Earth resistivity tomography for earthing system design

Benjamin Jauk[1*], Katrin Friedl[1], Robert Schürhuber[1]

[1]*Institute of Electrical Power Systems, Graz University of Technology, Graz, Austria*
** benjamin.jauk@tugraz.at*

Keywords: ARBITRARY SOIL RESISTIVITY DISTRIBUTION, APPLIED GEOPHYSICS METHODS FOR EARTHING SYSTEMS, FINITE ELEMENT METHOD (FEM), EARTH RESISTIVITY TOMOGRAPHY (ERT), INVERSE MODELLING

Abstract

Well designed earthing systems are needed to ensure that occurring fault currents can be safely transported into the ground. Soil models are a key parameter for the dimensioning process of earthing systems. In previous research the soil is often assumed to be homogeneous or layered in its resistivity distribution. But the soil is arbitrary in its resistivity distribution. This work will give an input, which errors on the earth surface potential and step voltage will occur, if the soil model is not constructed accurately enough. Different standardized methods are used to interpret the measurement of soil resistivity to build a soil model. To get the measurement values, Wenner's array is used within an earth resistivity tomography (ERT). For the interpretation, the method shown in IEEE Std. 80 will be used and compared with inversion theory. The impact of the different methods on the occurring earth surface potential and step voltages is analysed within a finite element method (FEM) simulation. It is expected, that the different methods for finding the soil model will influence the behaviour of the mentioned potentials. This analysis will help to use new methods to build up appropriate soil models for the designing process of earthing systems. The outcome can improve the efficiency of earthing systems and enhance personal safety.

1 Introduction

Earthing systems are important for the safety of people and power systems reliability. The calculation of the safety criteria in electrical networks depends on the earth surface potential distribution, which requires knowledge of the soil resistivity distribution. There are several standards e.g. [1, 2] which interpret the soil in a homogeneous or layered manner. But physical soil is neither homogeneous nor layered. The resistivity distribution is arbitrary in shape.

A common method to measure soil resistivity for power systems is Wenner's method [4]. This method uses four electrodes per measurement, where the two outer electrodes inject the current into the soil and the inner two electrodes are used for the potential measurement. All four electrodes have the same distance in between. In case of homogeneous soil, as shown in Fig. 2, it is not of significance where the electrodes are placed and which electrodes distance is used. The measured result would be always the same. If the measurement is performed on a "layered" soil, as shown in Fig. 3, the location of the electrodes would not be of significance, but the electrodes spacing. But, if the measurement is placed on physical soil, where the resistivity is arbitrary in shape, see Fig. 4, the location and the spacing is from significance. IEEE Std. 80 [2] suggests a homogeneous soil, if the measured values change not significantly, otherwise a two-layer model is suggested.

European standard EN 50522 [1], is suggesting in British Annex, several different electrodes spacing from $1\,\mathrm{m}$ to up to $100\,\mathrm{m}$. In electrical power systems this measurement is mostly performed manually, meaning the different electrodes spacing are set by the measurement personnel.

In the field of Applied Geophysics this kind of measurement is called vertical sounding (VES). With this method the mid point of the measurement stays the same and the electrodes are moved outwards apart from the middle. Another measurement method, used in the field of Applied Geophysics is earth resistivity tomography (ERT). For that measurement a defined number of equidistant electrodes are placed on the soil and the measurement unit switches the electrodes in an automatic manner, in a way that the maximum possible combination with the defined measurement array is reached.

In this work a synthetic soil model with a inhomogeneous volume is built. This model represents the soil which would be probably found on a site. The synthetic model is $69\,\mathrm{m} \times 15\,\mathrm{m} \times 12\,\mathrm{m}$ (x, y, z direction) in size, as shown in Fig. 1.

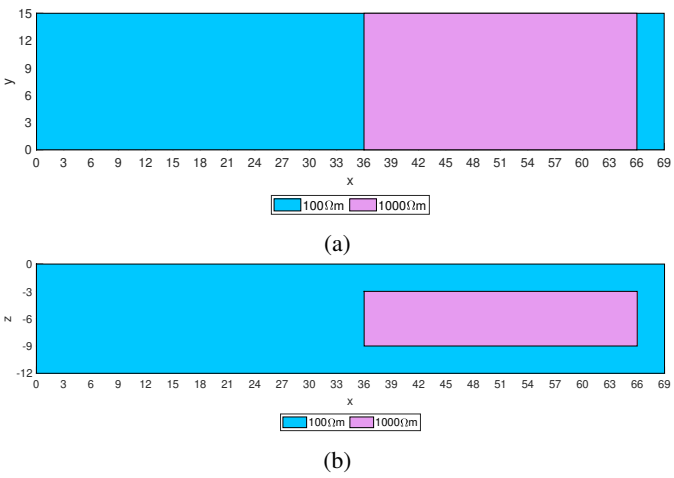


Fig. 1: Synthetic Soil Model
(a) top view in x/y direction, (b) cross section in x/z direction

Then the apparent resistivity values of the synthetic soil model are calculated, which represent the measurement values. The apparent resistivites are used in several ways to interpret the soil as homogeneous, layered and arbitrary in its resistivity distribution. The results are presented and discussed in the following sections.

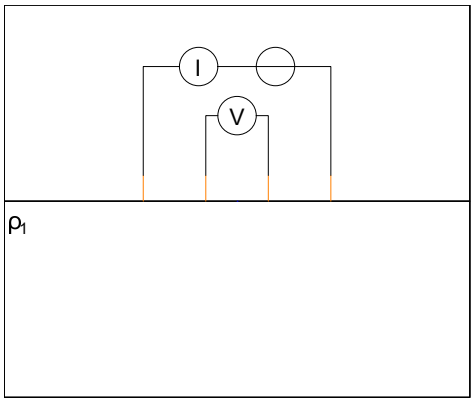


Fig. 2: Homogeneous soil model [3]

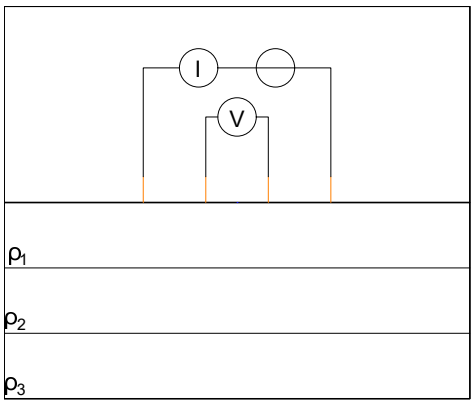


Fig. 3: Horizontal Layered soil model [3]

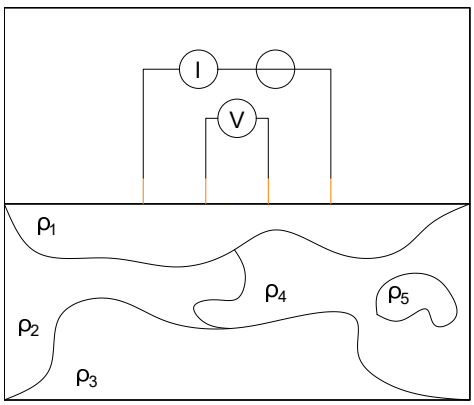


Fig. 4: Arbitrary soil model [3]

2 Methodology

2.1 Synthetic Soil Model

The synthetic model with the size: $69\,\mathrm{m} \times 15\,\mathrm{m} \times 12\,\mathrm{m}$ (x, y, z direction) consists of two different soil resistivty values $100\,\Omega\mathrm{m}$ and $1000\,\Omega\mathrm{m}$. The inhomogeneity with the higher resistivity value is embedded by the surrounding with the lower resistivity value. The size of the inhomogeneity is $30\,\mathrm{m} \times 15\,\mathrm{m} \times 6\,\mathrm{m}$, it is situated $3\,\mathrm{m}$ under the ground and starts at $x = 36\,\mathrm{m}$.

With the software RES3DMOD [7] the calculation of the potential values is performed. These represent the values which would be achieved in a measurement. For the simulation it is assumed, that the ERT is performed with Wenner's method [4]. The software RES3DMOD [7] calculates the potential values in x and y direction, but only the values in x direction are taken into account. Meaning only a pseudo-3D measurement, according to [5] is used. In total six ERT survey lines are used for potential values calculation. The positions of the electrodes are shown in Fig. 5.

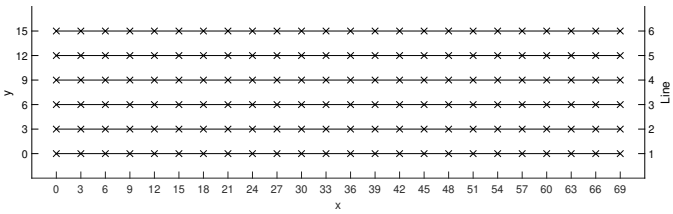


Fig. 5: ERT electrodes arrangement

2.2 Soil Analysis

The basic idea is to find the soil model with measured data only - meaning, solving this inverse problem. The following presented models are different methods to find an appropriate model to closely match the synthetic soil model. The different models are compared with the synthetic model to show their accuracy.

2.2.1 Homogeneous soil model: Three different homogeneous soil models are created: Homogeneous min., Homogeneous max. and Homogeneous avg.

The "Homogeneous min." and the "Homogeneous max." model represent the minimum and maximum apparent resistivity respectively, which are measured in the synthetic soil model.

The "Homogeneous avg." model represents the mean value of all apparent resistivity values. It is calculated according to IEEE Std. 80 [2].

2.2.2 Layered soil model: The "XGSLab Layered" model is a two-layer soil model. The model is created with the Soil Resistivity Analysis tool within the software XGSLab™ [6]. To generate the model resistivity values, all measurement values are used. This tool uses the trust region method (TRM) to solve the squared error function and also weights the input parameters [6].

2.2.3 Inversion model: The "Inversion" model is created with the software RES3DINV [8]. This kind of method is used in Applied Geophysics for ground investigations. It has not been used in the design of earthing systems so far. The software uses an optimized Gauss-Newton algorithm, based on the smoothness-constraint method [5, 8].

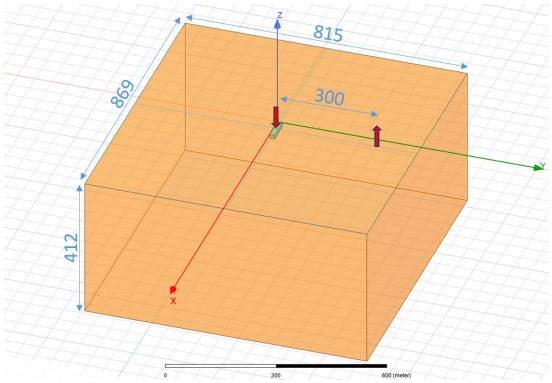
2.3 Data Analysis

To compare the different soil models, a simple earthing system consisting of a half-spherical shaped electrode is built. The soil model with the size: $69\,\mathrm{m} \times 15\,\mathrm{m} \times 12\,\mathrm{m}$ is embedded in homogeneous soil with $100\,\Omega\mathrm{m}$ soil resistivity, with the size: $869\,\mathrm{m} \times 815\,\mathrm{m} \times 412\,\mathrm{m}$. This size was chosen to reduce the effect of the boundaries and allows to place the second electrode for current flow, so that the influence of the electrodes to each other is reduced. The electrode for injection of the current, with amplitude $10\,\mathrm{A}$ (DC) is placed in the middle of the soil model and the sink is placed $300\,\mathrm{m}$ away from the first electrode, in the y direction.

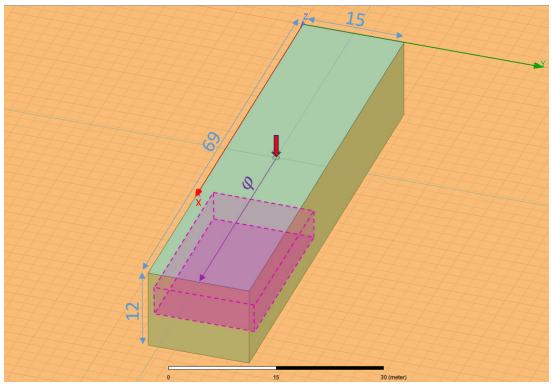
This simulation is built in Ansys Maxwell 3D [10] in DC Conduction mode. The earth surface potential φ and step voltage U_S are evaluated in x direction, starting at the source electrode until the end of the soil model.

To compare the different models, the quantity 'area under the curve' (AUC) is introduced. AUC is the area under the error curve. The smaller this value is, the smaller is the deviation compared to the synthetic model.

For pre-processing, building the synthetic soil model and post-processing, creating the diagrams and calculating the error, the software MATLAB [9] is used. Reference earth is considered as being zero potential [1], the curves in the diagrams are post-processed to fulfil this definition.



(a)



(b)

Fig. 6: (a) Overview of the FEM model, (b) Detailed view on the FEM model

3 Results

Fig. 7 depicts the apparent resistivity from the synthetic soil model, which are calculated with RES3DMOD [7] software. Tab. 1 depicts the resistivity values for the synthetic, layered and homogeneous soil model. The values for the inversion model are not printed because of too many different values.

The following figures Fig. 8 and 9 depict the earth surface potential φ and the step voltage U_S from the different simulated models and their related errors compared to the synthetic soil model. As shown in Tab. 2 it can be seen that the layered model matches the synthetic model slightly better than the inversion model. Taking a closer look on Fig. 8b-8c it can be seen that this is only true for the earth potential rise U_E but not for the total earth surface potential φ. Slightly outside the electrode, the earth surface potential φ matches the synthetic model better than the layered model. Also for the deviation of the step voltage U_S in Fig. 9b-9c, the inversion model follows the synthetic model just after the electrode.

Tab. 2 also depicts the area under curve AUC of the absolute value of the error E and is calculated using numerical integration with trapezoidal method.

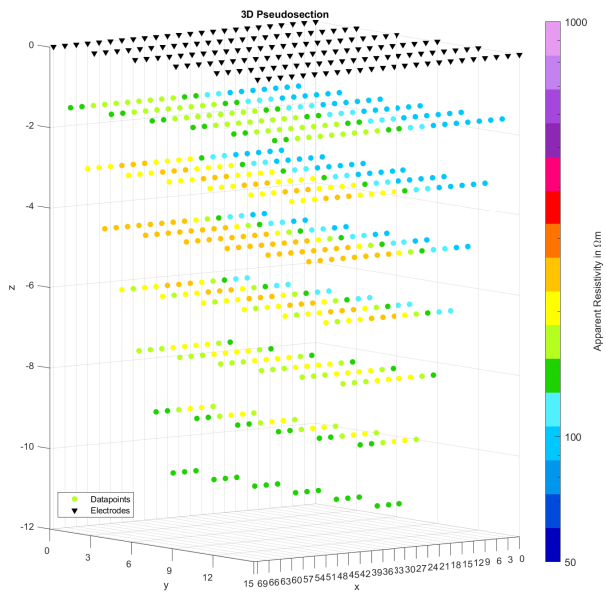
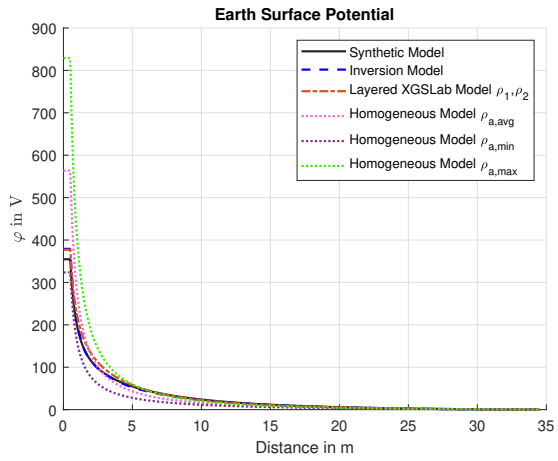
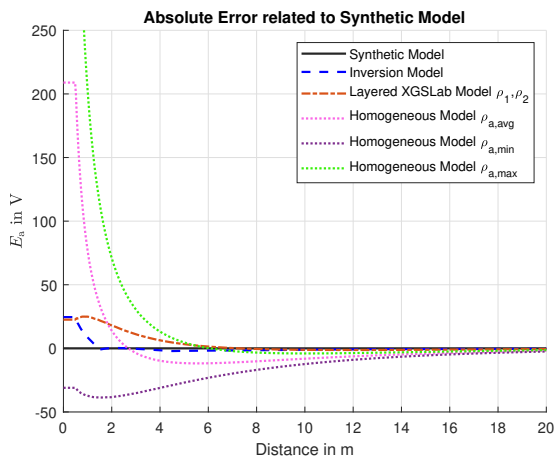


Fig. 7: Apparent resistivities from the synthetic soil model

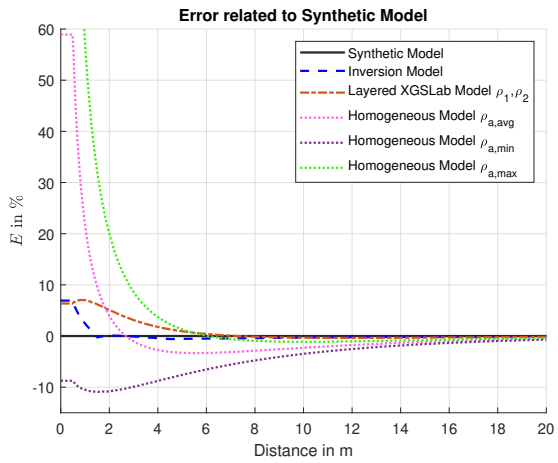
3.1 Figures



(a)

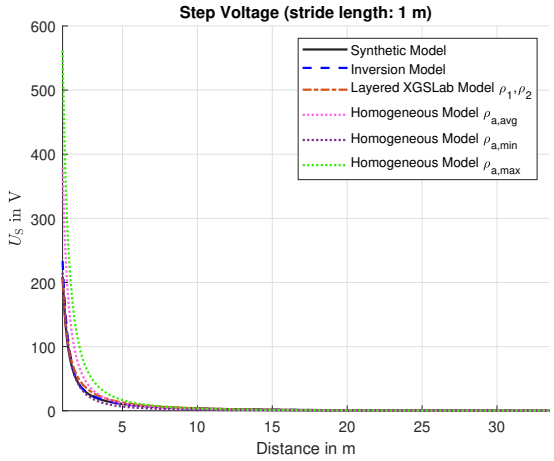


(b)

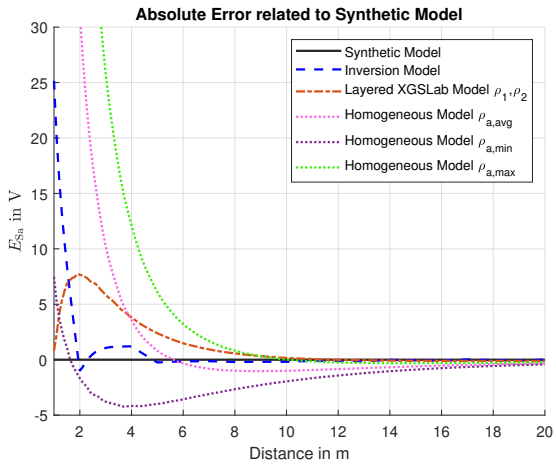


(c)

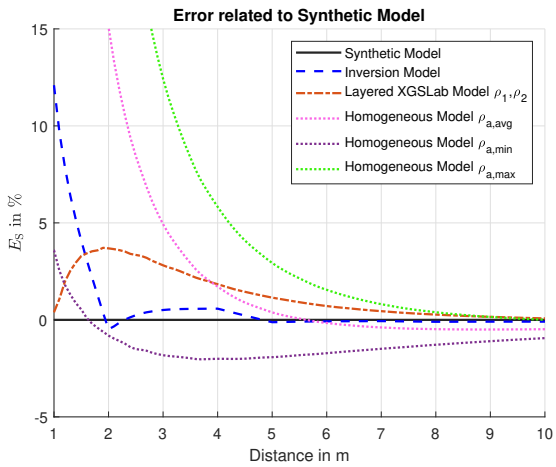
Fig. 8: (a) Total U_{E} along the line, (b) Detailed view on E_{a}, (c) Detailed view on E



(a)



(b)



(c)

Fig. 9: (a) Total U_{S} along the line, (b) Detailed view on $E_{\mathrm{S,a}}$, (c) Detailed view on E_{S}

3.2 Mathematical equations

To calculate the error E of the earth surface potential φ related to the synthetic model, the following equation is applied:

$$E = 100 \times \frac{\varphi_{\mathrm{i}}(x) - \varphi_{\mathrm{Synth}}(x)}{U_{\mathrm{E,Synth}}} = 100 \times \frac{E_{\mathrm{a}}}{U_{\mathrm{E,Synth}}} \quad (1)$$

Where:

E	Error of the earth surface potential in %
$\varphi_{\mathrm{i}}(x)$	earth surface potential of the ith model in V
$\varphi_{\mathrm{Synth}}(x)$	earth surface potential of the synthetic soil model in V
$U_{\mathrm{E,Synth}}$	Earth potential rise of the synthetic soil model in V
E_{a}	absolute error of the earth surface potential in V

The equation for the error for the step voltage E_{S}, related to the synthetic model, the following equation is used:

$$E_{\mathrm{S}} = 100 \times \frac{U_{\mathrm{S,i}}(x) - U_{\mathrm{S,Synth}}(x)}{\max(U_{\mathrm{S,Synth}})} = 100 \times \frac{E_{\mathrm{S,a}}}{\max(U_{\mathrm{S,Synth}})} \quad (2)$$

Where:

E_{S}	Error of the step voltage in %
$U_{\mathrm{S,i}}(x)$	Step voltage of the ith model in V
$U_{\mathrm{S,Synth}}(x)$	Step voltage of the synthetic soil model in V
$E_{\mathrm{S,a}}$	absolute error of the step voltage in V

3.3 Tables

Table 1 Resistivity values for the synthetic, layered and homogeneous soil models

Simulated model	ρ Ωm
Synthetic	100 1000
XGSLab Layered	93.8 (1.2 m) 365.2 (10.8 m)
Homogeneous avg.	180.9
Homogeneous min.	102.8
Homogeneous max.	267.8

Table 2 U_{E}, E, $U_{\mathrm{S,max}}$, E_{S} and AUC for simulated cases

Simulated model	U_{E} V	E %	$U_{\mathrm{S,max}}$ V	E_{S} %	AUC -
Synthetic	355	0	208	0	0
Inversion	380	6.9	234	12.1	0.118
XGSLab Layered	378	6.4	209	0.4	0.257
Homogeneous avg.	564	58.9	380	82.4	0.937
Homogeneous min.	324	-8.7	216	3.6	0.948
Homogeneous max.	829	133.8	562	169.9	1.794

4 Conclusion

It is shown that the different models vary in their earth surface potential φ and step voltage U_{S}.

If only the occurring U_{E} is compared, one would expect from the shown results, that a two-layer model is a better reflection of the synthetic model, due to the closer match of its value. But in fact the total curve of the earth surface potential φ has to be compared. This is done with the area under the error curve AUC. It can be seen that the inversion model matches the synthetic model better than the other ones, followed by the layered model. This conclusion is only limited to this synthetic model, by varying the size and location of the inhomogeneity, the different models and their behaviour change as well.

A negative error E or E_{S} means that the earth surface potential φ and step voltage U_{S} respectively, are lower than the values in the synthetic model. This negative deviation can be crucial for safety considerations. Care must be taken to ensure that this negative error does not become too large, otherwise no statement can be made about the safety of the earthing system.

It has to be mentioned that the method of AUC does not take into account whether the error is positive or negative. It quantifies the quality of the match with the synthetic model.

For a more general understanding the variation of the electrodes and variation of the inhomogeneity have to be done. Furthermore different directions and the practical relevance for less pronounced inhomogeneities will be analysed.

Future work will also contain field measurements to understand the behaviour in real soil. Probably a first step would be to build a lab model.

5 References

[1] ÖVE/ÖNORM EN 50522: ‘Earthing of power installations exceeding 1 kV a.c.’, 2011
[2] IEEE Std. 80: ‘IEEE Guide for Safety in AC Substation Grounding’, 2013
[3] Jauk, B.: ‘Influence of arbitrary resistivity distribution of ground on the surface potential of earthing systems’. Master thesis, Graz University of Technology, 2020
[4] Frank, W.: ‘A Method of Measuring Earth Resistivity’. Bulletin of the Bureau of Standards 12, Washington D.C., USA, July 1915
[5] Loke, M. H.: ‘Tutorial: 2-D and 3-D electrical imaging surveys’, Oct. 2019
[6] SINT srl, XGSLab™ ‘Electromagnetic Simulation for Power, Grounding and Lightning Protection Systems’
[7] Geotomo Software Sdn Bhd, Res3DMod ‘3-D Resistivity Forward Modelling Program’
[8] Geotomo Software Sdn Bhd, Res3DInv ‘3-D Resistivity Inversion Modelling Program’
[9] The MathWorks Inc., MatLab®
[10] ANSYS Inc., Ansys Maxwell