Model-based accuracy enhancements for guarded conductivity measurements: determination of effective electrode areas utilising numerical field simulation

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Abstract: Methods utilising current measurements for conductivity and permittivity determination require precise knowledge of the effective electrode area in order to obtain accurate results. Owing to field distortions (e.g. caused by fringing) in guarded electrode setups, the effective electrode area differs significantly from the geometrical calculated. Focusing on guarded electrode setups for conductivity determination, a generic method based on numerical field simulation is presented allowing a convenient determination of the relevant effective electrode area. For this purpose, a brief overview of yet existing normative guidelines and related research work is provided. State-of-the-art conductivity measurement setups are presented in order to identify parameters which affect the field distribution within the measurement arrangements. The description of the implemented method and its realisation in COMSOL multiphysics is followed by its validation using analytical fringing calculations. Furthermore, presented method is used for the evaluation of fringing effects and additional field distortion caused by design aspects of the measurement cell itself and potential imbalances related to the measurement setup. Moreover, dependencies on conductivity of the surrounding environment are considered. Achieved model-based accuracy enhancements are calculated and are leading to a gain in precision for conductivity determination of up to 25% compared to yet existing approaches.

1 Introduction

Field distribution within insulating systems for high-voltage direct current (HVDC) applications is under steady state mainly governed by the electrical conductivity of the used materials. The increasing attention on precise conductivity determination is highlighted by the fact that well-known standards recently changed. Exemplarily IEC 60093 [4] from 1980 was replaced by IEC 62631-3-1 [2] and IEC 6263-3-2 [3] in 2015 and 2016 and resulted in the consequence that [4] changed to [5, 6] in 2016 and 2017. Latest American standard is currently ASTM D257-14 [7] from 2014. It can be summarised that in the case of flat solid dielectrics, the use of guard ring electrodes is among others normatively accepted as state-of-the-art measurement method.

An overview of the normative suggested guard ring measurement setup is depicted in Fig. 1, and associated geometries are listed in Table 1. The national preface of [4] suggests that a guard gap width of 5 mm is unfavourable for measurement results, whereas errors due to too small gap widths ($g$) are considered more severe. Contrary to this, alongside the standard, a minimal gap width of 1 mm is mentioned. In [5, 6], electrode dimensions are currently only available for surface resistivity measurements. The measurement principle for volume resistivity/conductivity is simplified based on a DC voltage application $U_{DC}$ on electrode III and a current measurement $I_{M}$ using electrode I, whereas any surface current is suppressed by the guard ring electrode (electrode II). Based on terminal sizes and geometrical aspects, conductivity is calculated. For this purpose, the field distribution in guarded electrode setups and its associated effective electrode area is of high importance.

Fig. 1 Guard ring electrode setup

### Table 1

| Measurement arrangement | Standard       | $r_1$, mm | $r_2$, mm | $r_3$, mm |
|-------------------------|----------------|-----------|-----------|-----------|
| $M_1$                   | ASTM (1) [7]   | 12.5      | 19        | 25        |
| $M_{II}$                | DIN IEC 60093 [4] | 25        | 30        | 40        |
| $M_{III}$               | ASTM (2) [7]   | 38        | 44        | 50        |
Table 2  Overview of analytical corrections for $B$

| Equation | Additional information |
|----------|-----------------------|
| $B_A = 1 - \left( \frac{\pi}{2} \cdot \arctan \left( \frac{g}{\pi \cdot h_{TS}} \right) - \frac{2 \cdot h_{TS}}{\pi \cdot g} \cdot \ln \left( 1 + \left( \frac{g}{2 \cdot h_{TS}} \right)^2 \right) \right)$ | permittivity: thick electrodes [11] |
| $B_B = 1 - \left( \frac{2 \cdot h_{TS}}{\pi \cdot g} \left( \frac{\sqrt{p} - 1}{2 \cdot \sqrt{p}} \right) \right)$ and $\frac{\pi \cdot g}{2 \cdot h_{TS}} \cdot \frac{1}{2} \cdot \ln(p) + \frac{p - 1}{2 \cdot \sqrt{p}}$ | permittivity: thin electrodes [11] |
| $B_C = 1 - \left( \frac{4 \cdot h_{TS}}{\pi \cdot g} \left( \cosh \left( \frac{\pi \cdot g}{4 \cdot h_{TS}} \right) \right) \right)$ | conductivity [9, 10] |
| $B_D = \frac{2}{H + 1}$ and $\frac{\pi \cdot g}{h_{TS}} \left( H + \frac{1}{H} \right) + 2 \cdot \ln(H)$ | conductivity [14, 15] |
| $B_E = 1$ | conductivity [1, 4] |

2 Conductivity measurement: setups, fringing effects, and influential factors

The appropriate determination of the effective electrode area for conductivity and permittivity measurements is part of research and standardisation for more than 100 years. A brief excerpt of this research will be provided in Section 2.1. Focusing on properties of insulating materials for HVDC, guard ring electrodes are widely used. In order to investigate material behaviour under various conditions, such as thermal and electrical stresses, a multitude of test setups is existent. Some of those setups will briefly be discussed in Section 2.2.

2.1 Field distribution in guarded electrode setups

Conductivity calculation utilising guard ring electrodes is carried out using the applied voltage ($U_{DC}$) in combination with the measured current ($i_{DC}$) following

$$\sigma_{TS} = \frac{i_{M} \cdot h_{TS}}{A \cdot U_{DC}}$$

(1)

which requires information on the test specimen thickness ($h_{TS}$) and on the relevant electrode area ($A$) for the determination of the associated conductivity ($\sigma_{TS}$). The field distribution within the measurement arrangement is subjected to field distortion caused by the gap ($g$), resulting in the consequence that the effective area ($A_{eff}$) for the electric flow field differs from the geometrical area ($A_{geo}$) determined only by electrode dimensions. In order to obtain highest possible accuracy for conductivity measurements, various mathematical achievements for the precise determination of the effective electrode area exist.

In 1893, the effects caused by the gap between the guard ring and the plate on the capacity of a condenser were mathematically analysed by Thomson [8]. It was concluded that the effective electrode area compared against the geometrical electrode area of the plate is increased by an additional strip, whose width is depending on electrode thickness.

In 1947 [9] and 1949 [10], field distortion, namely fringing, in guard ring electrode setups was analytically analysed by Amey, concluding that in terms of resistivity measurements, a fringing parameter was introduced. Within these contributions ([8–10]), the authors are using analytical expressions, conjugate functions, and Schwarz–Christoffel transformation and conclude that $A_{eff}$ differs from $A_{geo}$. In 1963, Lauritzen [11] presented a work towards the determination of low dielectric constants considering a fringing parameter focusing on capacitance calculations. In [11], Thomson’s results ([8]) were adapted and fringing parameters were presented for thick and thin electrodes. Besides this, Amey’s findings ([9, 10]) are stated applicable for dielectric cases only when the specimen has an extremely high dielectric constant.

**Fig. 2** Impact of gap width/sample ratio ($g/h_{TS}$) on factor $B$ for equations from Table 2

The work of Endicott [12] in 1976 is fostering the results presented above, whereas especially for implicit equations, expansions are provided in order to allow direct calculations. In 1990, capacitance corrections for guard gaps were summarised by Goad and Wintle [13] and its close-form representation provides a good overview including several valuable corrections and further analytical expansions in order to avoid implicit calculations. Furthermore, in [13], it was concluded that the fringing parameter is only minor affected by electrode thickness. Moreover, computational calculations are presented considering different permittivities for the test sample and the gap of the guard ring setup and recommendations focusing on capacitance measurements are provided. From all these works, it becomes obvious that the accuracy of conductivity determinations can be significantly improved if instead of calculating the effective electrode area using

$$A_{eff \, B = 1} = \pi \left( r_1 + \frac{g}{2} \right)^2$$

(2)

as suggested in IEC 60093 [1, 4], a fringing parameter $B$ depending on $g/h_{TS}$, $B(g/h_{TS})$

$$A_{eff \, B} = \pi \left( r_1 + B \cdot \frac{g}{2} \right)^2$$

(3)

is considered. Therefore, in 2006 and 2009, Lisowski ([14, 15]) published recommendations for changes of the IEC 60093. Based on analytical calculations and under consideration of various research works, electrode area corrections for several measurement arrangements for resistivity/conductivity and capacitance/permittivity determination are derived and presented in [14, 15]. It is concluded that in the case of conductivity measurements and circular electrodes, the effective area may simplified be corrected applying Amey’s [9] findings.

Table 2 summarises analytical corrections for the fraction of half the gap width to be added to the radius of circular electrodes following (3) using geometry parameters from Fig. 1. Furthermore, a comparison for all analytical corrections is provided in Fig. 2. For this purpose, calculations are carried out in the interval $g/h_{TS} = 0.01:0.01:10$ and implicit equations were solved numerically each step utilising MATLAB.

Further investigation on fringing coefficients were carried out in 2014 focusing on insulating liquids and considering rounded edges of the measurement and guard electrodes instead of sharp corners [16]. This work is especially meaningful for high-voltage applications, as rounded electrode corners may reduce associated field enhancements within the electrode arrangement and therefore related material stresses. Numerical field simulations ([16, 17]) show that factor $B$ may depend on chosen edge radius, result in negative values. Therefore, recommendations for test setup design
are provided and the authors conclude that edge radius should be considered in the determination of the effective electrode area \(A_{\text{eff}}\) [16].

### 2.2 Conductivity measurement setups

As a consequence of the variety of conductivity investigations, focus will be in the following on measurement setups related to solid dielectrics, especially on those setups focusing on evaluation of conductivity of cable materials for HVDC application.

It can be summarised that electrometer/picoammeter are utilised in most concepts, e.g. [18–28]. Therefore, as far as determinable, the voltmeter–ammeter method ([1, 4, 7]) appears to be the commonly used one. Owing to the fact, that state-of-the-art electrometer/picoammeter typically utilise transimpedance amplifiers with a voltage burden within the range of a few hundreds of microvolts, the potential imbalance between guarded (electrode I) and guard electrode (electrode II) is theoretically limited to those values. Using shunt ammeters without any countermeasures could lead to potential imbalances occurring between electrode I and II within the range of 200 mV–2 V [29].

Applicable voltages are increased up to 60 kV [20] or even 100 kV [23, 25]. In this context, additional superimposed capacitive charging currents due to voltage generation [27, 30–32] need to be considered. Whereas suppressing of those currents by voltage stabilisation on the HV side is, e.g. mentioned in [27, 28, 31], additional low-pass filters prior current measurement are presented in [20, 23, 25] and additionally in [27].

Besides this and due to the applied voltages, overvoltage protection in the case of specimen failure has to be considered. In [19], a 10 M\(\Omega\) resistor is used. A not otherwise specified overvoltage protection is used in [20], whereas Ghorbani [23] uses spark gaps in combination with zener diodes and an additional filter circuit. In [32], the commercially available protection device Sefelec – BAPA is mentioned, which acts, according to its manual, for currents \(\geq 1\) \(\mu\)A as a diode network and for currents \(\leq 1\) nA as a series resistor in the range of 100 M\(\Omega\). These additional components, such as overvoltage protection and filters prior current measurement, may increase potential imbalances between electrodes I and II.

Focusing on used materials for the cell design itself, especially focusing on the gap between guard and guarded electrode, information is rare. In [27], a gas-filled gap is used, whereas the work in [23, 25, 28] utilising Teflon/PTFE. Measurement deviations caused by relevant HV contact areas and electrode materials are addressed in [33–35].

### 3 Numerical modelling and model verification

For the evaluation of influential factors on field distortions and their associated effects, a parametrised numerical model is implemented in COMSOL multiphysics. Model realisation, meshing prerequisites, and the associated evaluation method are described in Section 3.1. In Section 3.2, the obtained simulations results are compared to the analytical results introduced in Section 2.1 allowing the calculation of resulting simulation accuracy.

#### 3.1 Simulation framework and evaluation method

In order to achieve great flexibility for parameter studies, a generic simulation framework was implemented in COMSOL multiphysics according to Fig. 3. This framework consists of a fully parametrised model and parametrised meshing routines on selected model areas and domains. The key model parameters are shown in Table 3 and related boundary and domain settings in Table 4. For the purpose of model verification, overall six base models following normative recommendations (cmp. Section 1) are realised: \(M_{\text{TS}}, M_{\text{TS}}, M_{\text{TS}}, M_{\text{TS}}, M_{\text{TS}}, \) and \(M_{\text{TS}}\). Models denoted with \(\star\) utilise a gap width \(g\) of 1 mm. The geometry was implemented as two-dimensional rotationally symmetrical arrangement according to Fig. 3. In order to keep model domain limitations constant, the parameters \(l_{I}\) and \(l_{II}\) are introduced. The length \(l_{I}\) describes the part of the specimen overlapping the electrode arrangement. Parameter \(l_{II}\) denotes the additional length which is applied to obtain the model domain and added to the height of the electrodes and the test specimen overlap.

For the determination of the relevant simulation-based fringing coefficient \((B_{\text{K}})\), reverse calculation, similar to [16], is chosen as due to the modelling fact, specimen conductivity is well known. The determination of the effective electrode area is carried out using

\[
A_{\text{eff}} = \frac{l_{S} \cdot h_{TS}}{\sigma_{TS} \cdot U_{DC}} \tag{4}
\]

and substituting \(A\) with the relevant equation for the determination of the effective electrode area

\[
A_{\text{eff}} = \pi \cdot \left( r_{I} + B_{K} \cdot \frac{g}{2} \right)^{2}, \tag{5}
\]

enabling a calculation of \(B_{K}\) based on simulation results as

\[
B_{K} = 2 \cdot \sqrt{\frac{l_{S} \cdot h_{TS}}{\sigma_{TS} \cdot U_{DC} \cdot \pi - r_{I}}} \tag{6}
\]

under assumption that besides simulation-related parameters \((\sigma_{TS}, \sigma_{TS}, r_{I}, g)\), the applied voltage \((U_{DC})\) and the simulated current \((I_{S})\) through the specimen are known. Whereas applied voltage may easily be set as boundary condition, for a convenient determination of the simulated current, the physical interfaces electrical currents and electrical circuits are coupled within the simulation. Instead of manually integrating current densities, an infinitesimal small ohmic resistor \((R_{I})\) is virtually connected (circuit terminal according to Table 4) to the measurement electrode allowing instant current determination. Calculation of the related fringing factor \(B_{K}\) may be carried out within COMSOL or MATLAB. For the purpose of further data processing, the export of simulation results to MATLAB is chosen.

Simulation accuracy is closely related to adequate meshing. Known from analytical calculations, fringing effects are to be expected, especially within the specimen at the coordinates \(r_{I} \leq r \leq r_{II}\) \((-h_{TS}/2) \leq z \leq (h_{TS}/2)\). For this purpose, mesh density is significantly increased in this area and 500 triangular elements are implemented each vertical and horizontal. Therefore,
horizontal resolution is expected to be constant 0.2% of $g$ and vertical resolution 0.2% of the test specimen height ($h_{TS}$). Furthermore, maximum element growth rate within the test specimen area ($r_1 \leq r \leq r_2$) is limited to 5% and maximum element size to $g/500$. In the remaining part of the test specimen, element growth rate is limited to 5%, whereas rest of the model is meshed COMSOL predefined as ‘extremely fine’. An impression on numerical simulated fringing effects for guard ring electrode setups is provided in Fig. 4 clearly showing the impact on field distribution caused by the gap between electrode no. I and no. II. In order to highlight fringing effects caused by the gap, for visualisation purpose, electrode height ($h_E$) is contrary to Table 3 chosen as 10 mm.

The resulting gain in accuracy for conductivity determination is achieved similar to [14] based on the relevant electrode area $A_{eff}$ following

$$p_A = \frac{A_{eff,B = 1} - A_{eff,B = x}}{A_{eff,B = 1}} \cdot 100$$

in which $p_A$ denotes the accuracy improvement in percentage, if fringing is considered following analytical calculations. In other words, $p_A$ defines the error which arises if fringing is not considered correctly. Model-based accuracy enhancements are calculated similar to (7) using

$$p_{A,B_{x,s}} = \frac{A_{eff,B = s} - A_{eff,B = x}}{A_{eff,B = s}} \cdot 100$$

with $x = B_C$ or $x = 1$. (8)

where $p_{A,B_{x,s}}$ denotes the accuracy improvement in percentage compared to $x = 1$ ([1, 4]) or proposed analytical calculations $x = B_C$ ([9, 10, 14]).
3.2 Model verification

Model verification is carried out utilizing parameter studies. For all base models, the fringing coefficient $B_3$ is determined within the simulation framework considering parameters according to Tables 3 and 4. For this purpose, the fraction $f = g/hB_3$ is varied from 0.1 to 10 with a step width of 0.1, resulting in 100 numerical field simulations for each model. Additional to this, fringing coefficients are calculated for $f = 15, 20, 25, 30$ ensuring model robustness.

Analytical results following (6) are depicted in Figs. 5a and c. Overall compliance of the model with analytical calculations can be stated as superb for those base models having a gap width of 1 mm. Severe discrepancies are observed for geometries with a gap width $g \gg 1$ mm and for $f = g/h < 1$, resulting in specimen up to ten times thicker than the gap width. For a detailed understanding of this effect, the associated simulation deviation $\delta_S$ in percentage is calculated following

$$\delta_S = \frac{B_C - B_S}{B_C} \times 100 \quad (9)$$

and depicted in Figs. 5b and d. The maximum absolute simulation deviation is calculated using $|\delta_S_{\text{max}}| = \max (|\delta_S|)$, whereas the mean simulation deviation is calculated as $\bar{\delta}_S = \frac{1}{n} \sum |\delta_S(I)|$. For base models with a gap width of 1 mm, a maximum absolute simulation deviation of $|\delta_S_{\text{max}}| = 2.29\%$ is observed, whereas the maximum mean simulation error occurs for model $M_I^*$ as $|\delta_S_{\text{max},M_{II}}| = 0.16\%$. Resulting deviations for $M_I$, $M_{II}$, and $M_{III}$ are shown in Fig. 5b. The absolute maximum overall simulation deviation occurs for $M_{III}$ leading to $|\delta_S_{\text{max},M_{III}}| = 88.62\%$ for $g/h = 0.1$. The maximum mean simulation error occurs for $M_I$, resulting in $|\bar{\delta}_S_{M_{III}}| = 1.48\%$. It is found that the mean simulation error is reduced with an increase in $r_I$. The mean modelling errors are fostering model accuracy.

As from simulation perspective obtained simulation results appear to be correct, attention is paid on the used geometries. It is found that for severe specimen thickness, the maximum simulation error for $f \leq 0.3$ is worse for those arrangements having a smaller width of the guard ring $(w)$, as illustrated in Fig. 5a. For this purpose, a parameter study with varying guard widths $(w)$ utilising $M_{III}$ is carried out. Results are displayed in Fig. 6. Simulation deviation to analytical calculations is reduced with an increase in guard ring width. This observation motivates further investigation on associated effects related to electrode edges and the maximum radius $r_I$ which can be considered in the simulation but not within analytical equations. Therefore, additional studies related to field distortion and countermeasures, associated with the overall electrode design, are intended. These investigations are related to accurate meshing of the surroundings and broached in Section 5 but not seen as a key aspect within this publication.

This leads to the conclusion that the simulation framework can be stated as fully verified and provides a convenient determination of the relevant fringing parameters $B_3$ with an maximum mean simulation deviation of $|\delta_S_{M_{III}}| = 1.48\%$.

4 Model-based accuracy enhancements

Using the verified simulation framework, $M_{III}$ is chosen as the representative for accurate measurements of specimen of higher resistivity. Several parameter studies are carried out utilising $f = 0.5:0.5:10$ and similar to Section 3.2, an extension of parameter sets is carried out for $f = 15, 20, 25, 30$. A short excerpt focusing on conductivities of surrounding and gap materials and potential imbalances will be provided in Sections 4.1 and 4.2.

In the last section, the resulting gain in accuracy for conductivity determination will exemplary be calculated if precise knowledge on field distortion is considered.

4.1 Conductivity of surrounding and gap materials

In terms of permittivity calculation, it was found e.g. in [11, 15] that the permittivity ratio of the test sample and the surrounding material affects the fringing effect. As focusing on fringing for conductivity measurements, the conductivity ratio of the test sample and the surroundings is varied. Therefore, new relations are added to the simulation framework

$$\sigma_S = \frac{1}{c_I} \cdot \sigma_{TS} \quad \text{and} \quad \sigma_{TS} = 1 \times 10^{-16} \text{ S/m} \quad (10)$$

and the conductivity ratio $c_I$ is set to $c_I = 0.1, 1, 10, 30, 50, 100, 1000$. Selected results are depicted in Fig. 7a, resulting for $c_I = 1$ in $|\delta_S_{\text{max}}| \leq 228.45\%$ (for $g/h = 30$), $|\delta_S| = 125.05\%$ and for $c_I = 10$ still in $|\delta_S_{\text{max}}| \leq 27.66\%$ (for $g/h = 30$) and $|\delta_S| = 14.82\%$. This effect is strengthened by conductivity ratios $c_I < 1$. The tremendous importance of the numerical determination of the fringing coefficient even gains in importance, if additional to various conductivities electrode heights $h_E$ are considered. In order to provide a first insight on this issue, in Fig. 7a, simulation results for $B_3$ under consideration of $c_I = 1$ for $h_E = 0.1$ mm and $h_E = 10$ mm are depicted. This is leading to an increase in deviation compared to analytical calculations of $|\delta_S_{\text{max}}| \leq 464.06\%$ (for $g/h = 30$), $|\delta_S| = 233.26\%$ if an electrode height of 10 mm is
considered. Consequently, electrode height and conductivities of gap and surrounding materials are of high importance for an accurate determination of the effective electrode area. Moreover, possible countermeasures for a suppression of influences caused by currents through the specimen surroundings (e.g. additional shielding concepts) gain in importance.

4.2 Potential imbalances

Reasons for an occurrence of potential imbalances between the measurement and guard electrode are summarised in Section 2.2. For this purpose, the potential of the measurement electrode is increased utilising parameter $U_{ME} = 0, 1, 10, 100 \text{ mV}, 1, 10, 50, 100 \text{ V}$. Simulation results are found in Fig. 7b. As expected, the effective electrode area is apparently reduced if the potential of the measurement electrode is increased. In other words, the field strength to be used for conductivity determination is reduced and needs to be considered. The associated effects are of minor importance for voltages up to $10 \text{ V}$, $\delta_S \leq 21.54\%$ (for $g/h = 30$), $\delta_S = 6.06\%$, but increase for higher potential imbalances. Overall, it need to be mentioned that generalised findings on this issue are challenging, as potential imbalances may lead to additional non-neglectable leakage currents through measurement cable dielectrics and the guard gap material. Therefore, potential imbalances have to be investigated with respect to the used gap material. For this purpose, Fig. 7b shows exemplary additional consequences for submerged electrodes and an increased electrode height.

4.3 Model-based accuracy enhancements: example

Obtained simulation deviations ($\delta_S$) compared to analytical calculation of $B$ do not automatically refer to accuracy enhancements ($p_A$) for conductivity determination of the same magnitude. Model-based accuracy enhancements follow (8). For this purpose, the fringing coefficients are calculated for an electrode arrangement with submerged electrodes for all three models $M_I, M_{II}, M_{III}$.

Fig. 5 Fringing parameters $B_C$, $B_S$, and simulation deviation $\delta_S$

Fig. 6 Simulation deviation $\delta_S$ for $M_{III}$ with varying guard ring width $w$

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normative setups considering $h_E$ as 10 mm, $\sigma_{TS} = \sigma_S = \sigma_G = 1 \times 10^{-15}$ S/m and $f = 0.1:0.1:10$. Results for $B_S$ and resulting accuracy enhancements are presented in Fig. 8. Resulting enhancements depend on the chosen electrode arrangement. Similar to observations in [14], accuracy enhancements are reduced if $r_1$ is increased or $g$ is reduced. Within the range $1 \leq g/h_{TS} \leq 10$, this leads for $M_I$ to a maximum accuracy improvement of $p_{A,B_S,1,max} \approx 25\%$ and compared to yet existing analytical considerations of $p_{A,B_S,R_{BC,max}} \approx 18.78\%$ with mean values $p_{A,B_S,R_{BC}} \approx 18\%$ and $p_{A,B_S,R_{BC}} \approx 16.59\%$. In chosen example, accuracy enhancements are within $1 \leq g/h_{TS} \leq 10$ smallest for $M_{II}$ resulting in $p_{A,B_S,1,max} \approx 9.2\%$, $p_{A,B_S,R_{BC,max}} \approx 6.36\%$ and $p_{A,B_S,R_{BC}} \approx 6.3\%$, $p_{A,B_S,R_{BC}} \approx 5.46\%$.

With the purpose of evaluating the impact of simulation accuracy on the overall obtained accuracy enhancements, possible simulation deviations are considered with respect to Section 3.2.

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**Fig. 7** Fringing parameters $B_C$, $B_S$ for $M_{III}$

(a) With varying conductivity ratios $c_r$ for gap and surrounding materials and an additional consideration of electrode height $h_e = 10$ mm denoted with I. (b) With varying potential of the measurement electrode $U_{ME}$ and an additional consideration of $c_r = 1$ and $h_e = 10$ mm denoted with II.

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**Fig. 8** Fringing parameters $B_C$, $B_S$ and model-based accuracy enhancement for the discussed example for all three normative setups $M_I$, $M_{II}$, $M_{III}$ with varying $g/h_{TS}$ ratios. The dotted line denotes the effect if parameter $B_S$ is only determinable with an accuracy of $\pm 5\%$ (worst case).

(a) $B_C$, $B_S$, (b) $p_A$ considering $x = 1$, (c) $p_A$ considering $x = B_C$.
being in worst case less than ±5%. The resulting error propagation is depicted in dotted lines and seen as worst-case scenario as for 1 ≤ g/δTS ≤ 10, as δg was clearly <5% during model verification process.

5 Conclusion and outlook
An adequate consideration of the effective electrode area is essential in order to determine accurate conductivities in guarded measurement setups. For this purpose, the concept of model-based accuracy enhancements is presented. Based on numerical field simulation, effective electrode areas are determined and allowed, besides yet available analytical calculations, a consideration of the electrode design area presented. Presented simulation framework was successfully verified by means of analytical equations from the literature ([9, 10, 14, 15]). It enables a convenient determination of applicable fringing factors and additional influences affecting the effective electrode area. Furthermore, this framework inherently provides a validated basis for future approaches towards conductivity modelling.

Besides known effects, e.g. related to the electrode edge radius ([16]), it is shown that potential imbalances, electrode height, conductivities of surrounding materials, as well as the gap material lead to significant changes of the fringing factor (δg) or more generally speaking of the effective electrode area. A generalised influence analysis is challenging as, for example, electrode height appears to be not crucial if surrounding and gap materials are highly resistive but tremendously affects the fringing parameter in the case of submerged electrodes. It is concluded that apart from fringing caused by the gap between guarded and guard electrode additional field distortion caused by the measurement cell design or the used measurement procedures need to be considered. Those aspects are among others related to arising potential imbalances, overall test specimen height, and electrode design. Owing to these observations, a simulation-based determination of the applicable fringing factor and the relevant electrode area is advisable. A parameter study is fostering this, as achievable accuracy enhancements are ranging up to 25% for 1 ≤ g/δTS ≤ 10.

It is observed that specimen being thicker than the gap width (f < 1) and being thicker than the guard width h/g > 1 lead to severe deviation compared to analytical calculations. A deeper understanding of this effect motivates future investigations. For a deeper understanding of this issue, attention needs to be paid on edge effects related to the overall electrode design under consideration of sufficient meshing parameters for curved boundaries and suitable reference geometries, e.g. Rogowski profiles. Based on the presented simulation framework, influence analysis and countermeasures for a suppression of currents through the specimen surroundings will be carried out. Moreover, suitable design recommendations for guarded conductivity measurement setups will be derived and analysed in future case studies.

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