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OPTIMAL DESIGN OF VARIABLE SPEED ELECTRIC MOTOR-GENERATOR DRIVES: AN OVERVIEW

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Abstract. Variable speed electric motor/generator drives with power electronics control of motion/voltage/power are heavily used to save energy and/or increase productivity in most variable-output industrial processes; from wind generators through robotics, e-transport to home appliances and info-gadgets.

And in all such systems optimal design of their components or of their optimal control (to quicken the response or improve its quality or save energy in transients) is paramount. As optimization is a field in itself and literature on it, even only in electric motor-generator drives, is very rich, we will touch only a few of its representative issues of optimal design such as:

∗ Key performance indexes
∗ Single multi-term (global) objective function design optimization
∗ Multi-objective robust (and intelligent) optimal design

The present paper deals in some detail with the above issues via a few case studies from literature and from authors previous experience, in the hope of offering a synthetic but coherent picture of optimal design of electric motor/generator drives state of the art and its trends for the future.

Key words*:* motor/generator drives, variable speed, optimal control, design optimization, multi-objective optimal design.

1. INTRODUCTION

Variable speed electric motor/generator drives are now ubiquitous in various industries, to save energy and increase productivity, and, consequently, reduce CO_2 footprint [1].

Two typical such systems are shown in Fig. 1a, b.

Multi-unit such systems are connected in parallel in more complex a.c. and d.c. power grids, power vehicular sources, robots, etc.

Components (electric machine, inverter, etc.) optimal design (dimensioning) for a mission profile is paramount [2, 3]. Components and system modeling for steady state transients and control of motion (position, speed, torque) for motoring and voltage amplitude, frequency, (in a.c.) active and reactive power is required to prepare for optimal design [2, 3].

For modeling, to reduce computation time/effort (at least in preliminary stages) nonlinear analytical field and circuit models are still used and proposed (for new motor/generator configurations: flux-modulation electric machines [4]) but, lately, FEM – based optimal design methodologies are used with a few commercial codes; available from ANSYS, COMSOL, etc.

However, in the later case computation time reduction is very important and various models (such as surrogate mode) are used to reduce the necessary 2D (3D) FEM runs.

The bigger picture for optimal design requires rather complete objectives to encompass all costs: of electric machine active plus auxiliary materials plus fabrication plus capitalized losses for an aggregated duty cycle and loading in the machine and inverter on its entire life and the inverter cost that depends on the peak kVA for its rating (that is, on machine power factor). Even maintenance and recyclability rate of materials at the end of their productive life should be considered (for circularity).

To simplify this “heavy” picture a few tools have been developed rather recently and are still improved by the day:

A. Key performance indexes for electric drives.

B. Single multi-term (global) objective optimal designs

C. Multi-objective optimal designs
D. Multi-objective robust optimal designs
E. Intelligent robust optimal designs

We will deal in what follows in some detail with A, B, C, D issues with sample case studies from literature and from our own (in sections 2, 3, 4) and will just mention issue E as it is on its early stages.

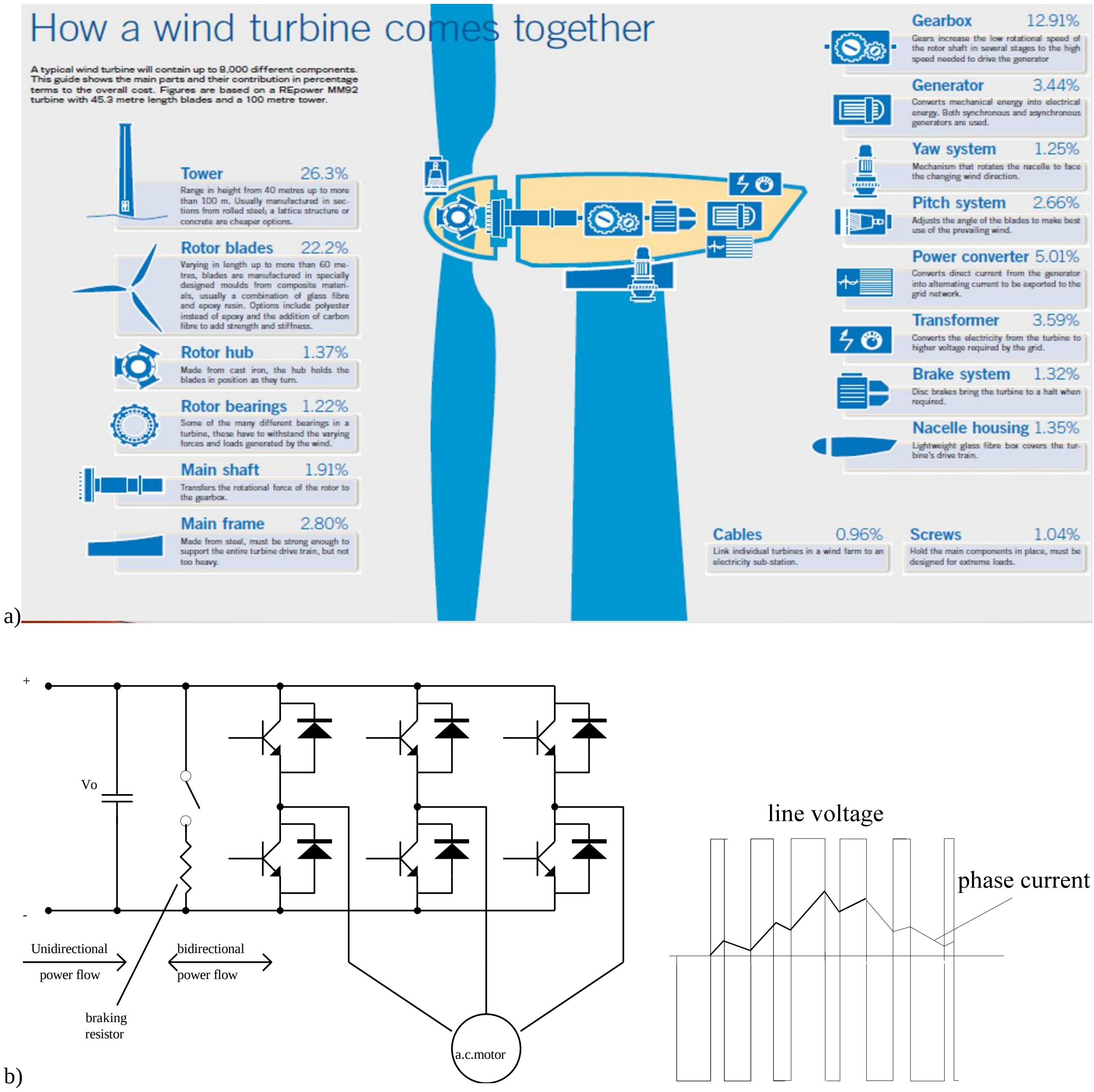


Fig. 1 – Generic wind tower power plant, a), and a.c. motor drive, b) [5].

2. PERFORMANCE INDEXES

Though not strictly standardized, performance indexes for a.c. machines even such as efficiency, power factor, starting current, starting torque etc. so typical for line-start induction machines have been introduced around 1900.

For variable speed drives a set of such performance indexes has been introduced in [5], first edition 1998, as divided in three categories extended here:

* Energy conversion indexes (power efficiency, power factor, energy efficiency of electric machine itself or including the inverter).
* Motor control response quality indexes (torque response quickness at zero speed: milliseconds or more, position, speed, torque control steady state error (precision) against perturbations (dynamic robustness), etc.
* Weights, costs, vibration, noise (+EMC).

All the above (and others: thermal, mechanical (stresses)) performance indexes may enter the objective (fitting or cost) function in the optimal design methodologies (codes).

However, for a.c. electric motor/generators (basically induction, synchronous and flux-modulation types with rotary or linear motion), which benefit by the use of dq (orthogonal or space vector circuit model), a few special performance indexes in their optimal design such as:

– Max. torque/winding losses (or MTPA)
– Max. torque/stator flux (MTPF) or per voltage
– Max. power factor (MPF),

have gained popularity because of their elegance (simplicity for great effects) on the way to meet the torque (power) versus speed envelopes for given inverter d.c. input voltage range, and thus have been introduced.

A unified synthetic/brief exposure of these key performances indexes is presented here starting from the dq (space vector) model equations of main a.c. machines.

Induction machine (IM):

$$\begin{aligned}
&\bar{I}_s R_s \mp \bar{V}_s = -\frac{\mathrm{d}\bar{\Psi}_s}{\mathrm{d}t} - j\omega_b \Psi_s; \quad \bar{\Psi}_s = L_s \bar{i}_s + L_m \bar{i}_r \\
&T_e = \frac{3}{2} p_1 \left(L_s - L_{sc}\right) i_d i_q; \quad L_{sc} = L_{sl} + L_{rl} \\
&i_r R_r \mp \bar{V}_r = -\frac{\mathrm{d}\bar{\Psi}_r}{\mathrm{d}t} - j(\omega_b - \omega_r)\Psi_r; \quad \bar{\Psi}_r = L_r \bar{i}_r + L_m \bar{i}_s; \\
&\bar{\Psi}_r = \Psi_r; \quad \bar{\Psi}_s = L_s i_d + jL_{sc} i_q; \quad i_q = i_d S\omega_1 L_r / R_r,
\end{aligned} \tag{1}$$

in rotor flux coordinates ($L_s >> L_{sc}$).

Reluctance synchronous machine (RSM):

$$\begin{aligned}
&\bar{I}_s R_s \mp \bar{V}_s = -\frac{\mathrm{d}\bar{\Psi}_s}{\mathrm{d}t} - j\omega_r \bar{\Psi}_s; \quad \bar{\Psi}_s = L_d i_d + jL_q i_q \ (L_d > L_q) \\
&T_e = \frac{3}{2} p_1 \left(L_d - L_q\right) i_d i_q,
\end{aligned} \tag{2}$$

in rotor coordinates ($L_d > L_q$).

The IM in rotor flux coordinates is similar to the RSM!

D.c. excited and PMSM

$$\begin{aligned}
&\bar{I}_s R_s \mp \bar{V}_s = -\frac{\mathrm{d}\Psi_s}{\mathrm{d}t} - j\omega_r \bar{\Psi}_s; \\
&\bar{\Psi}_s = L_d \bar{i}_d + \Psi_{PMd} \ (\text{or } \Psi_f = L_{dm} i_f) + jL_q i_q \\
&I_f R_f - V_f = -\frac{\mathrm{d}\Psi_f}{\mathrm{d}t}; \quad \Psi_f = L_{dm} i_d + L_f i_f; \\
&L_{dm} = L_d - L_{sl} \\
&T_e = \frac{3}{2} p_1 \left(\Psi_{PMd}(\Psi_f) + \left(L_d - L_q\right) i_d\right) i_q; \quad L_d > L_q,
\end{aligned} \tag{3}$$

in rotor coordinates (no damper cage on the rotor).

Note. The PM – assisted RSM has in general the magnets in axis q (Ψ_{PMq}), but otherwise their equations are rather similar ($L_q < L_d$, instead of $L_d < L_q$).

MTPA. For the induction machine we add $I_s^2 = I_d^2 + I_q^2$ to the torque equation, calculate torque derivative with respect to, say, i_q (with i_d as a function of I_s and I_q) and obtain, for constant parameters:

$$i_d = i_q \tag{4}$$

for the IM and RSM.

For the IPMSM, proceeding similarly we obtain in terms of "active flux" [4, pp. 371]:

$$i_d^* = -|i_s|\sqrt{\frac{|\Psi_d^a| - \Psi_{PMd}}{2|\Psi_d^a| - \Psi_{PMd}}};\ \ \Psi_d^a = \bar{\Psi}_s - L_q \bar{i}_s;\ \ i_q^* = \frac{2T_e^*}{3p_1|\Psi_d^a|} \tag{5}$$

i_s – measured, Ψ_d^a - estimated.

Note. For the d.c. – excited SM, the MTPA should consider both stator a.c. and rotor d.c. winding losses. Also note that for surface PMSM ($L_d = L_q$) MTPA implies $i_d^* = 0$! ("pure" i_q control). The above formulae should be modified in presence of magnetic cross saturation (heavy loads).

MTPF. The conditions may be deduced similarly as MTPA but from the torque and stator flux Ψ_s formula: $\Psi_s = \sqrt{\Psi_d^2 + \Psi_q^2}$; the expressions are more complicated and should be solved numerically to save time in the optimal design [4]. In essence though: $\Psi_d = \Psi_q$.

Max. power factor (MPF). The performance index (criterion) has not enjoyed so far much attention but it turns out to be independent of frequency (speed) and thus enjoying notable generality. Also, MPF is key in defining the inverter cost, $inv_{cost} \approx K_{voltage} \cdot \frac{P_{active}}{\cos\varphi_1}$; P_{active} – motor/generator terminal active power (6).

As the IM controlled along rotor flux is similar to RSM it is sufficient to use the space vector diagram of synchronous (flux-modulation machines are similar) machines.

Using simple trigonometry (Fig. 2):

$$\cos\varphi_1 = \cos\left(\overbrace{\tan^{-1}\frac{\Psi_q}{\Psi_d}}^{\gamma_{iv}} + \overbrace{\tan^{-1}\frac{i_d}{i_q}}^{-\gamma_{ii}}\right) \tag{6}$$

Alternatively, also:

$$\cos\varphi_1 = \frac{P}{\sqrt{P^2 + Q^2}};\ \ \Psi_d = \Psi_{PMd}(\Psi_f) + \mathrm{L}_d\, i_d;\ \ \Psi_q = \mathrm{L}_q\, i_q \tag{7}$$

will offer simple confirmation.

This simple formula may be of great help in reducing computation time in optimal design of a.c. machines for variable speed as its application is some-where in between MTPA and MTFF in terms of required voltage for given torque and speed.

The max. power factor, depending only on $\mathrm{i_d}$ and $\mathrm{i_q}$ (in fact) and on the given Ψ_{PMd} (or Ψ_f) may be found easily for IMs and RSM:

$$\begin{aligned}
&\Psi_d i_d = \Psi_q i_q;\\
&\frac{i_d}{i_q} = \sqrt{\frac{L_{sc}}{L_s}},\quad \cos\varphi_{i\max}^{IM} = \frac{1-\frac{L_{sc}}{L_s}}{1+\frac{L_{sc}}{L_s}}\ \text{ for } IM;\\
&\frac{i_d}{i_q} = \sqrt{\frac{L_q}{L_d}},\quad \cos\varphi_{i\max}^{RSM} = \frac{1-\frac{L_q}{L_d}}{1+\frac{L_q}{L_d}}\ L_d > L_q
\end{aligned} \tag{8}$$

Note. Again, heavy saturation will change (8).

For the IPMSM $\cos\varphi_{i\max}$ may not always have a solution while for d.c. excited SM $\cos\varphi_{i\max} = 1$ is a key design performance for wide constant power speed range (CPSR) – as required in e-transport power trains.

However, in all cases eqn (6) is valid and useful in design, say as a constraint.

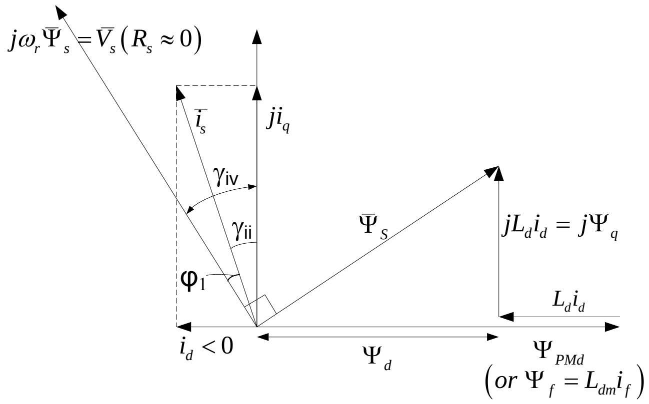


Fig. 2 – Space phasor diagram of SMs under steady state with no losses (ideal) and with $i_d < 0$.

Discussion. The MTPA, MTPF and MPF criteria may be used to mitigate maximum torque-speed envelope with constraint machine current and voltage: example: use MTPA at lower speeds (up to base speed) and lower than max. torque then max. power factor (MPF) criterion below and above base speed at full torque and then MPPF extended flux weakening (up to highest speed), when energy conversion performance and max torque speed envelope may be optimized for a give mission profile of the drive.

3. SINGLE MULTITERM (GLOBAL) – OBJECTIVE FUNCTION OPTIMAL DESIGNS

Single multiterm (global) objective function optimal designs refer mainly to the cases when small power or singular prototypes or preliminary designs based on simple nonlinear analytical field, or magnetic equivalent circuit models (to reduce computation time) are targeted; and then FEM inquires (refinements) are made at (or around) optimal design geometry, with corrections and reruns of optimization code a few times, for convergence via under relaxation coefficients.

Also, for smaller singular motors/generators 2D FEM or quasi 3D FEM model-based optimization design methodologies have been used.

Summarizing, single multiterm (global) objective function optimal designs are based on:

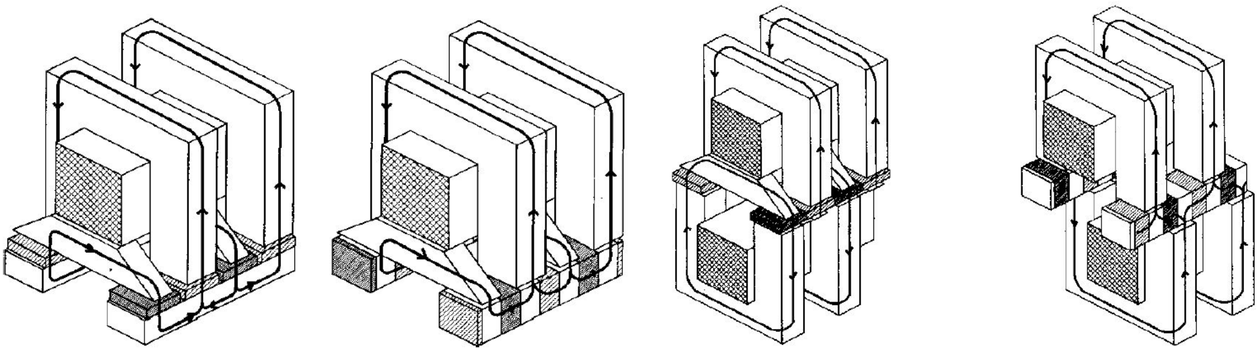
- Nonlinear analytical field machine models with data imported to circuit models, with FEM key validation
- With embedded 2D FEM (when a few FEM runs around the optimal design are performed until convergence is met)
- 2D (quasi-3D) – FEM based

Before presenting a few sample results on this kind of methods [5-24], we mention here first that an optimal design code contains:

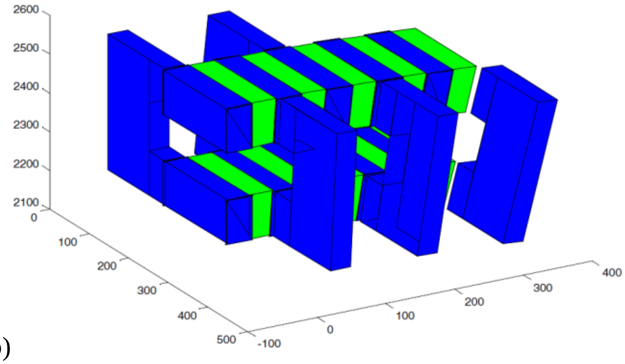
- Specifications (for steady-state and transients)
- Variable vector and its range
- Machine + converter + control model
- Multi-term (global) objective function, with constraints and a deterministic or evolutionary optimization algorithm [4].
- Postprocessing and presenting the output data, in numbers and graphs, to characterize the optimal design results.

Case study1. 3MW, 11rpm transverse flux directly driven wind PM generator: optimal design with key FEM validation [7]

The typical TF-PMSG topologies (Fig. 3a) [7] served as base to introduce an axial-airgap dual configuration (Fig. 3b).



a)



b)

Fig. 3 – TF-PMSG: a) typical configuration; b) proposed axial-flux configuration [7].

The 3D MEC model for one pole pair is shown in Fig. 4.

The variables vector contains 10 terms:

$$\bar{x} = \left[2p_{PM},\ D_{ext},\ W_{st},\ W_c,\ h_c,\ h_{ys},\ l_{PM},\ l_{m\_s},\ l_{m\_r1},\ l_{m\_r2} \right], \tag{9}$$

$2p_{PM}$ – rotor poles number, D_{ext} – outer machine diameter, W_c – stator slot width, h_c – slot height, h_{ys} – stator U shape core yoke thickness, l_{PM} – axial length of spoke-shape PMs, l_{m_s} , l_{m_r1} , l_{m_r2} – nondimensional (ratios) variables.

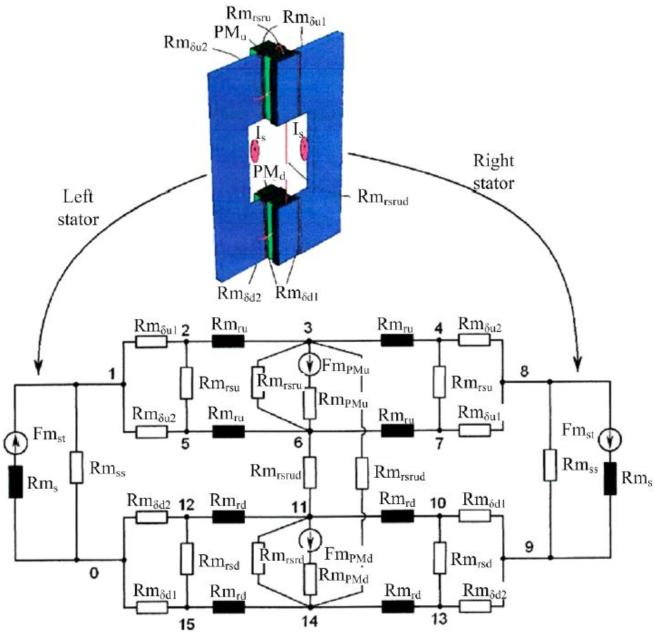


Fig. 4 – Axial – airgap TF-PMSD: 3D-MEC for one pole pair [7].

The single multiterm (global) objection function $f(\bar{x})$ is:

$$f(\bar{x}) = C_i(\bar{x}) + C_e(\bar{x}) + C_p(\bar{x}) \,, \tag{10}$$

with C_i – initial machine and PWM converter (per kVA) cost in USD, C_e – machine and converter loss cost for a given number of years (days) x hours of equivalent duty cycle (in USD), C_p – penalty function in USD for stator and rotor over temperature limitation (for a given equivalent convection heat transmission coefficient, say, α_{heat}= (14–100) W/m^2/°C) and PM demagnetization avoidance cost at the critical operation point (ex: 200% load).

The optimization algorithm is based on modified Hooke-Jeeves method [4] and sample results on the evolution of outer diameter, active weight, efficiency, power factor, are given in Fig. 5.

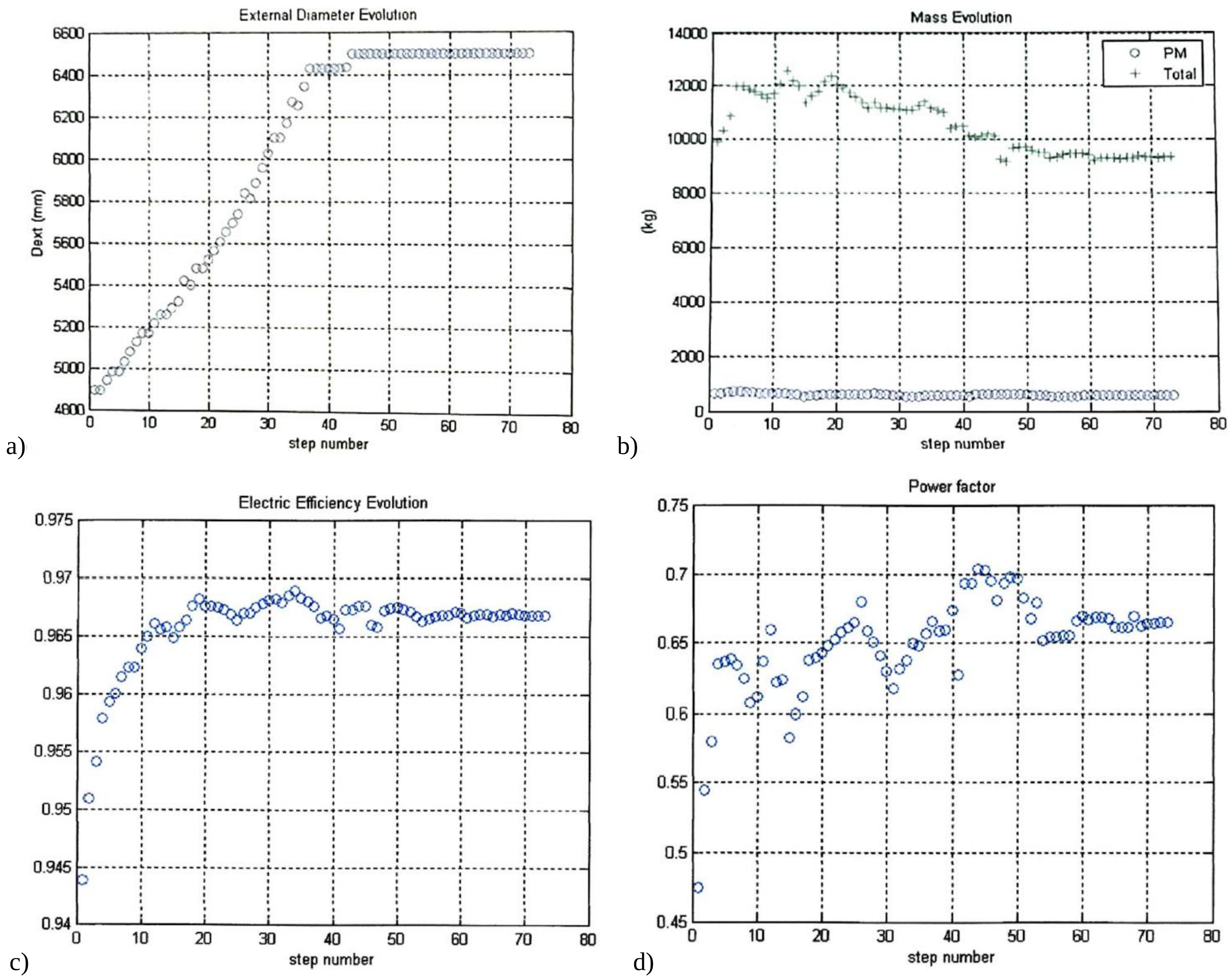


Fig. 5 – Axial-airgap TF-PMSG, 3 MW, 11 rpm: a) external diameter D_{ext}; b) active weight; c) efficiency; d) power factor [7].

Table 1

Lost breakdown of 3 MW, 11 rpm [7]

Cost parameters	Analytical model value	Optimized analytical value
Total copper cost: Cu_c	8018 [USD]	19140 [USD]
Total iron lamination cost: lam_c	35419 [USD]	28474 [USD]
Total active material cost: i_cost	144684 [USD]	134424 [USD]
Total passive material cost: pmw_c	69373 [USD]	65416 [USD]
Inverter cost: inverter_c	157842.6 [USD]	112781 [USD]
Energy cost: energy_c	267197 [USD]	153977 [USD]
Total generator cost: t_cost	639100 [USD]	466600 [USD]

The breakdown of costs for the 3 MW, 11 rpm optimal design is given in Table 1.

In essence, in spite of low power factor of TF-PMSG, the global objective leads to the apparent lowest weight so far design for the given specifications (9345 kg of active weight!), a key criterion for the global optimal design of a wind generator system (with tower).

Case study 2. Doubly salient ferrite rotor PM single phase small synchronous motor (DS-Ferrite rotor PMSM) drive (68W, 3krpm) [20]

The small "DS-Ferrite rotor PMSM" in Fig. 6, with auto-starting stator PMs, was optimally designed, with a global objective method, but using a 2D-FEM only machine model and the Hooke-Jeeves algorithm.

The optimization design in [20] with 13 variables targets only the motor, but global objective (cost) function (expressed in USD in all terms) concentrates on minimum materials costs, while accounting also for efficiency, demagnetization avoidance, minimum (0.1 Nm) starting torque from any rotor position and average torque (torque waveform with position: positive only) as constraints.

$$f_{ob} = C_{materials} + C_{Tmin} + C_{Taverage} + C_{efficiency} + C_{demag}\,. \tag{11}$$

Modified Hooke-Jeeves optimization algorithm required a maximum of 60 runs to secure a stable response.

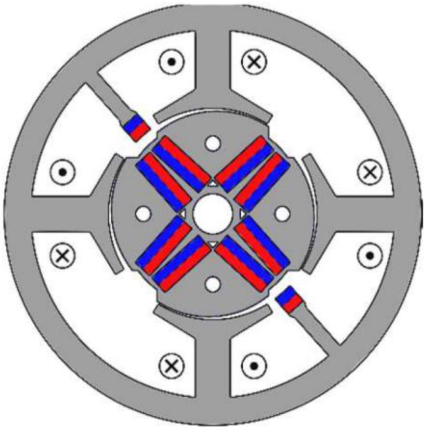


Fig. 6 – DS-Ferrite rotor single-phase PMSM cross-section [20].

Note. To increase the probability of obtaining a global optimum 10 random starting variables vectors may be tried, choosing finally the best global performance solution.

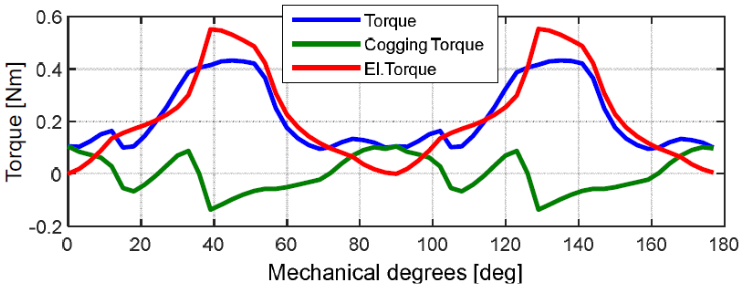


Fig. 7 – Torque versus rotor position at full torque (68 W, 3 krpm small motor [20]).

Figure 7 shows the optimal torque-angle waveform that secures the minimum of 0.1 Nm starting torque for any rotor initial position.

Controlled dynamics simulation included in the optimal design code has proved safe (stable) operation in driving a small compressor (with load torque heavy pulsations [20]).

Case study 3. Three phase inner claw pole stator PMSM [21]. Also, based on a nonlinear 3D-MEC model a 3 phase claw-pole- inner -stator -PMSM of 500 W at 2 400 rpm was optionally designed in [21], again with a multiterm (global) objective function and improved Hooke-Jeeves algorithm, obtaining rather impressive results:

– 94.68% efficiency, power factor 0.8 at 500W, 2 400 rpm
– Motor active weight: 1kg.

– Motor active materials cost: 7.6 USD
– The computation time for 30 runs, from random starting variables vectors, was only around 82 seconds on a contemporary standard desk computer.

Discussion. Characterized by easy implementation, relying in general on 2(3)D-MEC or even 2D – FEM machine models, but containing a single (global) objective (cost) function this kind of optimal designs may provide good results for a small computation time (effort). For comparative Hooke-Jeeves and G.A. optimal designs of IMs and PMSMs see Ref. [4].

However, as it will be seen in the next chapter, when 3D-FEM is a must, for more precision and robustness to materials quality and manufacturing tolerances, for a mass fabrication, robust multi-objective design methodologies are, in general, required. The computation time will be notably higher but kept "at bay" by intricate math tools that, in essence, reduce the 3D – FEM number at required runs.

4. MULTIOBJECTIVE ROBUST (AND INTELLIGENT) OPTIMAL DESIGNS [26-36]

Multi-objective optimal design methodologies rely heavily on "Pareto clouds (maps)" of two or three performance indexes; they use in general 3D-FEM machine models and evolutionary optimization algorithms.

Figure 8 shows such "Pareto clouds" of active weight versus machine losses, using Differential Evolution optimization algorithm and 3D-FEM machine model, for an axial-flux core-less PMSM (12 Nm, 3 krpm) with nonoverlapping stator a.c. coil winding.

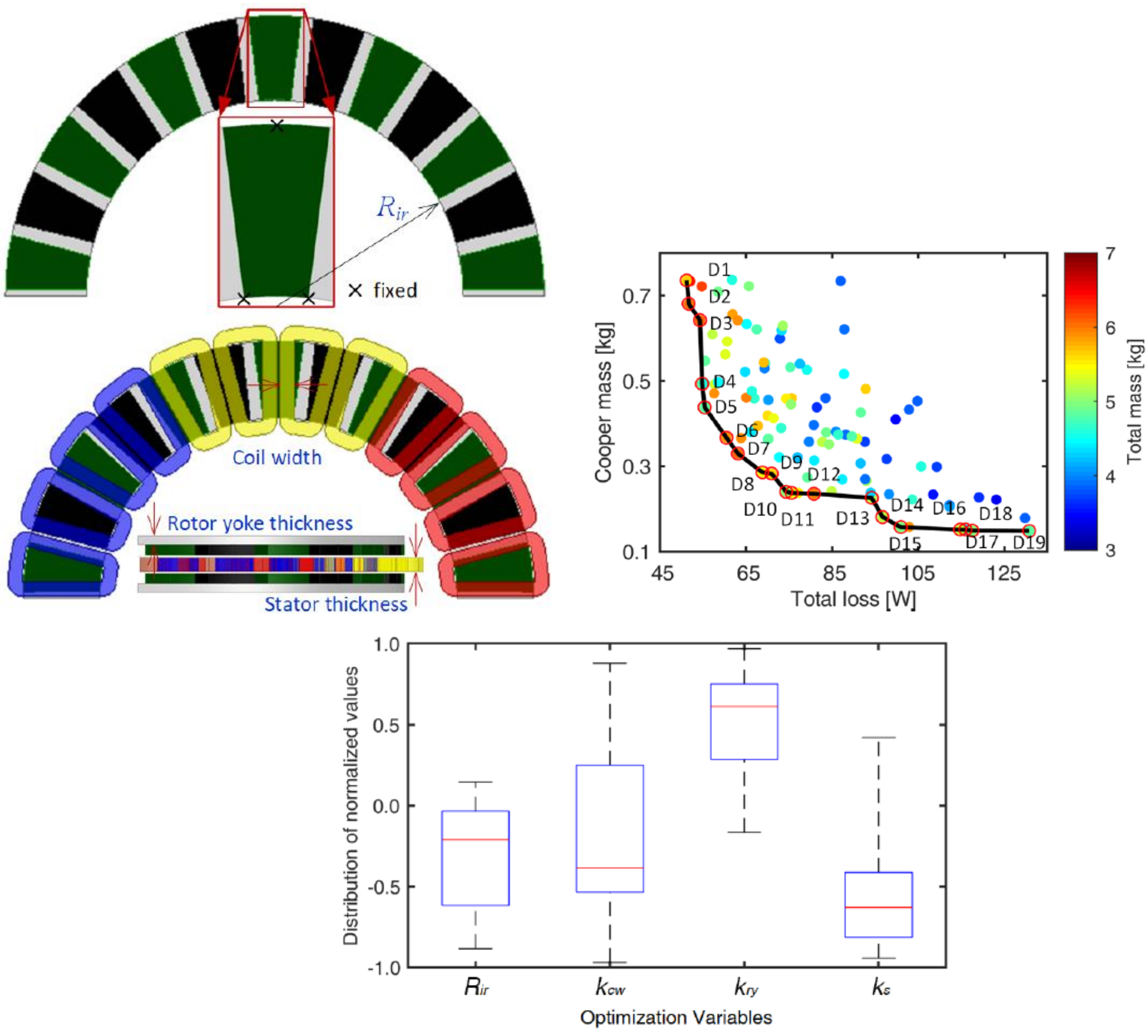


Fig. 8 – Pareto clouds for the multi-objective optimal design of an axial PMSM (12 Nm, 3krpm, [29]).

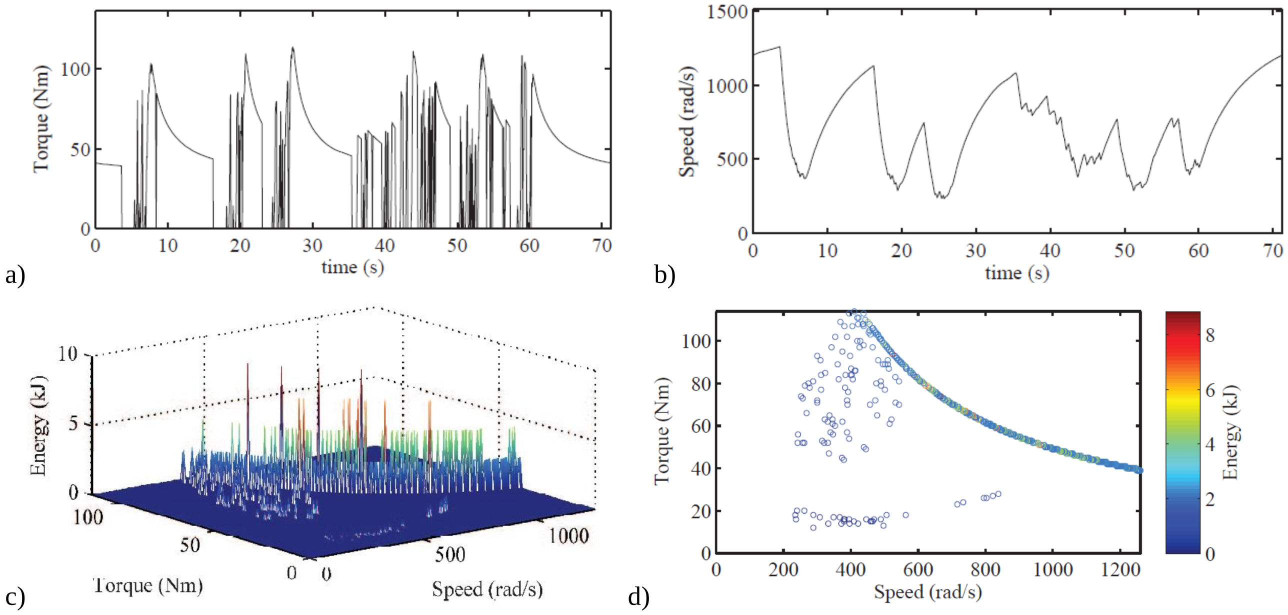
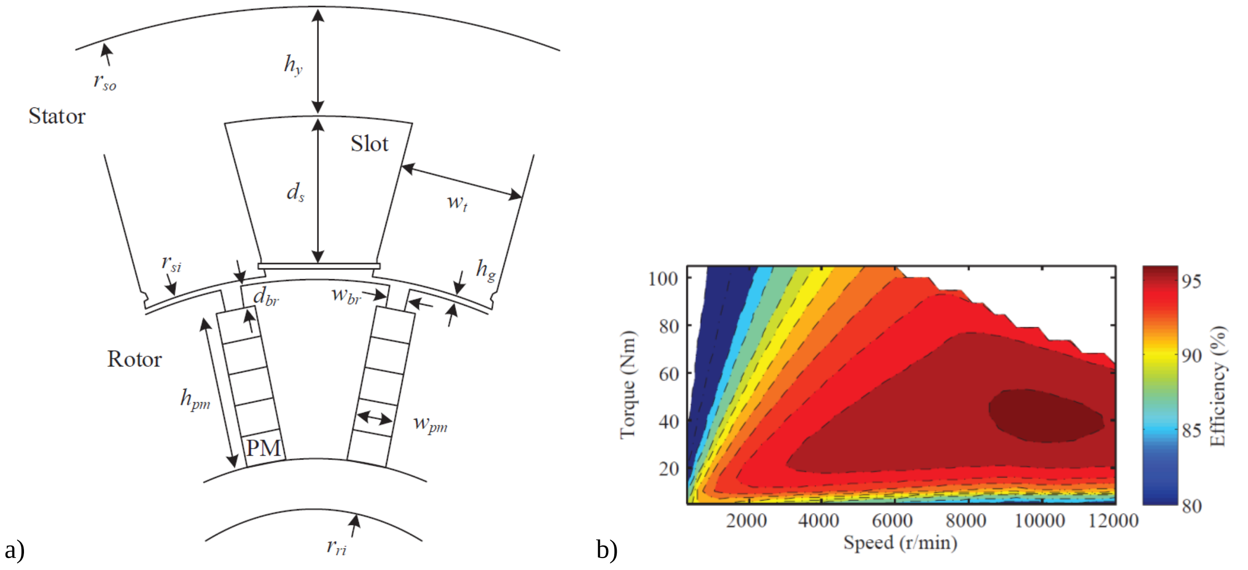
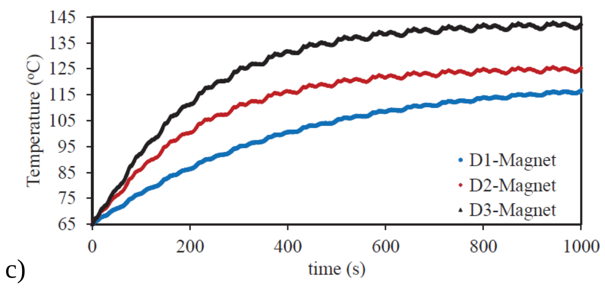


Fig. 9 – Le Mans driving cycle specifications [33]: a) torque-time; b) speed-time; c) energy versus torque and speed; d) energy distribution.





d)

	Type	Peak Torque (Nm)	Total Mass (kg)	TRW (Nm/kg)
New Design D2	IPM (spoke)	110	9	12.2
Nissan Leaf	IPM (flat)	300	46	6.5
YASA 400	Axial PM	360	24	15.0
Toyota Prius 04	IPM (V)	400	51	7.8
Tesla S	Induction	430	90	4.8

Fig. 10 – Performance maps of optimized spoke-type PMSM design for an E race power train: a) parametrized FEM model [33]; b) efficiency with torque and speed map [33]; c) temperature profiles [33]; d) examples of high tech. traction motors [33].

Two level optimization was used to reduce computation time: an inner differential evolution (DE) loop and kriging surrogate models, with 3 search space specifications [29].

A rather comprehensive such multi-objective design was also recently performed for an E-race car power train destined to Le Mans driving cycle (Fig. 9) [33].

Sample results offered here [33] characterize performance results (Fig. 10).

Robust multi-objective optimization of electric machines

Materials properties variance from fabrication (Fig. 11) with temperature and fabrication tolerance create variations in a batch of fabricated electric machine drives performance and these have to be gauged to guarantee a certain global performance level [33].

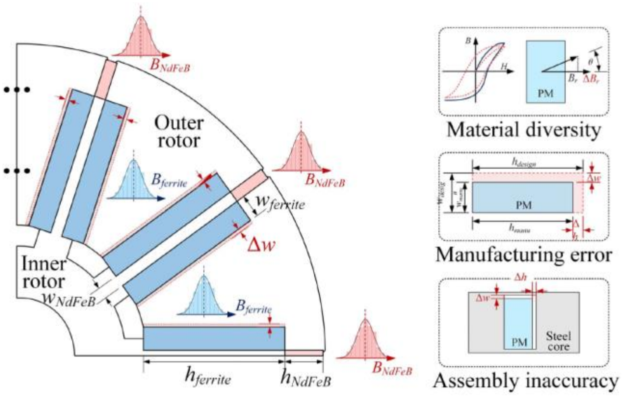


Fig. 11 – PM material uncertainties [33].

A rather complete flow chart of a robust multi-objective design of a 12/10 spoke dual PM rotor axial-airgap motor is illustrated in Fig. 12 [34].

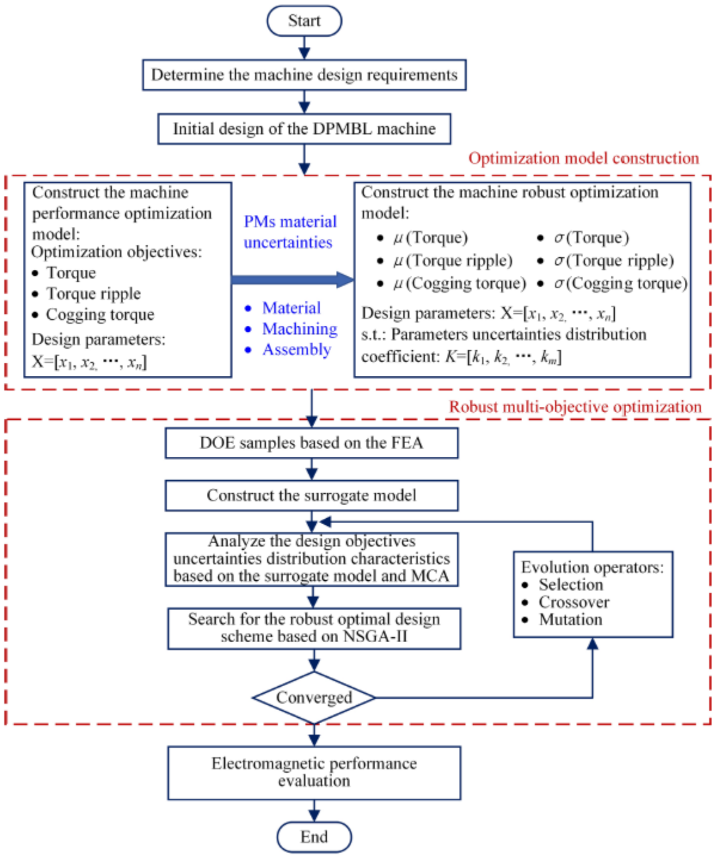


Fig. 12 – Flow chart of a multi-objective optimal design code turned robust by surrogate model and Monte-Carlo analysis (MCA) for uncertainties and nondominated sorted GA II (NSGA-II) for researching [34].

Distribution of design objectives of dual PM rotor SM for average torque, torque ripple and cogging torque offered in Fig. 13 show remarkably robust performance [34].

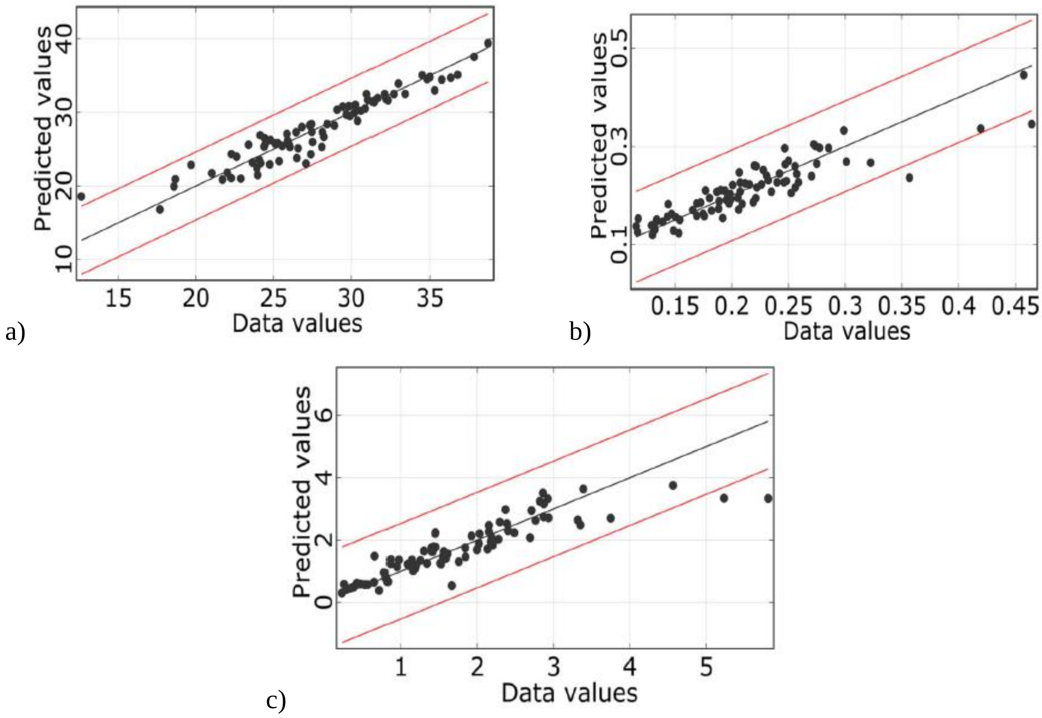


Fig. 13 – Design objectives distribution for robust multi-objective design of dual PM-rotor SM:
a) average torque; b) torque ripple; c) cogging torque [34].

As above noticed, multi-objective robust designs based on 3D-FEM models are more complex and go deeper in precision. They deal in a Multiphysics manner with electromagnetic, thermal and mechanical stresses, but so far consider only the electric machines, even in multiple operation point targets (in traction). The inverter with its performance, costs, etc. is not yet considered, though the efficiency and cost of the two are not much different.

To further expend multi-objective optimal design methodologies (and practical computer codes for them) so called “intelligent optimization”, has been recently proposed [35, 36]. This trend is expected to grow fast in the near future.

5. CONCLUSION

This present paper leads to remarks such as:

- Optimal design or optimal control are key processes in producing high performance electric motor-generator drives; only optimal designs are treated hereby.
- Nonlinear analytical field (circuit) or numerical field (FEM) models of electric machines are used in optimal design.
- Multiphysics (electromagnetic, thermal and mechanical) models of electric machines are implicit in their optimal design.
- Deterministic and evolutionary optimization algorithms are applied, but the latter are more probably producing global optimum though they show lower convergence (more computation time).
- Single (multi-term) objective or multi-objective functions characterize two main ways to approach optimal design of electric motor generator drives. Both have merits and demerits so that they seem almost complementary. While the former includes all cost components in the single (global) objective(cost) function, the latter go deeper, for more computation time.
- The present paper illustrated both optimal design methods – single (global) and multi-objective with sample case studies.

• Robust, intelligent optimal design codes of variable speed electric-motor drives are here to stay in the near future for better outputs/computation time.

Final note. As noticed, the present review paper used results for the case studies mainly from two rather related groups, for convenience. The literature on the subject is extremely rich and the interested reader is kindly advised to look for "optimal design of electric machines drives" and of optimal control design of electric motor-generator drives in various applications in IEEEXplore to round up our inevitably subjective view.

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