Core Axial Lengthening as Effective Solution to Improve the Induction Motor Efficiency Classes

Luigi Alberti, Nicola Bianchi
Department of Electrical Engineering,
University of Padova, ITALY

Aldo Boglietti, Andrea Cavagnino
Department of Electrical Engineering,
Politecnico di Torino, ITALY

September 30, 2011

This presentation has been given during the

3rd IEEE Energy Conversion Congress & Exposition (ECCE 2011)

held in Phoenix (Arizona, USA), Sept. 17–22, 2011.

1. **Introduction**
2. **The Axial Length Increase Solution**
3. **Analytical–FE–Based Motor Efficiency Evaluation**
4. **Prototype Definition**
5. **Experimental Model Validation**
6. **Efficiency Map**
   - Optimal Efficiency Trajectory
   - Electric and magnetic quantities along the optimal efficiency trajectory
7. **Higher Diameter Lamination**
8. **Conclusions**

New UE standards and regulations have been approved.

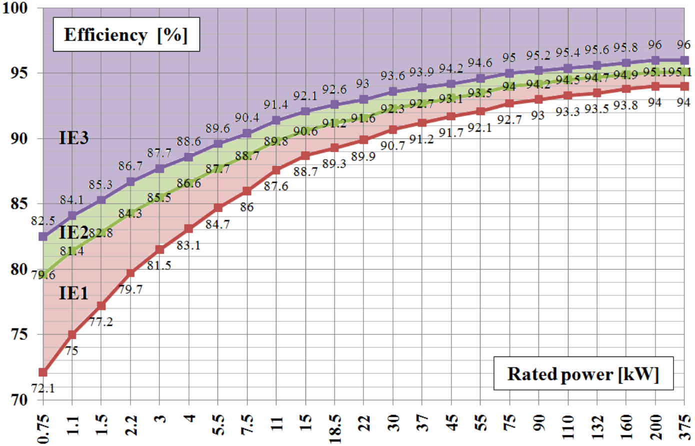
During the 2011–2017 period
the European manufacturers of induction motors
have to take into account the new regulations.

1. the IEC/EN 60034–30 (**2008**) defines energy efficiency classes (IE code, International Efficiency),
2. the IEC/EN 60034–2–1 (**2007**) establishes methods to determine efficiency from tests, and methods to distinguish the loss contributions.

On the basis of the successful US experience, in 2009 the European Parliament approved the **Minimum Energy Performance Standard** (**MEPS**) for the electric motors, acknowledging the efficiency values reported in the IEC/EN 60034–30 standard.

1. The MEPS sets the **minimum mandatory efficiency levels** for motors sold in the European market
2. The MEPS defines the agenda for its implementation.

MEPS: Efficiency Level



Efficiency classes for 4–pole, 50–Hz, three–phase IMs.

European MEPS Agenda

From June 16, 2011
Motors must meet the IE2 efficiency level
From January 1, 2015
Motors with a rated output of 7.5—375 kW must meet EITHER the IE3 efficiency level OR the IE2 level if fitted with a variable speed drive.
From January 1, 2017
Motors with a rated output of 0.75—375 kW must meet EITHER the IE3 efficiency level OR the IE2 level if fitted with a variable speed drive.

There are some problems and difficulties

that complicate the panorama

- standards are not yet completely defined,
- there are several differences between standards,
- high financial cost for investments.
  (This is critic for small and medium size producers).

In medium period

the increase of axial core length of the machine allows a proper efficiency improvements.

Such **No–Tool–Cost** process requires a minimum economical impact to modify the production process.

IM design preliminary considerations

With a given lamination geometry,
Nominal Torque and Voltage relationships:

$$T_r \propto L \cdot B \cdot J$$

$$V_r \propto L \cdot B \cdot N$$

Dimensionless ratios are introduced
so as to define the design variations:

$$\beta = \frac{B'}{B} \qquad \sigma = \frac{J'}{J}$$

$$\lambda = \frac{L'}{L} \qquad \nu = \frac{N'}{N}$$

IM design preliminary considerations

There are some restrictions for these design ratios:
From the torque equation:

$$\lambda \cdot \beta \cdot \sigma = 1$$

From the voltage equation:

$$\lambda \cdot \beta \cdot \nu = 1$$

These constrains impose the identity:

$$\sigma = \nu$$

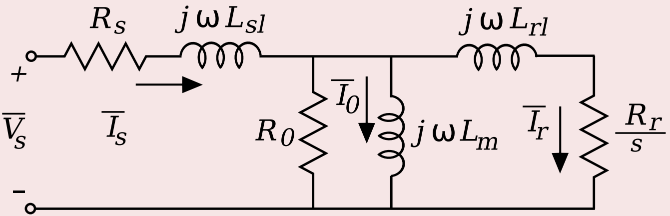
and then

$$\lambda \cdot \nu = \frac{1}{\beta}$$

A Combined Analytical–FE IM model

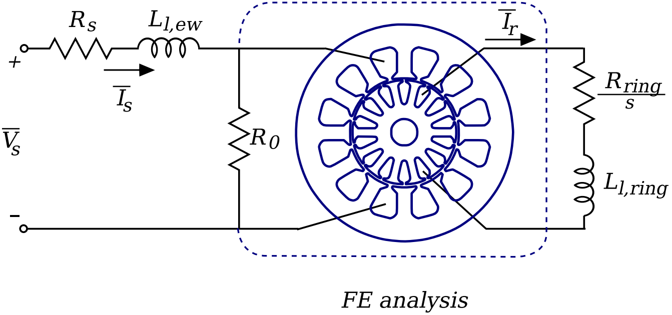
is used for a detailed analysis of induction machine.

Equivalent circuit of the three–phase induction machine



Finite element simulations are carried out so as to compute the lumped parameters of the traditional equivalent circuit.

Combined Analytical–FE IM model



Scheme of the combined analytical–FE model
of the three–phase induction machine.

Combined Analytical–FE IM model

2D simulations

referring to a laminated motor, a two–dimensional FE analysis is generally satisfactory.

3D parameters

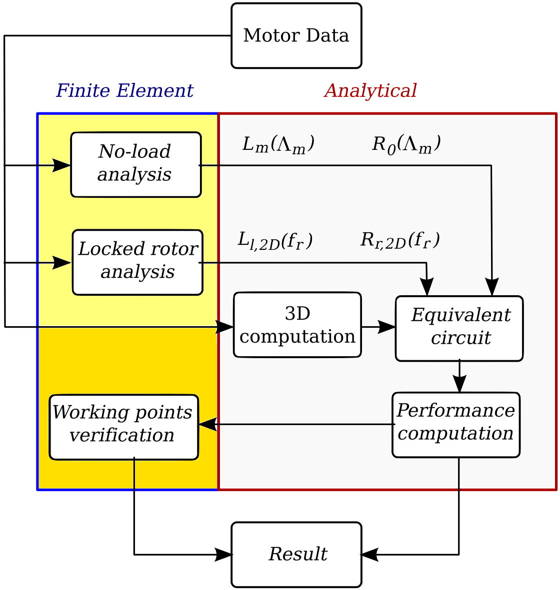
The three–dimensional effects are computed analytically and included later in the model.

- stator resistance,
- end–winding resistance and inductance,
- rotor ring resistance and inductance,
- skewing.

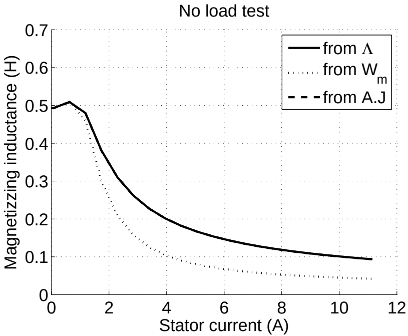
Advantages

- **The computation is rapid**, (few FE simulations are necessary),
- **The computation is accurate**, (effects of saturation and eddy currents are considered in the FE analysis),
- This approach overcomes the limits of the completely analytical or completely numerical procedures.
- The procedure is **easy to be implemented.**
- The procedure is suitable for **any FE software.**

Combined Analytical–FE IM model



Magnetizing inductance (No–load analysis)



Magnetizing inductance

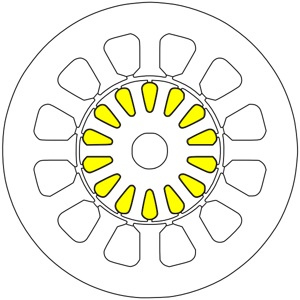
from flux linkages

$$L_m = \frac{\Lambda_m}{I_0}$$

Rotor Joule losses (Locked–rotor analysis)

Selecting the rotor bars, the Joule losses are computed.

$$P_{jr} = \frac{1}{2\sigma_{Al}} L_{stk} \int_{S_{Al}} \dot{J}_z \cdot \tilde{J}_z dS$$

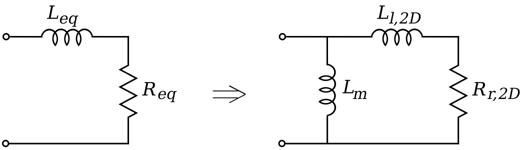


It is computed at various frequencies.

Rotor parameters as a function of the frequency

The equivalent resistance from the Joule losses
The equivalent inductance from the magnetic energy

$$R_{eq} = \frac{P_{jr}}{3 I^2} \qquad L_{eq} = \frac{2}{3} \frac{W_m}{I^2}$$



$$L_{l,2D} = L_m \frac{L_{eq}(L_m - L_{eq}) - (R_{eq}/\omega_r)^2}{(L_m - L_{eq})^2 + (R_{eq}/\omega_r)^2}$$

$$R_{r,2D} = R_{eq} \frac{L_m + L_{l,2D}}{L_m - L_{eq}}$$

1. FE results are associated only to the given lamination geometry and the winding distribution,
2. Normalized parameters are used: with unity stack length, and unity number of turns per slot.
3. This allows the results to be easily extended to any motor with its actual length and its actual number of turns simply rearranging the equivalent circuit.

Data of the Original Induction Motor

Nominal Power	(kW)	11
Nominal Voltage,	(V)	400
Pole number	–	4
Frequency	(Hz)	50
Current	(A)	22.5
Power factor	(p.u.)	0.84
Efficiency (*)	(p.u.)	0.88

(*) the rated efficiency is defined in accordance to IEC/EN 60034–2 (1996) .

Example: Efficiency Class for IM Prototype

The IEC/EN 60034–30 (2008) Efficiency Classes
for the 4–pole 50–Hz Induction Motor Prototype

Rated	Power	IE1	IE2	IE3
kW	HP	Standard efficiency	High efficiency	Premium efficiency
11	15	87.6 %	89.8 %	91.4 %

Example: Analytical considerations

Preliminary analytical estimation

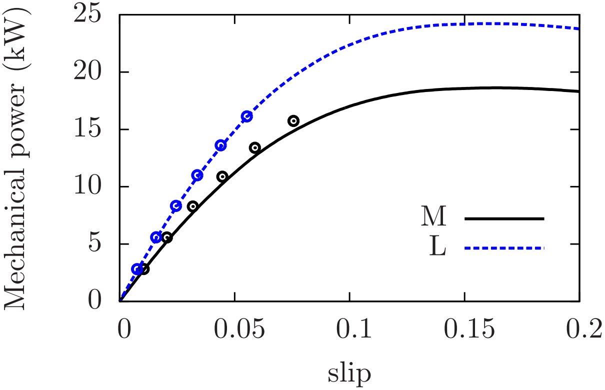
Resulting dimensionless ratios:

$\lambda = 1.16$	increase of axial length
$\beta = 0.96$	decrease of flux density
$\sigma = 0.90$	decrease of current density
$\nu = 0.90$	decrease of no. of turns

With such a modifications

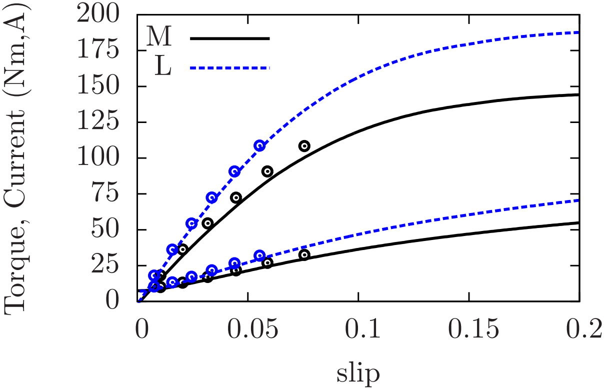
an increase of 2 % on the efficiency
is estimated for the prototype.

Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.



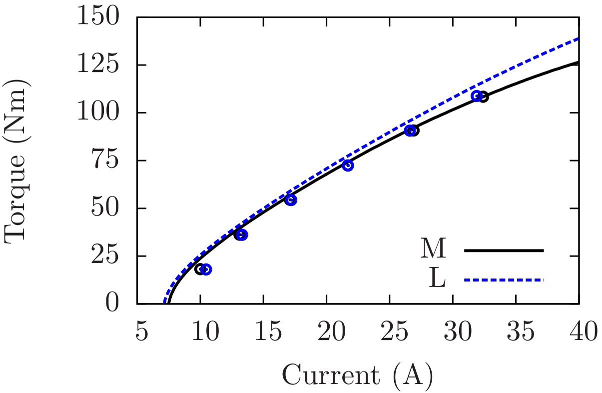
Experimental validation of the prediction

Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.



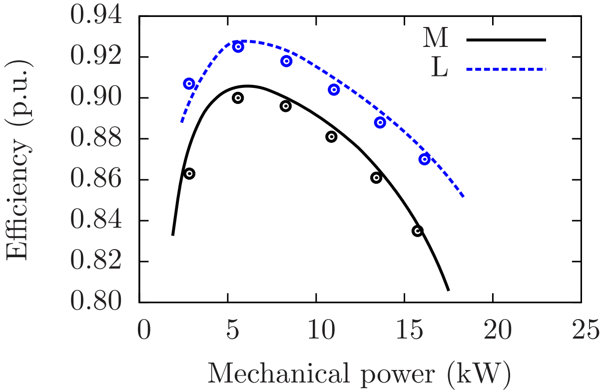
Experimental validation of the prediction

Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.

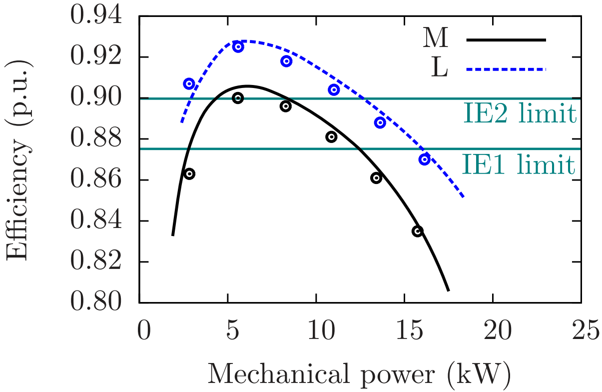


Experimental validation of the prediction

Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.

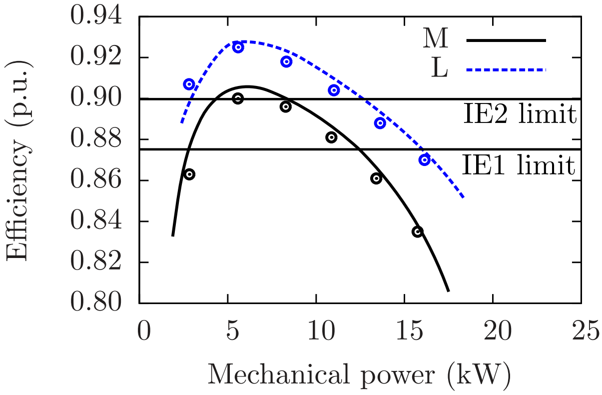


Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.

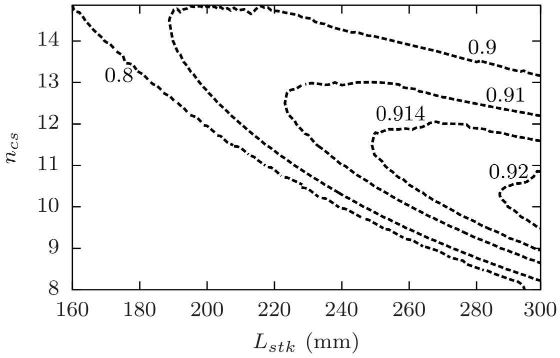


Experimental validation of the prediction

Results achieved from the analytical–FE model are compared with the experimental results referring to two IMs of different lengths.

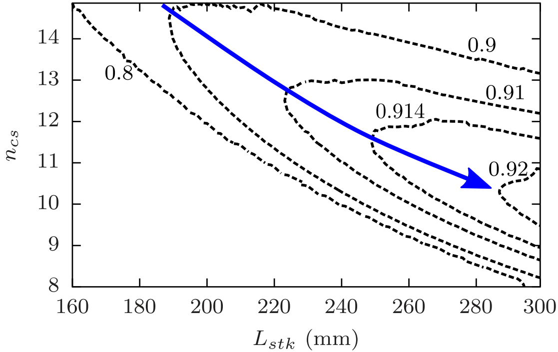


Efficiency map



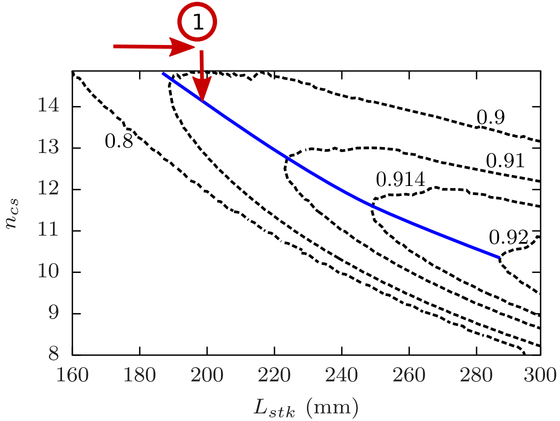
Efficiency Map of the motor under analysis.
Lamination geometry is fixed.
Rated power P_N=11 kW, rated voltage V_N=400 V.

Optimal Efficiency Trajectory



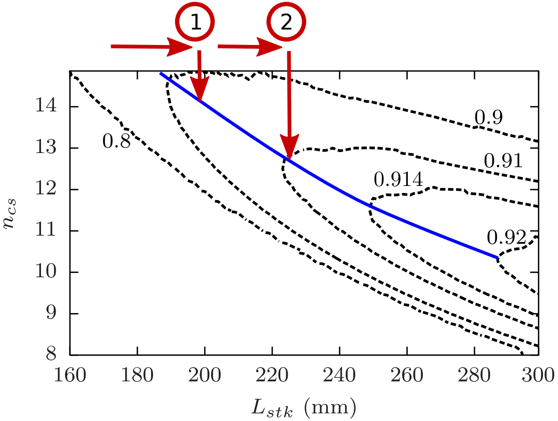
The optimal efficiency trajectory is found
by connecting the points of maximum efficiency
for a given stack length.

Optimal efficiency Trajectory



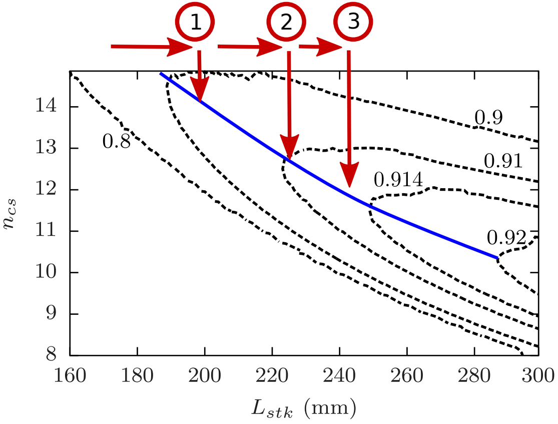
Procedure to search the operating point
along the optimal trajectory

Optimal efficiency Trajectory



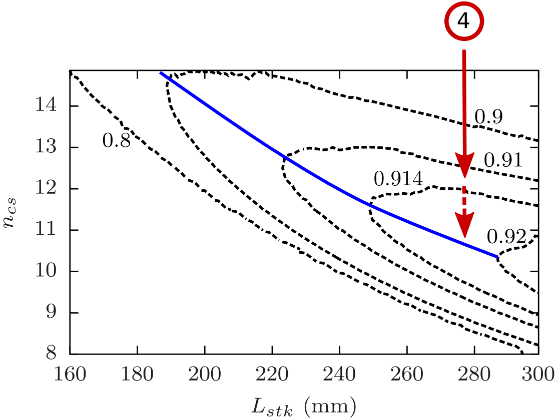
Procedure to search the operating point along the optimal trajectory

Optimal efficiency Trajectory



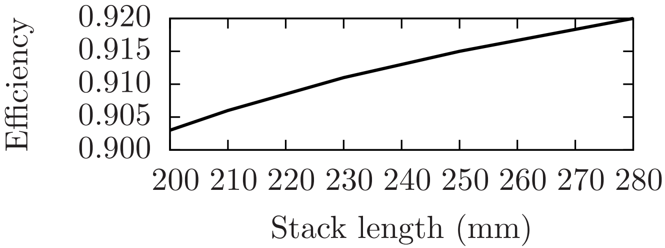
Procedure to search the operating point
along the optimal trajectory

Optimal efficiency Trajectory

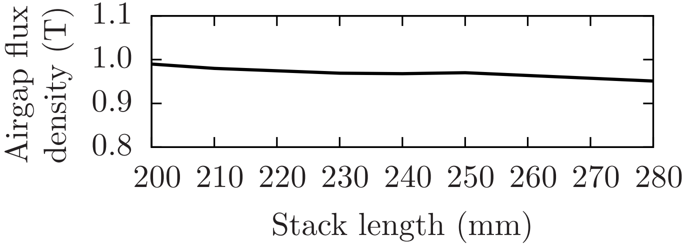


Procedure to search the operating point along the optimal trajectory

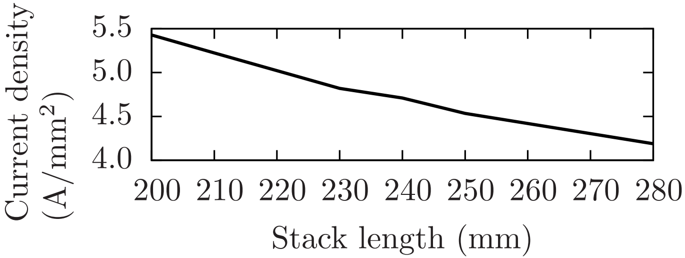
Along the Optimal Efficiency Trajectory

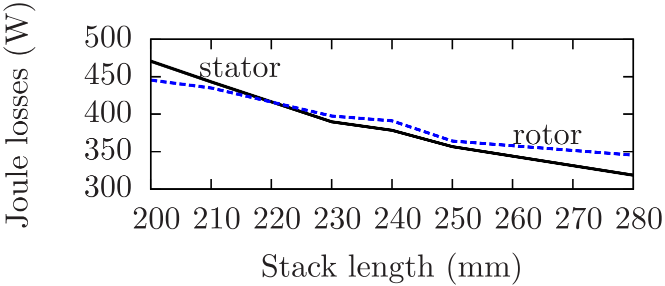


Along the Optimal Efficiency Trajectory

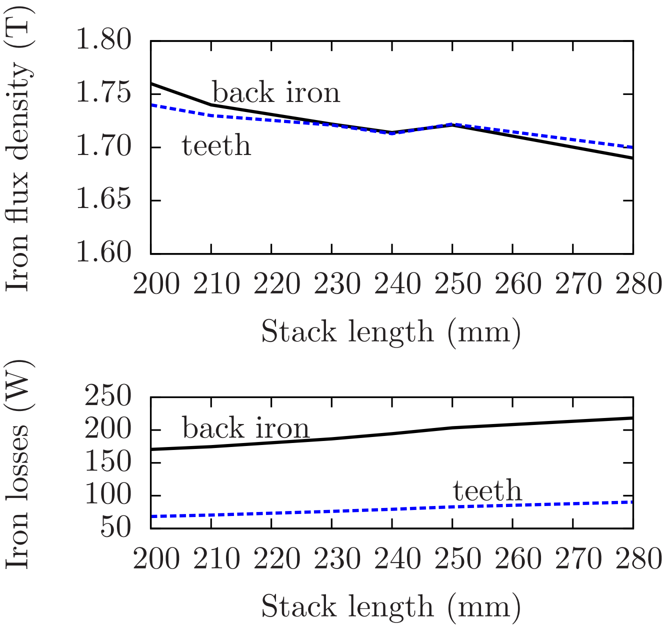


Along the Optimal Efficiency Trajectory



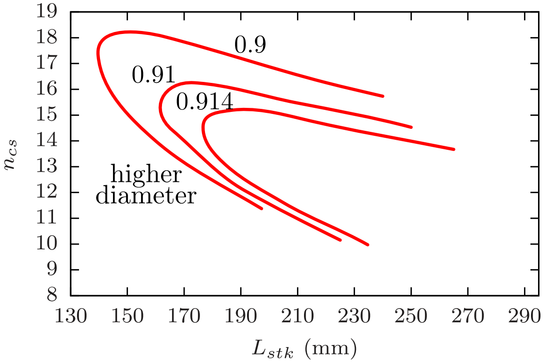


Along the Optimal Efficiency Trajectory



Efficiency map of motor with higher diameter

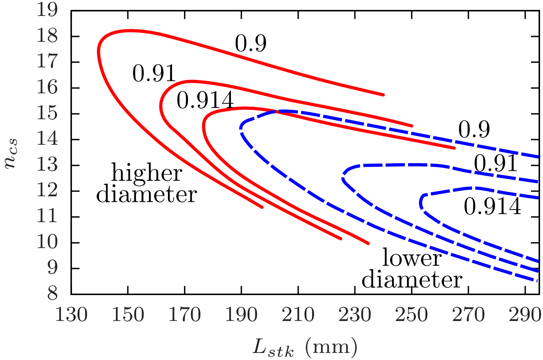
11–kW rated power and 400–V supply voltage



1. The behaviors of electric and magnetic quantities,
2. the behavior of the motor losses

are the same as in the previous case.

11–kW rated power and 400–V supply voltage



Comparing the two solutions allows to determine the convenience of a motor with lower diameter and higher length, or with higher diameter and lower length.

Conclusions (1/3)

- Theoretical developments and experimental validations of a design approach to increase the induction motor **efficiency class** are reported.

- The increase of axial core length is investigated as an effective no–tool–cost solution.

- The proper increase of the motor axial length is found using a procedure based on a **combined analytical–FE computation**.

Conclusions (2/3)

- A motor **prototype** has been built and tested to prove the validity of the proposed design approach.
- The satisfactory **agreement** is found between computed and measured motor efficiency, in a large load torque range.
- This confirms the **robustness** of the procedure and allows it to be used in an **optimization** process.

Conclusions (3/3)

- The **efficiency map** is built adopting the stack length and the number of turns per slot as main variable.
- The **optimal efficiency trajectory** is defined.
- The **behaviour of the design variables** (magnetic and electric loading) is shown along this trajectory.
- Various geometries are compared.
- The proposed design approach is suitable to "move" standard efficiency motors in **upper efficiency classes**.

Related Papers by the Authors

- A. Boglietti, A. Cavagnino, L. Ferraris, M. Lazzari, G. Luparia,
  "No Tooling Cost Process for Induction Motors Energy Efficiency Improvements", Transaction on Industry Applications, Vol.41, No.3, May/June 2005, pp.808-816.
- L. Alberti, N. Bianchi, S. Bolognani, "A Very Rapid Prediction of IM Performance Combining Analytical and Finite-Element Analysis",
  IEEE Transactions on Industry Applications, Vol.44, No.5, September/October 2008, pp.1505-1512.

Related Papers by the Authors (cont.)

- A.Boglietti, A.Cavagnino, M.Lazzari, M.Pastorelli,
  "International standards for the Induction Motor Efficiency Evaluation: A Critical Analysis of the Stray-Load Loss Determination", IEEE Trans. on Industry Applications, Vol.40, No.5, September/October 2004, pp.1294–1301.
- L. Alberti,
  "A Modern Analysis Approach of Induction Motor for Variable Speed Application", supervisor Prof. N. Bianchi, University of Padova, 2009, http://paduaresearch.cab.unipd.it/1685/
- L. Alberti, N. Bianchi and S. Bolognani,
  "Lamination Design of a Set of Induction Motors", Journal of Electrical Engineering: Theory and Application, issn 1737-9350, pp. 18-23, vol. 1, 2010.

Related Papers by the Authors (cont.)

- A. Boglietti, A. Cavagnino, M. Lazzari, M. Pastorelli, "International standards for the Induction Motor Efficiency Evaluation: A Critical Analysis of the Stay-Load Loss Determination", IEEE Transaction on Industry Applications, Vol.4, No.5, September/October 2004, pp.1294-1301.

Thank you!