2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)

Scaling Laws for Synchronous Permanent Magnet Machines

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***Abstract*—This paper defines the scaling laws for synchronous permanent magnet machines which include three separate procedures: rewinding, axial scaling, radial scaling. The derivation of scaling relations is based on the requirement that the magnetic fields in the scaled model should be the exact images of the fields in the referent model. The exact equations for the various parameters (torque, power, losses, mass, resistance, inductance) of the machine are derived using the three scaling factors, one for each scaling procedure. The equations are numerically validated using the state-of-the-art finite-element software.**

***Index Terms*—synchronous machine with permanent magnets, optimization, scaling laws, similitude laws, series of motors**

I. Introduction

Scaling (or similitude) laws are rather popular in physics and engineering and are often used in numerous examples, e.g. thermodynamic correlations, small-scale/large-scale models, fractals etc. They are used to predict the performance of a new design based on data from an existing, similar design. In the electromagnetics, new design and similar design will have the similar geometry, but in general not the same materials and electromagnetic excitation (both in terms of amplitude and time scale).

Hsieh and Kim [1] presented a detailed derivation of scaling laws for an electromechanical system using the electromagnetic diffusion equation, thermal diffusion equation, momentum equation and kinematic equation along with numerical validation on $\sqrt{2}$ times smaller electromagnetic launcher. Wood [2] was dealing with the general scaling laws for electromagnetical systems motivated by the thermal stability of the magnetic recording systems. From the Landau-Lifshitz-Gilbert equation he concluded that for non-linear ferromagnetic systems there are two independent scaling factors (λ for length, and τ for time). If the time is not scaled, there is only one scaling factor. Kofler *et. al.* [3] explored magnetic field in the end-winding space of a superconducting synchronous machine reduced by scaling laws from [4]. These laws are basically identical to the ones derived in [2].

Bone [5], [6] determined basic scaling laws for induction machines. These laws are not exact as the ones derived in this paper because the field solutions are changed but are very valuable as a tool for machine designer. Binns and Shimmin [7] tried to determine the basic scaling laws for the permanent magnet (PM) machines. Their scaling laws are based on keeping the current density equal for the radially scaled machine which does not keep the same field solution. Gu and Stiebler [8] dealt with the scaling laws for switched-reluctance machines. Their work was expanded in this paper and applied to PM machines to include the three separate scaling procedures.

The axial scaling (core lengthening) is a known NTC (no tool cost) procedure for the induction machines [9], [10] which can be applied also for PM machines, but has a technological limit in terms of stack length. Therefore radial scaling (using the larger frame size) can be utilized in order to achieve larger torque ratings when maximum allowed stack length is reached.

The main contribution of this paper is a comprehensive definition of scaling laws for PM machines which includes rewinding, axial scaling and radial scaling that preserves saturation levels in the original and scaled machine and allows quick and accurate calculation of parameters of the scaled machine.

978-1-4673-6785-1/15/$31.00

II. Motivation

The research related to the scaling laws for PM machines was started in order to explore the ability to design the optimal series (set) of the machines by optimizing only one design, so called *referent design*. All of the *particular machines* in the series are considered *scaled designs* (scaled from the referent design) and they are calculated by using the scaling laws. They have equal or similar lamination cross-section, the same voltage rating but different torque/power rating.

The three scaling procedures are: rewinding, axial scaling (lengthening or shortening) and radial scaling (increase or reduction in diameter). By using these three procedures it is possible to scale any PM machine to have different length, radial size or rated voltage and quickly calculate its parameters and characteristics (e.g. efficiency map). It is also possible to determine the size, the winding features and the characteristics of the similar machine with prescribed value of torque (power, efficiency etc.).

The derivation of scaling relations is based on the requirement that the magnetic fields in the scaled model should be the exact images of the fields in the referent model (magnetic flux density is unchanged in all active parts after the scaling procedure). This is the main characteristic of all scaling laws derived in this paper. The geometry of the scaled model is similar to the one in the referent model (equal also means similar), all the materials and the technology (winding type, slot-fill factor) utilized are the same and the machines operate at the same temperature. The mechanical losses (friction and windage) and 3D effects in magnet losses are neglected but can be also scaled according to the principles mentioned below. In the following text, index 0 denotes that the quantity is referring to the referent machine or otherwise it is referring to the scaled machine.

III. Rewinding

Rewinding is a well known procedure related to electrical machines and normally is used to adapt the winding of the machine to the voltage (or current) rating of the power supply system. It in fact means a change of the numbers of turns per coil (N_c) and the number of parallel paths (a_p) of the referent machine in the same ratio while keeping the cross-section geometry, stack length and slot current density unchanged. The equations are derived for a three-phase two-layer winding but are also valid for any winding type.

The referent machine will generally have N_{c0} turns per coil and a_{p0} parallel paths. The peak value of the rated phase current for the referent machine can be written as

$$I_0 = \sqrt{I_{d0}^2 + I_{q0}^2} = \sqrt{2}\frac{a_{p0}}{N_{c0}} J_0 \frac{A_{slot0}}{2} k_{Cu0}, \qquad (1)$$

where J_0 is the winding current density, A_{slot0} is the slot cross-section area, k_{Cu0} is the slot fill factor of the referent machine.

The rewound (scaled) machine will generally have N_c turns per coil and a_p parallel paths. Its rated phase current can be expressed as

$$I = \sqrt{I_d^2 + I_q^2} = \sqrt{2}\frac{a_p}{N_c} J \frac{A_{slot}}{2} k_{Cu}, \qquad (2)$$

With regard to the initial assumptions ($J = J_0$, $A_{slot} = A_{slot0}$, $k_{Cu} = k_{Cu0}$) one can write

$$I = \frac{a_p}{N_c}\frac{N_{c0}}{a_{p0}} I_0 = \frac{1}{k_W} I_0. \qquad (3)$$

where k_W is the rewinding factor.

All the following equations are derived for the specific case of the referent machine with 1 turn per coil ($N_{c0} = 1$) and no parallel paths ($a_{p0} = 1$) in order to reduce the size of the equations. The winding scaling factor is therefore

$$k_W = \frac{N_c}{a_p}. \qquad (4)$$

There is no loss of the generality because the ratio of the N_c and a_p is of the key importance. If the current density in the slot is unchanged, the magnetic field solutions are unchanged which is evident from the Poisson's equation

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right) = -J_z. \qquad (5)$$

It is known that the rewound machine will have a different flux linkage than the referent machine

$$\Psi = \frac{N_c}{a_p}\Psi_0 = k_W \Psi_0, \qquad (6)$$

but the magnetomotive force (MMF) of the stator winding and the magnets will not change.

The electromagnetic torque will not change as one can see from

$$T_{em} = \frac{3}{2}p|\Psi \times I| = \frac{3}{2}p|k_W \Psi_0 \times \frac{I_0}{k_W}| = T_{em0}. \qquad (7)$$

The phase winding of the scaled machine will have N_c/a_p, i.e. k_W times more turns connected in series, but will be made of a_p parallel paths. The cross-section area of one turn will be N_c times smaller. The resistance of the phase winding is therefore

$$R = \frac{1}{a_p}\rho\frac{l_t\dfrac{Q_s}{3}k_W}{\dfrac{1}{2}A_{slot}\dfrac{1}{N_c}k_{Cu}} = k_W^2\rho\frac{l_t\dfrac{Q_s}{3}}{\dfrac{1}{2}A_{slot0}k_{Cu}} = k_W^2 R_0 \tag{8}$$

where l_t is the mean turn length, Q_s is the number of stator slots, and ρ is the resistivity of the stator winding material.

For example, q-axis inductance can be expressed as

$$L_q = \frac{\Psi_q}{I_q} = \frac{k_W\Psi_q}{\dfrac{1}{k_W}I_q} = k_W^2 L_q. \tag{9}$$

The rewinding procedure can be independent of any other scaling procedures but in this paper it is not separable from the axial and radial scaling because the scaled machine must have prescribed voltage rating. Rewinding can be of high importance when determining the optimal winding parameters for a traction drive with prescribed drive cycle [11]–[13].

IV. Axial Scaling

Axial scaling means in fact the variation of the axial core length in by keeping the lamination cross-section preserved. It is considered that the axial length of the stator stack, the rotor stack and the magnets is changed in the same ratio. The stack length of the scaled machine l_{Fe} is determined from

$$l_{Fe} = k_A l_{Fe0}, \tag{10}$$

where k_A is the axial scaling factor and l_{Fe0} is the referent machine stack length. Axially scaled machine is also rewound so it has a certain number of turns per coil and parallel paths generally different from 1 and chosen to satisfy the prescribed voltage rating.

The slot current density must be preserved in the axial scaling procedure so that magnetic field solutions would stay unchanged. The change of the axial length does not affect the $2D$ solutions but affects magnetic flux, voltage, torque, losses, resistance and inductance. The phase current is therefore only influenced by rewinding

$$I = \frac{1}{k_W}I_0. \tag{11}$$

Stator and rotor MMF remain unchanged with the combined axial scaling and rewinding which additionally confirms that the saturation in all active parts of the scaled machine will be the same as in the referent machine. This is also evident from the Poisson's equation (5).

The end-winding arrangement and shape is determined only by the lamination cross-section and not by the stack length. There is a technological influence of the number of turns per coil and parallel paths, but it can be neglected in this analysis. It means that all the machines of the same cross section will have equal end-winding. Only one part of the scaled machine's flux linkage is affected by the change of the stack length - it is the core part, the one with index co. The end-winding part, with index ew remains unchanged. For example, the d-axis stator flux linkage can be written as

$$\Psi_d = \Psi_{dco} + \Psi_{dew} = k_W k_A \Psi_{d0co} + k_W \Psi_{0ew}. \tag{12}$$

The q-axis inductance is given by:

$$\begin{aligned} L_q &= \frac{1}{a_p}\frac{\Psi_q}{\dfrac{1}{a_p}I_q} = \frac{k_W k_A \Psi_{q0co} + k_W \Psi_{q0ew}}{\dfrac{1}{k_W}I_{q0}} \\ &= k_W^2 k_A L_{q0co} + k_W^2 L_{0ew}. \end{aligned} \tag{13}$$

The phase resistance of axially scaled machine can be calculated as

$$\begin{aligned} R &= \frac{1}{a_p}\rho\frac{(l_{co}+l_{ew})\dfrac{Q_s}{3}k_W}{\dfrac{1}{2}A_{slot0}k_{Cu0}\dfrac{1}{N_c}} \\ &= k_W^2\rho\frac{\dfrac{Q_s}{3}k_A l_{co0}}{\dfrac{1}{2}A_{slot0}k_{Cu0}} + k_W^2\rho\frac{\dfrac{Q_s}{3}l_{ew0}}{\dfrac{1}{2}A_{slot0}k_{Cu0}} \\ &= k_W^2 k_A R_{0co} + k_W^2 R_{0ew}, \end{aligned} \tag{14}$$

where l_{co} is the core part and l_{ew0} is the end-winding part of the mean turn length l_t.

The end-winding does not take active part in the torque generation therefore the electromagnetic torque of the axially scaled machine is proportional only to the change of the stack length,

$$\begin{aligned} T_{em} &= \frac{3}{2}p\Big[k_W k_A \Psi_{md0}\frac{1}{k_W}I_{q0} - k_W k_A \Psi_{mq0}\frac{1}{k_W}I_{d0} + \\ &+ k_W^2 k_A\left(L_{d0}-L_{q0}\right)\frac{1}{k_W^2}I_{q0}I_{d0} + k_W^2 k_A L_{dq0}\frac{1}{k_W^2}\left(I_{q0}^2 - I_{d0}^2\right)\Big] \\ &= \frac{3}{2}p\Big[k_A\Psi_{md0}I_{q0} - k_A\Psi_{mq0}I_{d0} + k_A\left(L_{d0}-L_{q0}\right)I_{q0}I_{d0} + \\ &+ k_A L_{dq0}\left(I_{q0}^2 - I_{d0}^2\right)\Big] = k_A T_{em0}. \end{aligned} \tag{15}$$

More detailed derivation of all the similar expression for the axial scaling can be found in [14].

V. Radial Scaling

Radial scaling considers proportional change of all dimensions of the cross-section. It is important to determine under which conditions the magnetic flux densities of the scaled machine are preserved. The Poisson's equation for the referent machine is

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right)=-J_z, \tag{16}$$

and for the scaled machine

$$\frac{\partial}{\partial x'}\left(\frac{1}{\mu'}\frac{\partial A'_z}{\partial x'}\right)+\frac{\partial}{\partial y'}\left(\frac{1}{\mu'}\frac{\partial A'_z}{\partial y'}\right)=-J'_z. \tag{17}$$

Let x and y dimensions be scaled by factor of k_R, and slot current density scaled by factor k_J. The terms in the parentheses must be equal for both the scaled and the referent machine in order to preserve the exact same saturation, i.e. the value of μ:

$$\frac{1}{k_R}\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)+\frac{1}{k_R}\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right)=-k_J J_z \tag{18}$$

This is accomplished if

$$k_J=\frac{1}{k_R}. \tag{19}$$

It is again necessary to rewind the scaled machine in order to satisfy the voltage rating so these two procedures are performed one after another. All the areas of the cross-section are scaled by factor k_R^2 so the phase current (after rewinding) must be scaled by factor k_R/k_W

$$I=\sqrt{2}\frac{1}{k_W}\frac{1}{k_R}J_0k_R^2\frac{A_{slot0}}{2}k_{Cu0}=\frac{k_R}{k_W}I_0 \tag{20}$$

Flux linkage related to the active part (i.e. core) is proportional to factor k_R due to the increase of the stator bore circumference by the factor k_R while the stack length remains unchanged. Flux linked by the end-windings is proportional to k_R^2 due to the increase of both circumference and end-winding axial length. After rewinding, the d-axis stator flux linkage can be written as

$$\Psi_d=\Psi_{dco}+\Psi_{dew}=k_Wk_R\Psi_{d0co}+k_Wk_R^2\Psi_{0ew}, \tag{21}$$

and the q-axis inductance as

$$L_q=\frac{\Psi_q}{I_q}=\frac{k_Wk_R\Psi_{q0co}+k_Wk_R^2\Psi_{q0ew}}{\frac{k_R}{k_W}I_{q0}}=k_W^2L_{q0co}+k_W^2k_RL_{0ew}. \tag{22}$$

The phase resistance of radially scaled machine can be calculated as

$$\begin{aligned}R&=\frac{1}{a_p}\rho\frac{(l_{co}+k_Rl_{ew0})\frac{Q_s}{3}k_W}{\frac{1}{2}k_R^2A_{slot0}k_{Cu0}\frac{1}{N_c}}\\&=k_W^2\rho\frac{\frac{Q_s}{3}l_{co}}{\frac{1}{2}k_R^2A_{slot0}k_{Cu0}}+k_W^2\rho\frac{\frac{Q_s}{3}k_Rl_{ew0}}{\frac{1}{2}k_R^2A_{slot0}k_{Cu0}}\\&=\frac{k_W^2}{k_R^2}R_{0co}+\frac{k_W^2}{k_R}R_{0ew}.\end{aligned} \tag{23}$$

The rewinding does not affect the produced electromagnetic torque, but due to change of the rotor volume with radial scaling the torque is changed by the factor k_R^2

$$\begin{aligned}T_{em}=&\frac{3}{2}p\Big[k_Wk_R\Psi_{md0}\frac{k_R}{k_W}I_{q0}-k_Wk_R\Psi_{mq0}\frac{k_R}{k_W}I_{d0}+\\&+k_W^2\left(L_{d0}-L_{q0}\right)\frac{k_R^2}{k_W^2}I_{q0}I_{d0}+k_W^2L_{dq0}\frac{k_R^2}{k_W^2}\left(I_{q0}^2-I_{d0}^2\right)\Big]\\=&\frac{3}{2}p\Big[k_R^2\Psi_{md0}I_{q0}-k_R^2\Psi_{mq0}I_{d0}+k_R^2\left(L_{d0}-L_{q0}\right)I_{q0}I_{d0}\\&+k_R^2L_{dq0}\left(I_{q0}^2-I_{d0}^2\right)\Big]=k_R^2T_{em0}\end{aligned} \tag{24}$$

VI. General Scaling Laws

It is possible to derive the generalized scaling laws using the aforementioned principles. They include rewinding, axial scaling and radial scaling without consideration of the order of performing these actions because, in the way they are presented, they are independent of each other. Three key parameters that will change the frame size, the stack length and the rated voltage are k_R, k_A and k_W respectively. If the referent machine is excited with the current I_0 and has all the right-hand side parameters indexed with 0 in (26) to (48), then the scaled machine will have all the left-hand side parameters listed in (26) to (48) if excited with current according to (25).

$$I=\frac{k_R}{k_W}I_0 \tag{25}$$

$$\Psi_d=k_Wk_Rk_A\Psi_{d0co}+k_Wk_R^2\Psi_{0ew} \tag{26}$$

$$\Psi_q=k_Wk_Rk_A\Psi_{q0co}+k_Wk_R^2\Psi_{0ew} \tag{27}$$

$$\Psi_{mag,d}=k_Wk_Rk_A\Psi_{mag,d0co} \tag{28}$$

$$\Psi_{mag,q}=k_Wk_Rk_A\Psi_{mag,q0co} \tag{29}$$

$$T_{em}=k_R^2k_AT_{em0} \tag{30}$$

$$T_{shaft}=k_R^2k_AT_{shaft0} \tag{31}$$

$$V_d = k_W\left\{ \left(\frac{k_A}{k_R}R_{0co} + R_{0ew}\right) I_{d0} - k_R k_A \omega_0 \Psi_{magq0} - \omega_0 \left[\left(k_R k_A L_{q0co} + k_R^2 L_{q0ew}\right) I_{q0} + k_R k_A L_{qd0} I_{d0}\right] \right\}, \tag{32}$$

$$V_q = k_W\left\{ \left(\frac{k_A}{k_R}R_{0co} + R_{0ew}\right) I_{q0} + k_R k_A \omega_0 \Psi_{magd0} + \omega_0 \left[\left(k_R k_A L_{d0co} + k_R^2 L_{d0ew}\right) I_{d0} + k_R k_A L_{dq0} I_{q0}\right] \right\}, \tag{33}$$

$$V = \sqrt{V_d^2 + V_q^2} \tag{34}$$

$$P_{shaft} = k_R^2 k_A P_{shaft0} \tag{35}$$

$$P_{in} = k_R^2 k_A \left(P_{em0} + \frac{1}{k_R^2} P_{Cu0co} + \frac{1}{k_R k_A} P_{Cu0ew}\right) \tag{36}$$

$$P_{Cu} = k_A P_{Cu0co} + k_R P_{Cu0ew} \tag{37}$$

$$P_{Fe} = k_R^2 k_A P_{Fe0} \tag{38}$$

$$P_{mag} = k_R^2 k_A P_{Fe0} \tag{39}$$

$$\eta = \frac{P_{shaft0}}{P_{em0} + \frac{1}{k_R^2} P_{Cu0co} + \frac{1}{k_R k_A} P_{Cu0ew}} \tag{40}$$

$$cos\varphi = \frac{V_d I_d + V_q I_q}{VI} \tag{41}$$

$$L_d = k_W^2 k_A L_{d0co} + k_W^2 k_R L_{d0ew} \tag{42}$$

$$L_q = k_W^2 k_A L_{q0co} + k_W^2 k_R L_{q0ew} \tag{43}$$

$$L_{dq} = L_{qd} = k_W^2 k_A L_{dq0co} = k_W^2 k_A L_{qd0co} \tag{44}$$

$$R = \frac{k_W^2}{k_R^2} k_A R_{0co} + \frac{k_W^2}{k_R} R_{0ew} \tag{45}$$

$$m_{Cu} = k_R^2 k_A m_{Cu0co} + k_R m_{Cu0ew} \tag{46}$$

$$m_{Fe} = k_R^2 k_A m_{Fe0} \tag{47}$$

$$m_{mag} = k_R^2 k_A m_{m0} \tag{48}$$

These purely analytical scaling laws can be used to obtain the parameters of the scaled machine without the need to recalculate all the parameters with the method (e.g. analytical or numerical) that was used to calculate the parameters of the referent machine. This is very useful if calculation of the parameters for the referent machine uses a numerical method (e.g. FEA) which is very common for the synchronous permanent magnet machines. The benefit is obvious if the scaling calculation is performed inside an optimization routine where thousands of designs are checked in one study.

VII. Example

In order to show the correctness of the derived expressions one can use any FEA software package with the post-processing procedure to extract the parameters or even specialized analytical+FEA packages such as SPEED PC-BDC+PC-FEA, MotorCAD Emag. As an example, the referent 1 kW IPM machine (12s4p) was created and calculated using PC-BDC software (analytical+embedded FEA analysis using PC-FEA).The results are shown in the 2nd column (original) in table I and on Fig. 1.

In order to create similar 2 kW machine, the geometry was scaled using the factors $k_R = 1.2$, $k_A = 1.4$, the machine was rewound for the original voltage of 24 V with $k_W = 0.5965$ and recalculated in the same software package (results in the 3rd column and on Fig. 2). The results in the 4th (SL = scaling laws) column are obtained using the scaling laws derived in this paper and the parameters of the referent 1 kW machine. The percentage difference between the recalculated parameters and the scaled parameters is negligible, yet the scaling procedure takes significantly less computational time (it is purely analytical).

VIII. Conclusion

Generalized scaling laws for PM machines using three scaling factors are presented and numerically verified. Utilization of the scaling laws for PM machines leads to significant time savings when optimized design of a series of machines is performed. While calculating the parameters for every candidate (referent machine) in the optimization procedure, one can very quickly calculate all the parameters for all the machines in the series (axially and/or radially scaled machines). It is then easy to calculate the optimization cost function e.g. the total cost of the material for the series of motors or the inequality constraint e.g. the minimum efficiency of each machine in the series.

TABLE I

IPM, 1 kW SCALED TO 2 kW, 1000 min^{-1}, 24 V, RATED LOAD

	FEA 1 kW	FEA 2 kW	SL 2 kW	% diff.
N_c	19	17	17	0,0
a_p	2	3	3	0,0
OD, mm	530	636	636	0,0
l_{stk}, mm	120	168	168	0,0
l_t, mm	419	551	551	0,0
l_{co}, mm	240	336	336	0,0
l_{ew}, mm	179	215	215	0,0
A_{slot}, mm^2	626	902	902	0,0
J, A/mm^2	2,9	2,4	2,4	0,0
I, A	37,6	75,7	75,7	0,0
T_{shaft}, N m	9,6	19,3	19,3	0,0
T_{em}, N m	9,6	19,4	19,4	0,0
P_{shaft}, W	1005	2025	2025	0,0
P_{in}, W	1097	2148	2148	0,0
P_{Cu}, W	90,2	118,6	118,6	0,0
P_{Fe}, W	2,0	4,1	4,1	0,0
η, %	91,59	94,29	94,29	0,0
V_{ph}, V	13,8	13,7	13,7	0,2
V_{LL}, V	24,0	23,7	23,7	0,2
$\cos\varphi$	0,70	0,69	0,69	0,1
L_d, mH	0,62	0,31	0,31	0,6
L_q, mH	1,90	0,95	0,95	0,2
L_{ew}, µH	23,5	10,0	10,0	0,0
R_{ph}, mΩ	21,23	6,90	6,90	0,0
m_{Cu}, kg	5,6	10,6	10,6	0,0
m_{Fe}, kg	17,3	35,0	35,0	0,0
m_{mag}, kg	1,1	2,2	2,2	0,0
$B_{gap,Load}$, T	0,18	0,18	0,18	0,0
$B_{mag,Load}$, T	0,17	0,16	0,16	0,3

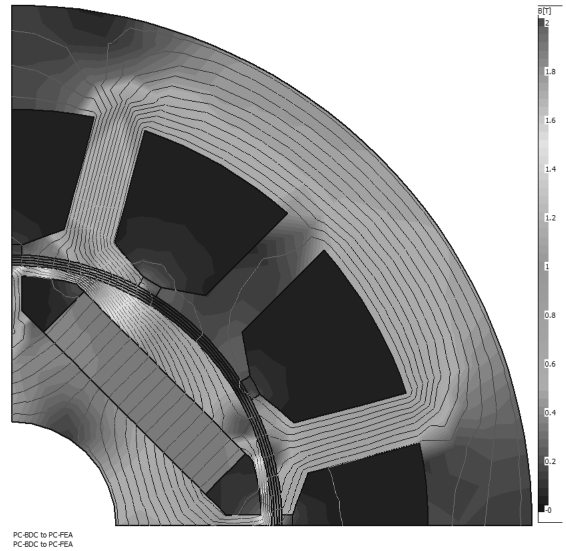

Fig. 1. 2D finite element field solution at rated load point for 12s4p IPM, referent design

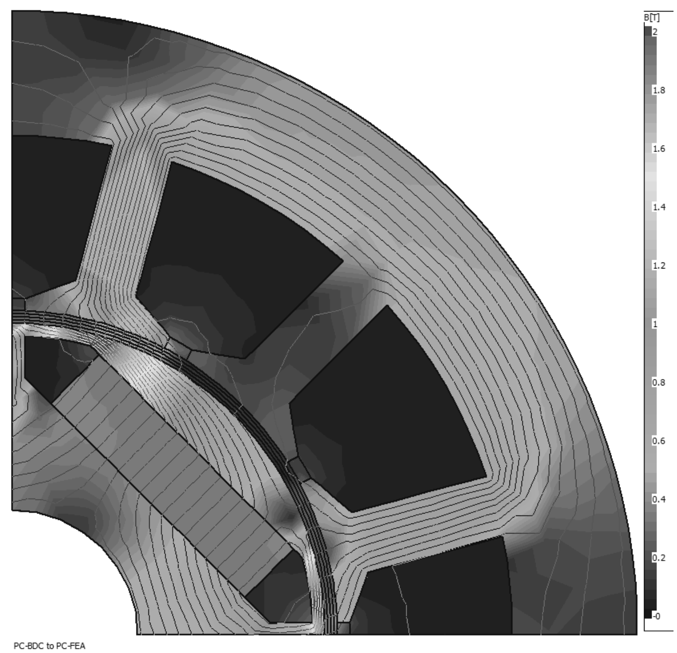

Fig. 2. 2D finite element field solution at rated load point for 12s4p IPM, scaled design

ACKNOWLEDGMENT

This paper is part of the ADvanced Electric Powertrain Technology (ADEPT) project which is an EU funded Marie Curie ITN project, grant number 607361. Within ADEPT a virtual and hardware tool are created to assist the design and analysis of future electric propulsions. Especially within the context of the paradigm shift from fuel powered combustion engines to alternative energy sources (e.g. fuel cells, solar cells, and batteries) in vehicles like motorbikes, cars, trucks, boats, planes. The design of these high performance, low cost and clean propulsion systems has stipulated an international cooperation of multiple disciplines such as physics, mathematics, electrical engineering, mechanical engineering and specialisms like control engineering and safety. By cooperation of these disciplines in a structured way, the ADEPT program provides a virtual research lab community from labs of European universities and industries [15]. Stjepan Stipetic is currently Marie Curie PostDoc Fellow at Motor Engineer s.a.r.l, Biviers, France.

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