	Select Other Materials				
	General Varia	bles			
	N. Conductor in Slot	2			
	Steck Length	200			
	Current	330			
	Eps Angle	84			
	Rotational Speed	14000			
	Airgap	0,5			
	Shaft Diameter	60			

Rotor Vari	ables
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



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# Output: evolution of the optimized design

Perign Optimization Result
Price reading from 2         Price reading from 2

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# Output: evolution of the flux density

Design Optimization Result
Construction     Projection   <

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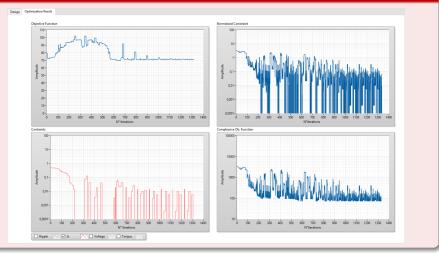
# Output: evolution of mechanical stress

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## Output: trend of objective and constraint functions



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# **Design evolution**


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## 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/mm²	10.4 A/mm <sup>2</sup>	6.99 A/mm <sup>2</sup>

Material Cost Objective Function 79.6	0.9€
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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 !!!

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