TESTCASE: a benchmark problem for coupled field-circuit simulations

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Abstract

Purpose – The purpose of this paper is to present an experimental setup for the verification of coupled electromagnetic field-circuit simulation, called TESTCASE. By means of simple and well-defined geometries, the comparison of different coupling approaches among each other and with measurements should be possible.

Design/methodology/approach – The physical setup consists of a C-core in conjunction with a reluctance rotor. The TESTCASE is designed to work in static operation and with motion induced voltage.

Findings – Simulation results using different approaches as well as measurement results are presented. Practical issues in measurement and simulation are discussed. It was found that particular care has to be taken concerning the modeling the air around the TESTCASE structure.

Originality/value – With the proposed approach, it is possible to evaluate the coupled field circuit problem on a defined and well-known geometry. Simulation results can be compared to measurements.

Keywords Electromagnetism, Circuits, Simulation, Electric machines

Paper type Research paper

1. Introduction

The design of electrical drives or switch-mode power supplies increasingly focus on the interaction between magnetic components and electrical circuitry. The magnetic behavior is governed by Maxwell's equations, whereas the electric circuit is governed by Kirchhoff's laws and the current/voltage characteristics of individual lumped components.

To evaluate the effects of circuit-FE model interactions, it is necessary to solve the physically coupled problem. This can be done by numerically weak- or strong-coupled simulations. If circuit equations are written together with FE equations in a large system of equations, the procedure is considered numerically strong coupled (Lombard and Meunier, 1992; Dreher and Meunier, 1995). If both systems are solved separately, possibly with different packages, the procedure is considered numerically weak coupled (Kanerva *et al.*, 2005; Lange *et al.*, 2008).

The coupled simulations are often applied in the area of electrical machinery, in conjunction with power electronic converters. A good example for this may be a brushless DC motor drive, a switched reluctance machine or a claw pole alternator.

Most applications of coupled circuit-FE models are however presented in the literature in the context of analysis of real-life devices (Canova *et al.*, 1999; Lai *et al.*, 1997; Zhou *et al.*, 2006). This, however, has two significant drawbacks: first, the geometries are then, in general rather complex, which makes it hard to exclude inaccuracies in modeling the structure. Second, most authors do not publish all details of the model, and therefore no independent comparison and benchmarking of the individual approaches is possible. On the other hand, existing benchmark problems in

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electromagnetic field computation, such as the series of TEAM workshops by the International Compumag Society (2008), do not address field-circuit interaction.

The TESTCASE proposed in this paper tries to overcome these drawbacks. A simple geometry of the magnetic circuit is chosen and all dimensions are given.

2. Proposal of TESTCASE

2.1 Requirements

One requirement for the design of the TESTCASE is a well-defined problem, consisting of a simple geometry, an excitation and the properties of the material involved.

The TESTCASE is intended to serve two purposes: first, to compare different numerical approaches on a standardized problem; and second, to compare the numerical results with measurements so as to obtain a quantitative statement about the overall accuracy of the modeling and simulation procedure.

To compare the ability of the different numerical approaches to cope with non-linearities, the considered magnetic materials are to be chosen with a non-linear BH-characteristic.

The designed TESTCASE should show significant interaction between the electromagnetic field and the circuitry, even without power electronic switches involved. Additionally, switches should be added in a future development in order to evaluate the distinct influence of these devices.

A model with only a few degrees-of-freedom easily allows for solving the field and circuit problem individually by a state-space approach.

Finally, within the analysis of the TESTCASE, it should be possible to separate the aspects of standstill operation, i.e. induced voltage by variation of currents and operation with motion induced voltages.

2.2 Concept

The basic concept consists of a ferromagnetic core with a rotating segment that can act as the rotor of an unipolar reluctance generator. The geometry of the developed TESTCASE is shown Figure 1. Table I gives the numerical values of its dimensions. Dividing the primary and secondary winding into two partitions each allows for a variety of different connections on the test bench. The winding data are given in Table II.

The core is made of a M250-35 A magnetic steel, BH-characteristic is shown in Figure 2.

The layout of the magnetic circuit and the winding is done according to the standard design procedure of electrical machines (Vogt, 1996).

2.3 Problem definitions

For the static problem, the rotor is locked in aligned position. The series connected primary windings are supplied with a sinusoidal voltage and the secondary windings are left open, or a resistive load is applied. The question is to determine the primary current waveform.

The problem with motion induced voltage is defined by the speed of the rotor (nominal 1,500 min^{-1}), a constant dc excitation on the series connected primary windings (nominal 2,000 Aturns), and the load on the secondary winding, also connected in series. The load condition may either be no-load, resistive load (nominal 30 Ω) or open-circuit.

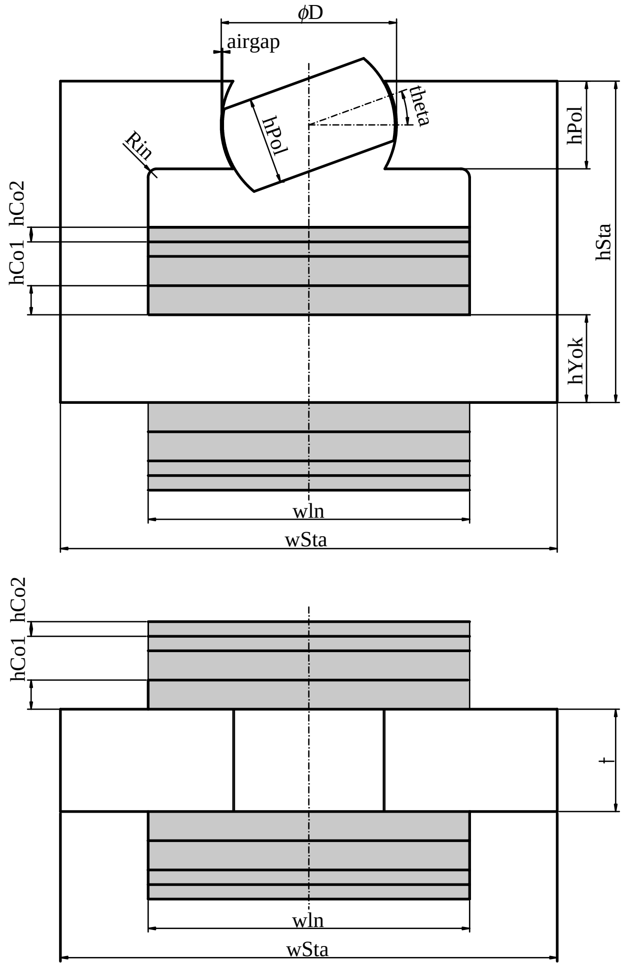

Figure 1.
TESTCASE geometry

3. Results

3.1 Numerical simulation

3.1.1 State-space simulation. The first approach to the studied coupled field-circuit problem is a state-space approach, in which the field and the circuit problem are solved separately by using FE and MATLAB.

The magnetic flux linkage is first computed as a function of rotational angle and current in the secondary winding by a series of static 3D finite element analysis. The excitation due to the primary winding is constant 2,000 Aturns. Figure 3 shows the simulation results. The non-linearity due to the magnetic steel can be seen, as well as a strong dependency of the flux linkage on the rotational angle.

Since flux linkage is monotonously increasing with current, a lookup table $I = f(\Psi, \theta)$, which is used for the state-space simulation, can be derived. The block diagram for simulating the state-space model is shown in Figure 4. As the characteristic

Dimension	Value (mm)
h_{Sta}	110
h_{Pol}	30
h_{Yok}	30
h_{Co1}	10
h_{Co2}	5
Thickness	35
Airgap	0.5
w_{In}	110
w_{Sta}	170
w_{Spa}	2
w_{Yok}	30
D	60
R_{in}	3

Table I. Dimensions of the test-case geometry

Winding	1	2	3	4
Number of turns	106	106	150	150
Diameter of wire (mm)	2.52	2.52	1.60	1.60
Estimated resistance (mΩ)	76.50	76.50	430.50	430.50
Measured resistance (mΩ)	60.47	79.41	373.60	336.90

Table II. Winding data

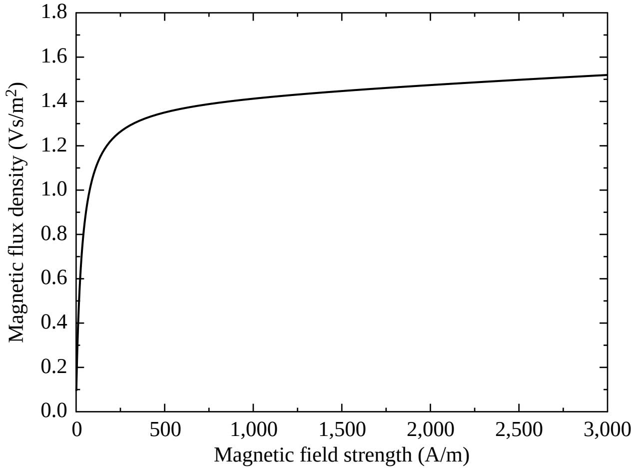

Figure 2. Material characteristic of M250-35 A magnetic steel

of the magnetic circuit is stored in the lookup table the computational effort for a specific experiment is comparatively low, since only the simple non-linear dynamic circuit equation has to be solved. This can be done, e.g. using MATLAB/Simulink. The results of three typical load cases are shown in Figures 5-7.

3.1.2 Numerically strong and weak field-circuit coupled simulation. Next, the TESTCASE is used to compare different coupled numerical approaches.

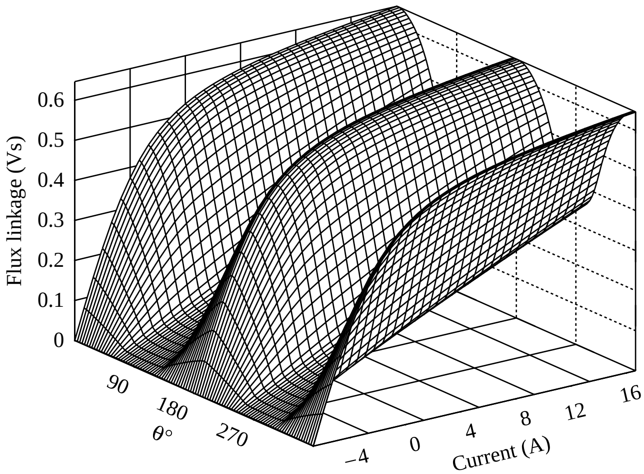

Figure 3.
Flux linkage from static 3D FEM

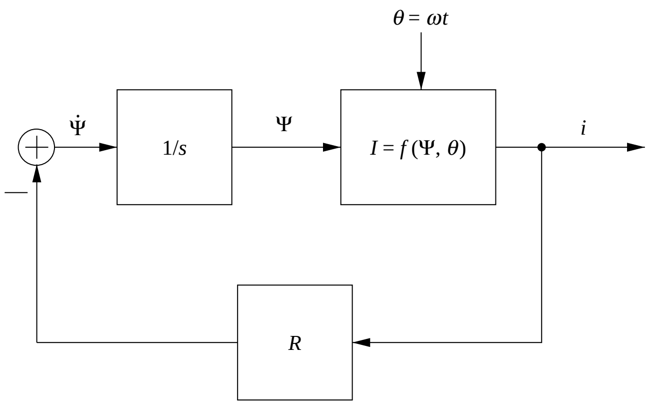

Figure 4.
State-space representation

Figures 8 and 9 show the results of the TESTCASE for a load case of $R = 5\,\Omega$ and a speed of 1,500 min^{-1} with numerically strong- and weak-coupled approaches. The first one is described in Lombard and Meunier (1992), and the latter in Lange *et al.* (2008). For the numerically weak-coupled approach, it is possible to establish the series connection of the secondary winding in the circuit simulation or in the field simulations. A good agreement between the different methods can be observed. The difference in the initial phase of the transient simulation is due to the fact that in the strong-coupled implementation a static computation is done before, of which the result is used for the initial step. In all simulations, the constant dc excitation is given as source current density in the FE model and it is not included in the circuit simulation.

3.2 Experimental realization

In order to compare simulation results with measurements a prototype is constructed and put on a laboratory test bench. The magnetic circuit, stator and rotor, are cut from laminated steel sheets, M250-35 A, using electro-discharge machining.

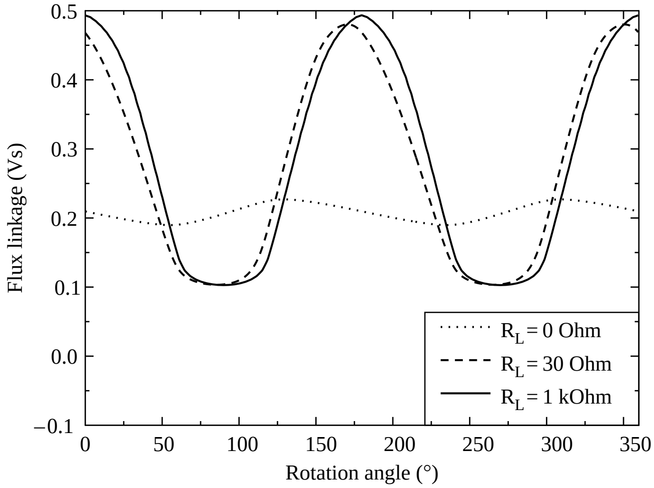

Figure 5.
Results from state-space simulation

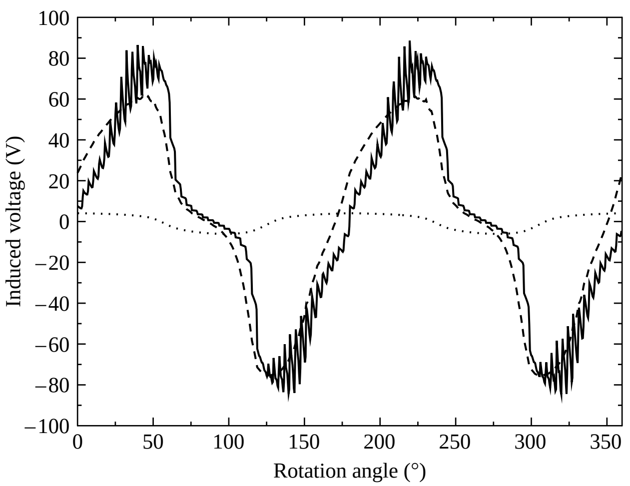

Figure 6.
Results from state-space simulation

The stator consists of three parts: one cuboid and two L-shaped pieces. All four winding layers are wound on a winding body, which is placed on the cuboid. The L-shaped pieces, are positioned and fixed inside an aluminum housing. To withstand the attracting reluctance forces, they are equipped with additional holding pins, which are considered magnetically irrelevant.

The rotor is mounted on a steel shaft, which is made of ferromagnetic steel with a diameter of 15 mm. At one axial position, the shaft has a rectangular cross-section, which can be used for locked rotor tests. As the primary winding is residing on the same stationary yoke, the excitation mmf can be adjusted very accurately and no slip rings are required. The laboratory setup is shown in Figure 10.

On the test bench, the shaft is connected to a driving servo motor via a torque gage[1]. On the other side of the shaft, an encoder with 2,000 slots per revolution is

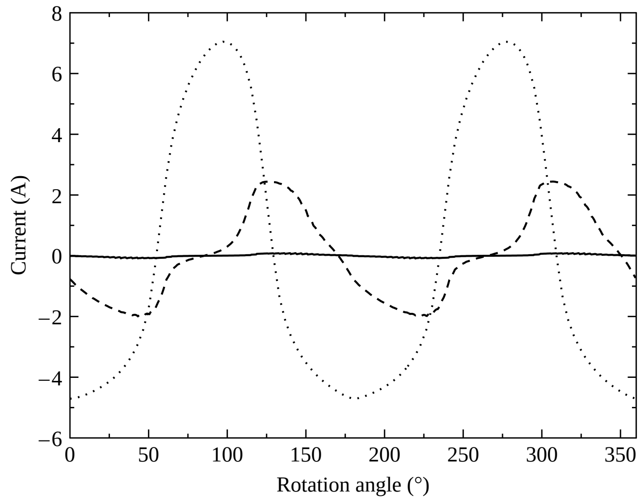

Figure 7.
Results from state-space simulation

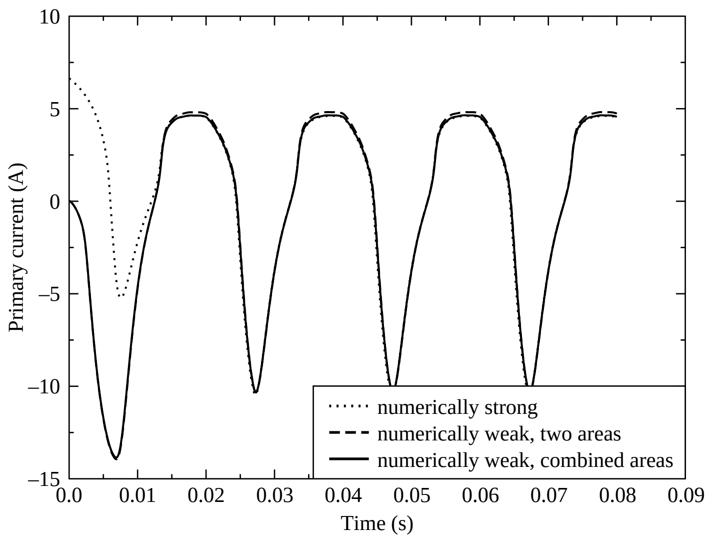

Figure 8.
Comparison of numerically strong- and weak-coupled simulation for $R = 5\,\Omega$

attached to determine rotor position. Currents and voltages are measured and converted analog to digital. All measurements are then captured using a PC and stored in MATLAB.

3.3 Comparison of numerical results and measurements

The first tests are static measurements, in which the TESTCASE is working as a transformer. Figure 11 shows the comparison of primary current waveforms obtained from measurement and from numerically weak-coupled simulation using the approach

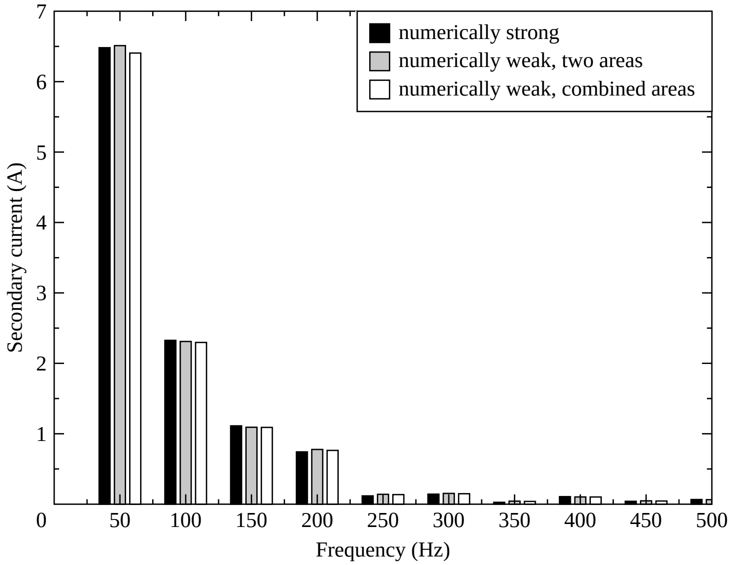

Figure 9.
Spectral comparison of numerically strong- and weak-coupled simulation for $R = 5\,\Omega$

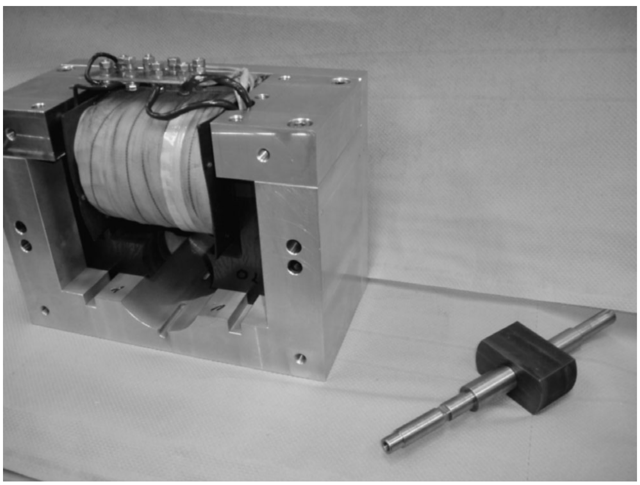

Figure 10.
Laboratory setup

proposed in Lange *et al.* (2008). The applied voltage is 90 V on the primary side, the secondary side is open circuit. The spectral comparison of the primary current is shown in Figure 12, where significant harmonics due to saturation can be observed. The results show a good correlation between measurement and simulation. Using a $30\,\Omega$ resistive load, a second measurement is performed using the same primary voltage as excitation. The results are shown in Figures 11 and 12 as well. This experiment also shows a good correlation with simulation results.

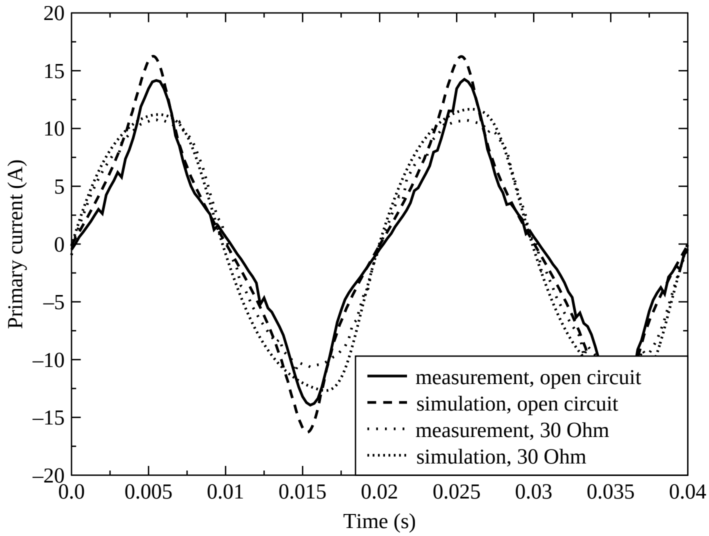

Figure 11.
Comparison of waveform from measurement and simulation

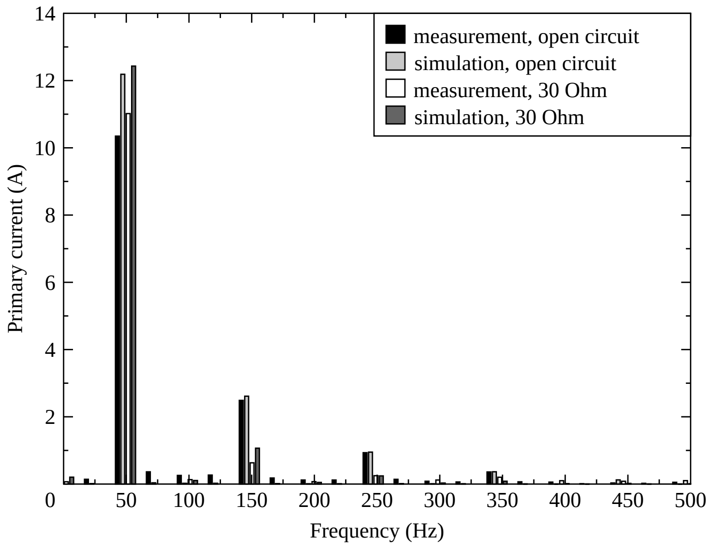

Figure 12.
Spectral comparison of measurement and simulation

As the TESTCASE is designed to also validate motion induced voltages, the rotor is driven at a constant speed of 1,500 $\min^{-1}$ and a constant direct current of 10 A is supplied to the primary winding. The comparison between measurements and results from different simulation is shown in Figures 13 and 14. All simulations lead to approximately the same results. A rather poor agreement, with up to 40 percent of relative error, can be noticed with respect to measurements. The reason for that is investigated in the next section.

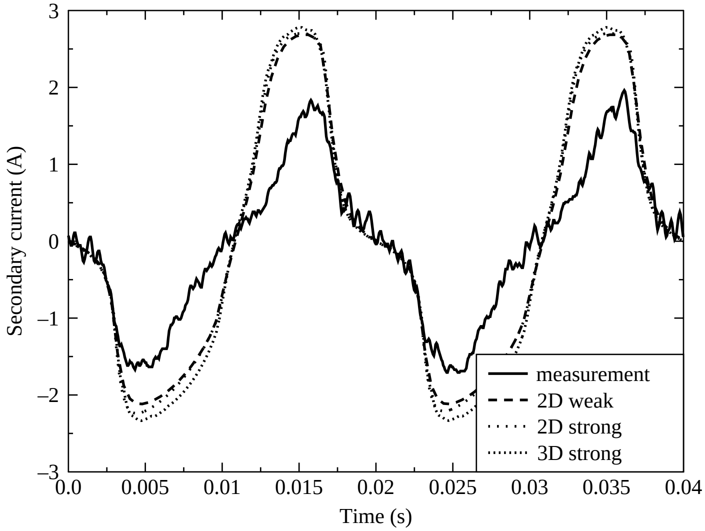

Figure 13.
Comparison of measurements and simulation results for n = 1,500 min^{-1}

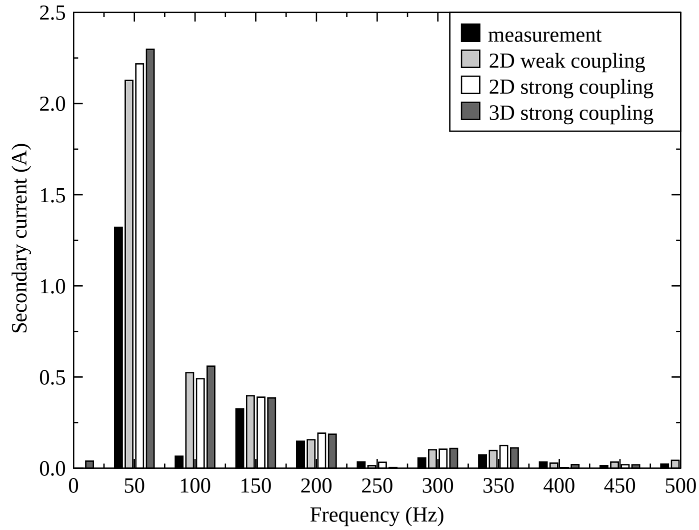

Figure 14.
Spectral comparison of measurements and simulation results for n = 1,500 min^{-1}

3.4 Practical issues

Since the variation of flux due to motion not only induces a voltage in the secondary winding, but also in the primary winding, the primary current has to be actively regulated. This is done using a power electronic converter with a comparatively large additional inductance in series. Different regulation schemes have been evaluated and the simple hysteresis control is found to give the lowest current ripple. The measured primary current waveform and the current spectrum are shown in Figures 15 and 16. It can be seen that the amplitude of the most significant harmonic, the 50 Hz component,

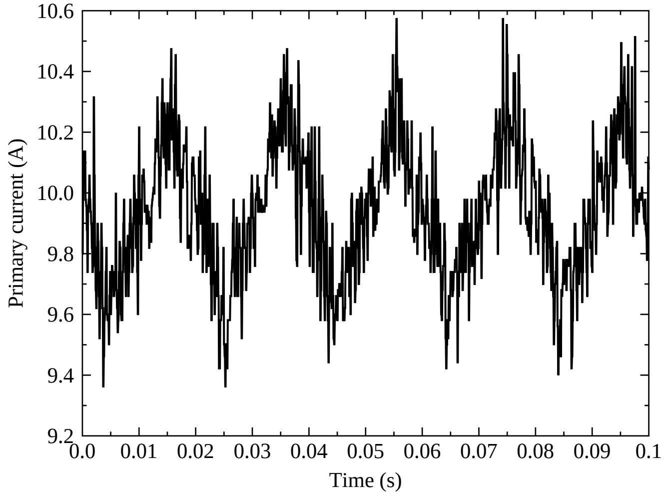

Figure 15.
Primary current waveform

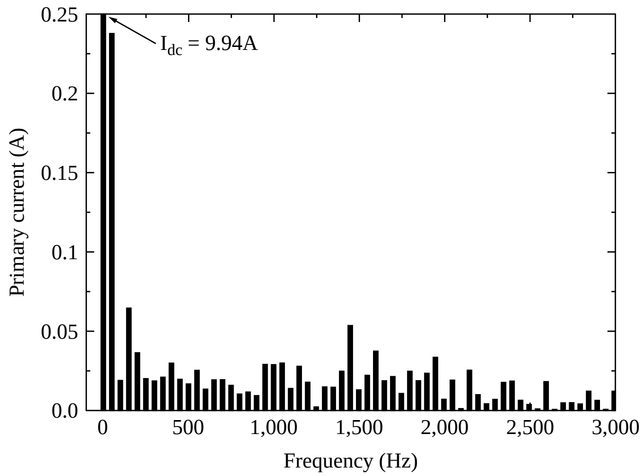

Figure 16.
Primary current spectrum

is less than 3 percent of the direct current component. All other harmonics are lower. Therefore, the harmonic content of the excitation current is considered irrelevant. However, to validate this assumption, a simulation excited by the measured current waveform is performed. It yields a secondary current with the same fundamental and only little ripple.

Since the excitation current ripple does not explain the deviation between measurements and simulation, other possible reasons are investigated. For example, eddy currents in the aluminum housing are taken into account in the simulation, but the induced voltage obtained from the simulation with and without eddy current consideration match closely.

Since the TESTCASE has significant torque ripple, it is questioned, whether the assumption of constant speed is valid. Observing the speed on the test bench yields a deviation of speed from its average value of less than 0.5 percent.

Next, inaccuracies of the fabrication are considered. Measurements of the outer rotor and inner stator diameter show that the nominal airgap of 0.5 mm is reached within an accuracy of 0.01 mm. In addition, the good agreement of the transformer measurements with simulation results and for the linear case even with analytical calculation confirm this.

Measuring voltage and current and calculating the inductance and the magnetic resistance in the unaligned position, however, reveals a large difference between the simulation and the measurements.

At first, additional masses for balancing the rotor, which are not modelled in the numerical simulation are suspected of being responsible for the deviation. However, it can be shown from experiments, removing the masses, and from simulations, modelling them, that their influence is negligible.

The reason for the inaccuracies is finally found in the surrounding air volume in the 3D simulation, which was chosen too small to include all relevant flux paths. Considering a larger air volume around the TESTCASE leads to sufficient accuracy concerning the inductance and the magnetic resistance, as it can be seen from Table III. It is clear that the 2D model and very short 3D model cannot be compared with measurements, for these only the validation of individual implementations is meaningful. It can be seen that for the unaligned position particular care has to be taken regarding the air volume, or specific techniques are required to include the stray effects. The aligned position can be computed very accurately even with a short 3D, or 2D model.

4. Summary, conclusions and future work

The TESTCASE presented in this paper, based on a unipolar reluctance generator, can be used to validate and benchmark coupled electromagnetic field and circuit simulations. It either serves the purpose of comparing different numerical approaches or to validate the individual techniques against measurements.

With the proposed TESTCASE, it is possible to perform two types of test: standstill experiments and experiments with motion induced voltages. The non-linear material properties of the magnetic steel allows for testing non-linear solvers.

Measurement/simulation	R_m (kA/Vs)	Error (%)
Measurement with balancing masses	3,032.6	
Measurement without balancing masses	3,048.0	
Measurement without rotor	3,178.9	
Measurement without iron core (only air coil)	29,975.4	
2D simulation	9,568.8	
3D simulation (very short model)	10,142.8	
3D simulation without shaft	4,852.6	59
3D simulation with shaft	4,815.4	58
3D simulation with shaft and balancing masses	4,647.6	53
3D simulation with shaft (model with extended air volume)	2,635.8	−14

Table III. Magnetic resistance in the unaligned position

The proposed coupled field-circuit problem is solved with different approaches: state-space representation, numerically weak and numerically strong coupling. The TESTCASE is implemented in a laboratory test bench and measurement results are presented and compared. Good agreement for the aligned static case are shown and the poor agreement of the rotating measurements are investigated. The reason for the mismatch is found in the insufficiently large chosen air volume surrounding the TESTCASE for the 3D simulation. This, however, shows the need for measurements rather than comparing only the numerical techniques against each other, because only by measurements the complete approach including modelling and simulation technique can be validated.

Future work on this subject will include the incorporation of the torque gage into the measurements, a detailed description of standardized measurements and the publication of the corresponding measurement and simulation results.

Note

1. At the time of writing, the torque gage was not available for measurements.

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