Intuitive Interface for a Quicker Electromagnetic Motor Design

L. G. Frigoli*, A. Tassi*

Abstract **– In this paper we describe a software tool for quick design of electric motors. The main features of this tool are ease to use, intuitive and suitable for calculation. We describe two different approaches, the first is a "Discrete Scanning" of a defined number of configurations, the second is a "Continuous Scanning" where there's an optimization algorithm. Both approaches follow the "Black Box" idea, where the user defines the design variables and observes the results. The internal working between algorithm and computation software is hidden.**

Index Terms **– Analytical methods, Electrical motors, Electromagnetic design, Estimated errors, Finite-Element methods, Motor design, Optimization algorithm.**

I. INTRODUCTION

IN recent years more and more frequently design engineers request a fast, simple and intuitive, as well as focused calculating tools.

II. TECHNICAL DESCRIPTION

In the "Fig. 1" it is shown the diagram that describes the main idea of the tool. For the user, the interaction between algorithm and computation software is a "Black Box". The user fills the interface setting with the I/O data and the constraints. The algorithm and computation software create a loop until the best configuration is found.

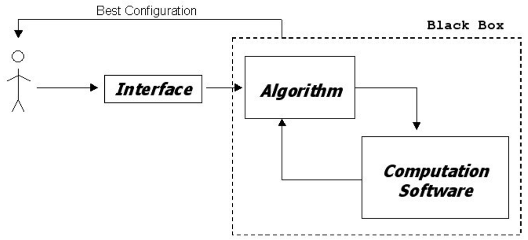


Fig. 1. Main Diagram

A. Computation Software

The computation software packages for electric motors may be divided in two categories:

1) based on classical analytical method
2) based on numerical method employed with finite-element method

The classical analytical method refers to mathematical equations derived from the electrical machine theory [1].

The finite-element method (FEM) is a numerical technique to find approximate solutions of partial differential equations. For the electric motors, FEM involves the use of computationally efficient approximations to Maxwell's equations [2].

The classical analytical method is faster than FEM method in the order of 10-1000 factor, so a much higher number of calculations per time can be performed: just this feature of analytical method can be profitably used in the research of best model of electric motors .

The FEM method can be used for advanced optimization and analysis the machine details.

B. Algorithm

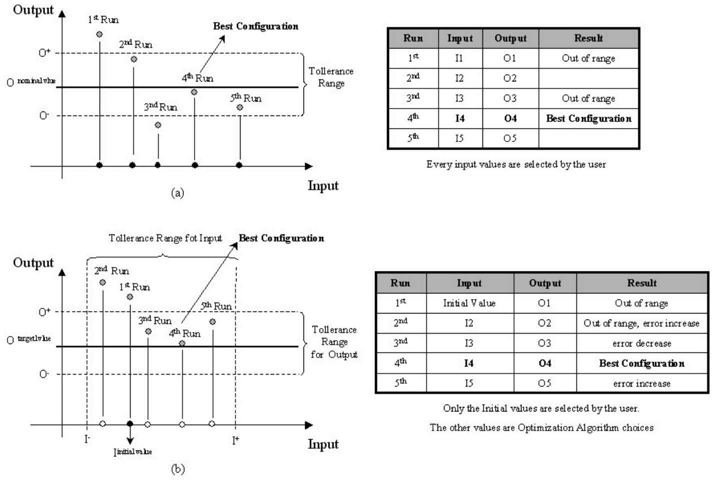
There are two different approaches:

1) "Discrete Scanning"
2) "Continuous Scanning"

In the "Discrete Scanning", from a starting electric motor model, the user defines a matrix of possible configurations. The best configuration is chosen by an algorithm based on estimated errors or other statistical risk functions.

In the "Continuous Scanning" the user defines a domain and a numerical optimization algorithm, chooses step-by-step the configurations to be analyzed, in order to get the best one.

In the "Fig. 2" we report a graphical explanation of two approaches for a simple SISO system (Singular Input Singular Output).



Run	Input	Output	Result
1st	I1	O1	Out of range
2nd	I2	O2	
3rd	I3	O3	Out of range
4th	**I4**	**O4**	**Best Configuration**
5th	I5	O5	

Every input values are selected by the user

Run	Input	Output	Result
1st	Initial Value	O1	Out of range
2nd	I2	O2	Out of range, error increase
3rd	I3	O3	error decrease
4th	**I4**	**O4**	**Best Configuration**
5th	I5	O5	error increase

Only the Initial values are selected by the user.

The other values are Optimization Algorithm choices

Fig. 2. SISO System (a) "Discrete Scanning", (b) "Continuous Scanning"

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III. EXAMPLE 1: INDUCTION MOTOR

In this example we consider an induction motor ("Fig. 3") with this characteristics:

- AC Three Phase
- 4 Poles
- 24 Slots
- 19 Bars

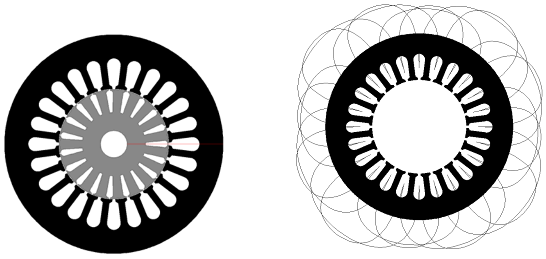

(a) (b)

Fig. 3. AC Induction motor Section (a) and Winding (b)

We perform a steady state analysis using a computation software (PC-IMD [3]) and a “Discrete Scanning” approach.

A. Design Variables

In this example the design variables are:

- Rotor radius (Rad1)
- Airgap length (Gap)
- Number of turns (TC)
- Stator outer radius (Rad3)
- Stator stack lenght (Lstk)

INPUT

- Torque (Tshaft)
- Copper Losses (WCus)
- Efficiency (Effcy)

OUTPUT

TABLE I
EXAMPLE 1: DESIGN VARIABLES SUMMARY

INPUT		
Name [Units]	*Values*	*Step Number*
Rad1 [mm]	From 20 to 30 with Step = 2	6
Gap [mm]	From 0.2 to 0.4 with Step = 0.1	3
TC	From 150 to 160 with Step = 5	3
Rad3 [mm]	From 50 to 60 with Step = 2	6
Lstk [mm]	From 45 to 55 with Step = 2.5	5
	Total Configurations	**1620**
OUTPUT		
Name [Units]	*Reference Values - Tollerance*	
Tshaft [Nm]	0.22	
Wcus [W]	4 ± 5 %	
Effcy [%]	75 ± 2	

B. Algorithm

The algorithm used based on minimum mean squared error (MMSE).

In signal processing, a minimum mean square error (MMSE) estimator describes the approach which minimizes the mean square error (MSE), which is a common measure of estimator quality:

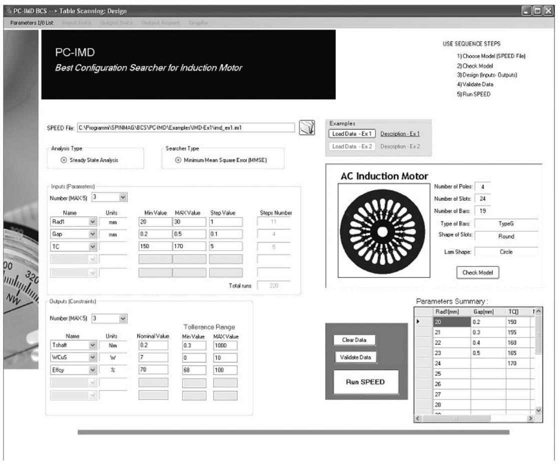
$$\min_{s}\left\{ J(\vartheta) = \frac{1}{N}\sum_{i=1}^{N}(e_i) \right\} \quad (1)$$

- N: number of outputs
- $e_i = y_i - y_i^o$: difference between i-th output and i-th reference values
- $\vartheta = [x_1, x_2, x_3, ...x_p]^T$: parameters vector

Basically the goal is to search the parameters vector that minimize the $J(\vartheta)$ function. This parameters vector represents the best configuration [4].

C. Interface

The interface ("Fig. 4" and "Fig. 5") is very user-friendly, simple and intuitive [5]. The interface is easy to learn and the user can follow a precise and clear sequence steps that manage him to the solution, from the input data to the output report.



USE SEQUENCE STEPS
1) Choose Model (SPEED File)
2) Check Model
3) Design (Inputs- Outputs)
4) Validate Data
5) Run SPEED

SPEED File: C:\Programmi\SPINMAG\BCS\PC-IMD\Examples\IMD-Ex1\imd_ex1.im1

Analysis Type: ⦿ Steady State Analysis

Searcher Type: ⦿ Minimum Mean Square Error (MMSE)

Inputs (Parameters)
Number (MAX 5): 3

Name	Units	Min Value	MAX Value	Step Value	Steps Number
Rad1	mm	20	30	1	11
Gap	mm	0.2	0.5	0.1	4
TC		150	170	5	5

Total runs: 220

Outputs (Constraints)
Number (MAX 5): 3

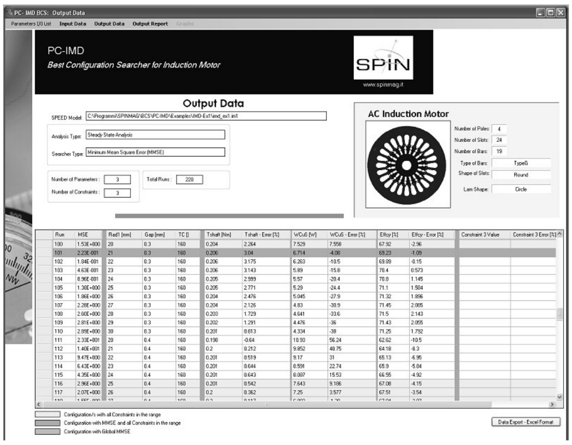
Name	Units	Nominal Value	Tollerance Range Min Value	Tollerance Range MAX Value
Tshaft	Nm	0.2	0.3	1000
WCuS	W	7	0	10
Effcy	%	70	68	100

AC Induction Motor
Number of Poles: 4
Number of Slots: 24
Number of Bars: 19
Type of Bars: TypeG
Shape of Slots: Round
Lam Shape: Circle

Parameters Summary :

Rad1[mm]	Gap[mm]	TC[]
20	0.2	150
21	0.3	155
22	0.4	160
23	0.5	165
24		170
25		
26		
27		
28		

Fig. 4. Interface: Input Data



Output Data

SPEED Model: C:\Programmi\SPINMAG\BCS\PC-IMD\Examples\IMD-Ex1\imd_ex1.im1
Analysis Type: Steady State Analysis
Searcher Type: Minimum Mean Square Error (MMSE)
Number of Parameters : 3
Number of Constraints : 3
Total Runs : 220

AC Induction Motor
Number of Poles: 4
Number of Slots: 24
Number of Bars: 19
Type of Bars: TypeG
Shape of Slots: Round
Lam Shape: Circle

Run	MSE	Rad1 [mm]	Gap [mm]	TC []	Tshaft [Nm]	Tshaft - Error [%]	WCuS [W]	WCuS - Error [%]	Effcy [%]	Effcy - Error [%]	Constraint 3 Value	Constraint 3 Error [%]
100	1.53E+000	20	0.3	160	0.204	2.264	7.529	7.558	67.92	-2.96		
101	2.23E-001	21	0.3	160	0.206	3.04	6.714	-4.08	69.23	-1.09		
102	1.84E-001	22	0.3	160	0.206	3.175	6.263	-10.5	69.89	-0.15		
103	4.63E-001	23	0.3	160	0.206	3.143	5.89	-15.8	70.4	0.573		
104	8.96E-001	24	0.3	160	0.205	2.989	5.57	-20.4	70.8	1.145		
105	1.38E+000	25	0.3	160	0.205	2.771	5.29	-24.4	71.1	1.584		
106	1.86E+000	26	0.3	160	0.204	2.476	5.045	-27.9	71.32	1.896		
107	2.28E+000	27	0.3	160	0.204	2.126	4.83	-30.9	71.45	2.085		
108	2.60E+000	28	0.3	160	0.203	1.729	4.641	-33.6	71.5	2.143		
109	2.81E+000	29	0.3	160	0.202	1.291	4.476	-36	71.43	2.055		
110	2.89E+000	30	0.3	160	0.201	0.813	4.334	-38	71.25	1.792		
111	2.33E+001	20	0.4	160	0.198	-0.64	10.93	56.24	62.62	-10.5		
112	1.40E+001	21	0.4	160	0.2	0.212	9.852	40.75	64.18	-8.3		
113	9.47E+000	22	0.4	160	0.201	0.519	9.17	31	65.13	-6.95		
114	6.43E+000	23	0.4	160	0.201	0.644	8.591	22.74	65.9	-5.84		
115	4.35E+000	24	0.4	160	0.201	0.643	8.087	15.53	66.55	-4.92		
116	2.96E+000	25	0.4	160	0.201	0.542	7.643	9.186	67.08	-4.15		
117	2.07E+000	26	0.4	160	0.2	0.362	7.25	3.577	67.51	-3.54		

Configuration/s with all Constraints in the range
Configuration with MMSE and all Constraints in the range
Configuration with Global MMSE

Fig. 5. Interface: Output Data

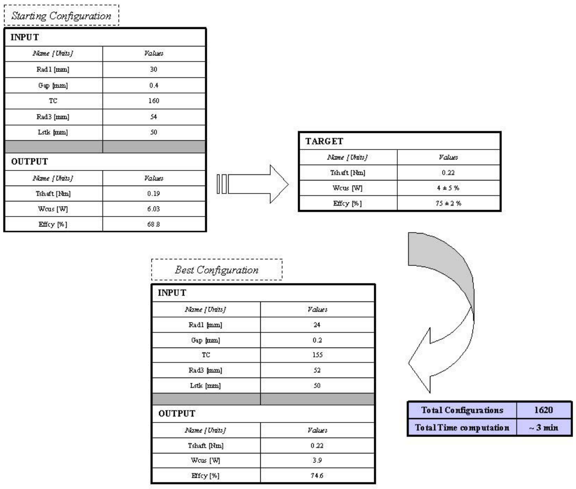
D. Results

From a *Starting Model* with Rad1 = 30 mm, Gap = 0.4 mm, TC = 160, Rad3 = 54 mm and Lstk = 50 mm, that get

Tshaft = 0.19 Nm, WCus = 6.03 W and Effcy = 68.8 %; we obtain a *Best Configuration* with Rad1 = 24 mm, Gap = 0.2 mm, TC = 155, Rad3 = 52 mm and Lstk = 50 mm, that get Tshaft = 0.22 Nm, WCus = 3.09 W and Effcy = 74.6 %.

We highlight that the total time computation of the 1620 possible configurations is about 3 minutes.

TABLE II
EXAMPLE 1: RESULTS SUMMARY



Starting Configuration

INPUT	
Name [Units]	*Values*
Rad1 [mm]	30
Gap [mm]	0.4
TC	160
Rad3 [mm]	54
Lstk [mm]	50
OUTPUT	
Name [Units]	*Values*
Tshaft [Nm]	0.19
Wcus [W]	6.03
Effcy [%]	68.8

TARGET	
Name [Units]	*Values*
Tshaft [Nm]	0.22
Wcus [W]	4 ± 5 %
Effcy [%]	75 ± 2 %

Best Configuration

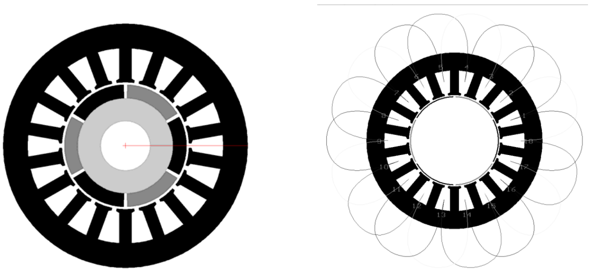
INPUT	
Name [Units]	*Values*
Rad1 [mm]	24
Gap [mm]	0.2
TC	155
Rad3 [mm]	52
Lstk [mm]	50
OUTPUT	
Name [Units]	*Values*
Tshaft [Nm]	0.22
Wcus [W]	3.9
Effcy [%]	74.6

Total Configurations	**1620**
Total Time computation	**~ 3 min**

IV. EXAMPLE 2: BRUSHLESS MOTOR

In this example we consider a Brushless motor ("Fig.6") with this characteristics:

- Three Phase
- 6 Poles
- 18 Slots



(a) (b)

Fig. 6. Brushless PM motor Section (a) and Winding (b)

We perform a dynamic simulation using a computation software (PC-BDC [6]) and a "Continuous Scanning" approach.

A. Design Variables

In this example the design variables are:

- Rotor radius (Rad1)
- Length of Magnet (LM)
- Number of turns (TC)
- Slot depth (SD)

} PARAMETER

- Length of Magnet (LM)
- Current Density (Jrms)
- Total Losses (WTotal)

} CONSTRAINTS

- Torque (Tshatf)
- Efficiency (Effcy)

} TARGETS

TABLE III
EXAMPLE 2: DESIGN VARIABLES SUMMARY

PARAMETERS	
Name [Units]	*Initial Values*
Rad1 [mm]	25
LM [mm]	5.5
TC	24
SD [mm]	14
CONSTRAINTS	
Name [Units]	*Min Value – MAX Value*
LM [mm]	5 - 8
Jrms [A/mm2]	3 -7
Wtotal [W]	15 - 30
TARGETS	
Tshaft [Nm]	maximize
Effcy [%]	maximize

B. Algorithm

In this case we used a typical multi-objective and constrained optimization techniques:

$$\min f(x) = (f_1(x), f_2(x), \ldots, f_k(x)) \qquad (2.1)$$

where $x \in R^n$, f_i: $R^n \rightarrow R^n$ and F is the feasible set of the problem which is described by inequalities as follows:

$$F = \{x \in \Re^n : g_i(x) \leq 0, i = 1,2,\ldots,p\} \qquad (2.2)$$

Equation (2.1) defines the multi-objective function, in this particular case $k = 2$.

An ideal solution of (2.1) would be a point $x^* \in F$ that is a *Pareto-Optimal* solution, therefore does not exist any feasible point $x \in F$ such that:

$$f_i(x) \leq f_i(x^*) \qquad \forall i \in \{1,2,\ldots,k\}$$

and

$$f_j(x) \leq f_j(x^*)$$

for at least one index $j \in \{1,2,..,k\}$.

In literature, there exist several methods that can be used to compute *Pareto-Optimal* solution in the multi-objective function for the electrical machine design [7],[8],[9].

A widely used technique consist in the reducing the multi-objective problem (2.1) to a single-objective one by means of so-called "scalarization" procedure.

There are three different "scalarization" techniques, in this case we used the "cost function method" that consists of assigning each objective function a cost coefficient and then minimizing the function obtained by summing up all the objective functions scaled by their cost coefficients [10], that is:

$$\min_{x\in F}\sum_{i=1}^{k} c^i f_i(x) \tag{3}$$

In this example we have chosen two objective functions:

f_1) Electromagnetic Torque (to maximize)
f_2) Efficiency (to maximize)

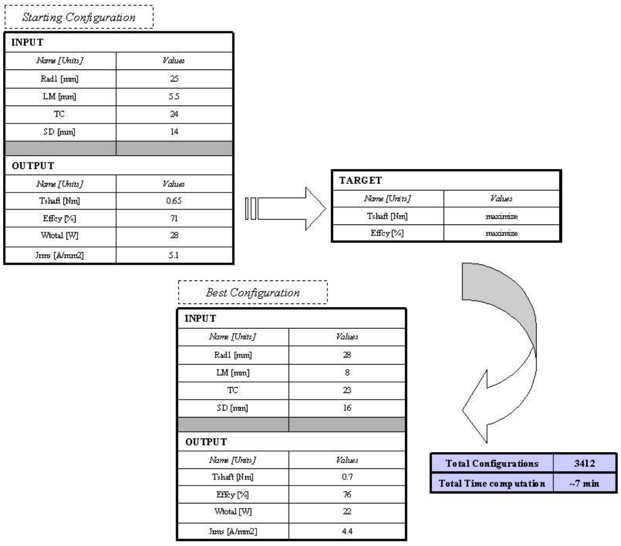
Then we have considered the following multi-objective formulations:

$$\min_{x\in F} -0.5 f_1(x), -f_2(x) \tag{4}$$

C. *Results*

From a *Starting Model* with Rad1 = 25 mm, LM = 5.5 mm, TC = 24 and SD = 14 mm, that get WTotal = 28 W, Jrms = 5.1 A/mm^2, Tshaft = 0.65 Nm and Effcy = 71 %; we obtain a *Best Configuration* with Rad1 = 28 mm, LM = 8 mm, TC = 23 and SD = 16 mm, that get WTotal = 22 W, Jrms = 4.4 A/mm^2, Tshaft = 0.7 Nm and Effcy = 76.1 %.

TABLE IV
EXAMPLE 2: RESULTS SUMMARY



Starting Configuration

INPUT	
Name [Units]	*Values*
Rad1 [mm]	25
LM [mm]	5.5
TC	24
SD [mm]	14

OUTPUT	
Name [Units]	*Values*
Tshaft [Nm]	0.65
Effcy [%]	71
Wtotal [W]	28
Jrms [A/mm2]	5.1

TARGET	
Name [Units]	*Values*
Tshaft [Nm]	maximize
Effcy [%]	maximize

Best Configuration

INPUT	
Name [Units]	*Values*
Rad1 [mm]	28
LM [mm]	8
TC	23
SD [mm]	16

OUTPUT	
Name [Units]	*Values*
Tshaft [Nm]	0.7
Effcy [%]	76
Wtotal [W]	22
Jrms [A/mm2]	4.4

Total Configurations	**3412**
Total Time computation	**~7 min**

V. CONCLUSION

This type of tools are very useful in electromagnetic design because are fast and intuitive and because it is possible to analyze many configurations in a very short time, defining many parameters (geometric parameters, winding parameters, material proprieties and drive circuit model).

The choice of computation software depends on the goal: if a first initial sizing and preliminary design are required n it is better a classical analytical method than the FEM method, because it is possible investigate a larger number configurations in a quicker way.

It is possible to perform steady state analysis and dynamic simulation.

There are several types of algorithms, such as different estimator quality, deterministic algorithms or stochastic algorithms.

All this in an easy way for the user, in fact the approach follow the “Black Box” idea, so the user defines only the inputs, filling a user-friendly interface, and observes the results.

These tools fulfill a frequent design engineers demand, because they help to automate a series of tasks that, up to now, are performed, in a more complicated way, in a classical electrical design of motors.

Moreover this tools help the design engineers in choosing the best configuration and with a more appropriate optimization.

VI. REFERENCES

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VII. BIOGRAPHIES

LucaGregorio Frigoli was born in Codogno, Italy, on 10th June 1981. He received his degree in Automation Engineering at Politecnico di Milano in 2006. He wrote his thesis in the field of the FEM simulation for induction heating welding. He currently work in Spin on different issues regarding the simulation and design of magnetic applications.

Alessandro Tassi was born in Ferrara, Italy, on July 4th 1964. He received the degree in Physics in 1989 at Milano University. He has been device designer in a electromechanical company for ten years, dealing with FEM computation and magnetic measurements. In 1999 he founded the company Spin Applicazioni Magnetiche to go deeper in FEM computation activity and the design of electric machines.