

Electric field Calculations for AC and DC Applications of Water Controlled Cable Termination

Tanumay Karmokar^{1*}, Dr. Ralf Pietsch*

* HIGHVOLT Prüftechnik Dresden GmbH, Dresden, Germany

*Marie-Curie Street 10, 01139 Dresden, Germany; karmokar@highvolt.de¹

Abstract: The computation of electric field strength is the state-of-the art technique for designing and optimising high voltage (HV) equipment. The challenge in this presented work is to indicate the feasibility of Cable Termination (CaTr) for testing High Voltage Direct Current (HVDC) cables which were originally designed and manufactured for applying Alternating Current (AC) voltages (75 kV - 800 kV) for cable testing. The importance lies in understanding the coupled behaviour of the electric field stress and the temperature profile as both these factors have a strong influence on the space charge effects under the influence of HVDC voltage. An outlook is provided towards considering laminar flow of the water being circulated inside the CaTr with a controlled electrical conductivity for its influence to be seen on both, electric field and convective heat transfer. COMSOL Multiphysics® is found to be completely adaptable to our modelling and design requirements for such multiphysics i.e., interdependent simulation, as could be seen in this presented work.

Keywords: Electric field simulation, Cable Termination, HVDC cables, electrical conductivity, convective heat transfer.

1. Introduction

The HV tests on plastic insulated cables are mainly performed with AC voltages of power frequency in accordance with the most common valid standards [1]. The cable tests at factory cover a wide range within routine, development and type tests on cable samples and long delivery lengths from medium voltage up to extra-high voltage levels. To check the insulation integrity HV tests are performed in conjunction to Partial Discharge (PD) or Dissipation Factor ($\tan \delta$) measurements.

The ends of the cable are characterized by strongly inhomogeneous electric field distribution (i.e., locally very high field

strengths) unlike the slightly inhomogeneous electric field inside the cable itself. This prevents decisive HV tests to be performed on cables. Therefore, the electric field distribution at cable ends has to be improved by a suitable field control. This is realized by Cable Termination (CaTr) [2]. The CaTr manufactured by HIGHVOLT has been successfully applied for the past several years to test cables with voltages ranging from 75 kV to 800 kV AC. These terminations are filled with deionised water of defined electrical conductivity (σ_w). The water acts as a forced resistive control and smoothes down the strongly inhomogeneous electric fields at the cable ends.

The recent focus of power sector on HVDC systems has made it inevitable for the increased application of HVDC voltages in the area of design and testing of such HV equipment. This forms the underlying motivation for carrying out the presented investigations for analyzing the already designed AC CaTr for its application towards testing HVDC cables (500 kV DC) equivalent to testing a 350 kV AC cable for its peak voltage ($350 \times \sqrt{2} \cong 495$ kV). This equivalence of voltage level is significant because in order to examine the breakdown behaviour, peak voltages are to be analyzed closely for the electric stress it produces. Thus, by working towards the feasibility electric field studies, nuances of the CaTr model for the application of both, AC and DC voltages using COMSOL Multiphysics® has been developed.

2. Electrical and thermal design principle

The CaTr is based on the principle of linear electric field control achieved by using water with a specific and controlled electrical conductivity (σ_w) together with its high dielectric constant ($\cong 80$) [2]. The conductivity is a function of water temperature and could be understood by the following equation [2];

$$\sigma_u = \sigma_o \{1 + \alpha \Delta T + \beta (\Delta T)^2\} \quad (1)$$

where;

- σ_u - Electrical conductivity of water [S/m]
- σ_o - Value of electrical conductivity of water at 20°C [S/m]
- α - Temperature dependency coefficient of water [K⁻¹]
- β - Volumetric coefficient of water [K⁻¹]
- ΔT - Temperature gradient in water w.r.t. the reference temperature of 20°C

As cable diameter of the cables to be tested can vary due to different designs and their rated voltages, the electric field distribution can change significantly within the same CaTr. Thus, a suitable linear field-control within the CaTr is needed. The significance of an optimum conductivity within the CaTr can be appreciated from the fact that when it is increased significantly in order to smooth the electric field distribution, there will be an increase in the electric energy dissipated as heat loss inside CaTr. Therefore, an additional cooling system is used [2]. As is seen from the developed COMSOL model *Figure 3* replicating reality, the

water is made to circulate inside CaTr *Figure 2*. *Figure 3* shows the 2D COMSOL modelling for realizing the practical construction of CaTr *Figure 1* and the implementation of the real-life physics.

The CaTr is, in principle, a two tube system *Figure 1* which allows the realization of both, water inlet and outlet at the bottom i.e., at the ground electrode. The water is pumped through the inner tube (i.e., between the outer and inner tube) towards the top electrode. This practical setup is realized in the Physics settings of COMSOL model too *Figure 2*. The water is circulated by using a pump, which is present inside the conditioning unit, at a flow rate of 60 liters/min ($\cong 0.001 \text{ m}^3/\text{s}$). This forced flow of water has twofold advantage; on one hand it removes the excess heat by heat exchange process that occurs inside the water conditioning unit and on the other hand it facilitates convective heat transfer through the CaTr due to the heating effect of current through the conductor of the cable being tested.

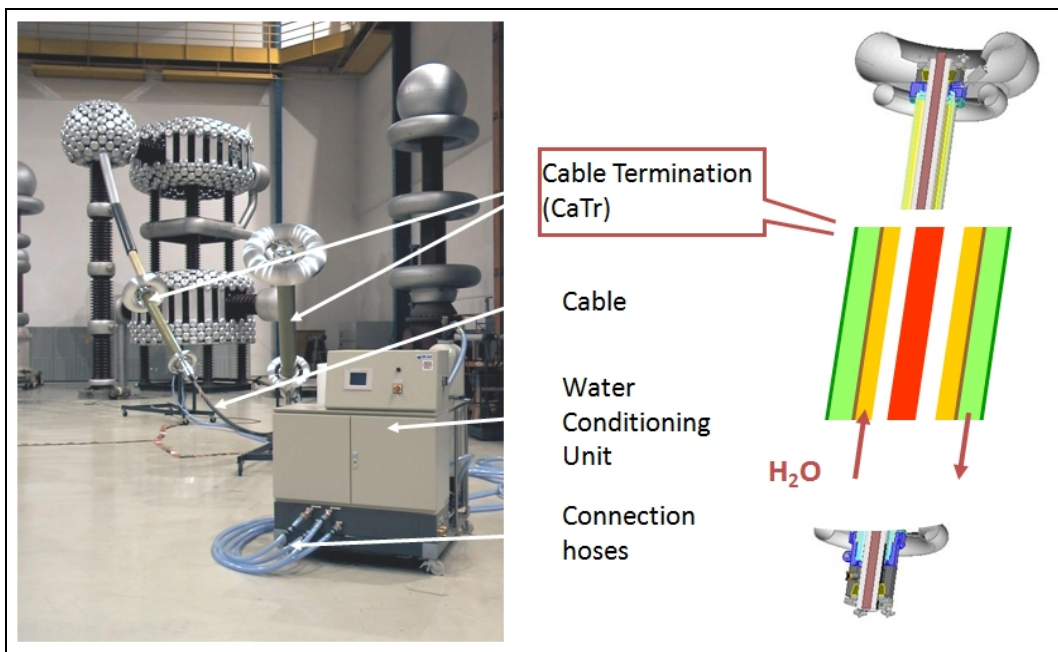


Figure 1. The actual setup of a Cable Termination (CaTr) in a high voltage laboratory with the water conditioning unit and test connection arrangement.
Ref [2], [5]

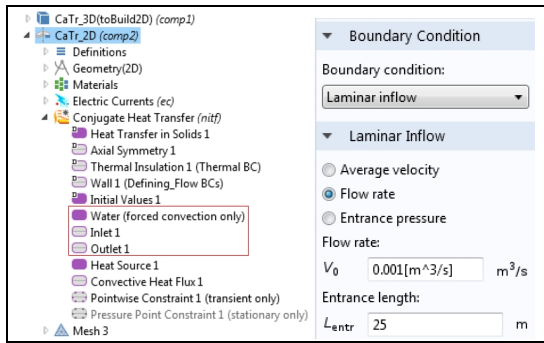


Figure 2. A screenshot of the actual Physics settings highlighting the simulation of water inlet, outlet and its flow rate guided by the conditioning unit.

The Reynold's number for the circulating water is calculated to be 0.472 for this model of CaTr using the standard formula;

$$R = \frac{\rho g \ell}{\mu} \quad (2)$$

where;

- ρ - Density of water as referred from the COMSOL material parameters.
- g - Mean velocity of water as referred from the initial COMSOL calculation with natural convection.
- ℓ - Characteristic length i.e., the travelled length of water.
- μ - Dynamic viscosity of water as referred from the COMSOL material parameters.

The low value of Reynold's number (R) makes it appreciable to assume the viscous forces to be greater than the inertial forces and hence laminar flow has been considered for the modelling purpose in order to characterize the fluid (water) regime inside the CaTr.

3. COMSOL Modelling

The considered physical system modelling in COMSOL is governed by the boundary conditions of having a high voltage applied to the top electrode *Figure 3* for observing the influence of AC and DC electric field stress and at the same time having a test current of 500 A flowing through the cable to be tested, which is present inside the CaTr. This leads to the formulation of a multiphysics interface between

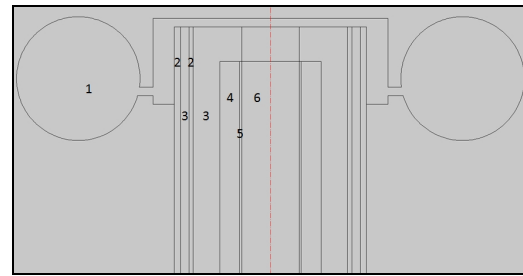


Figure 3. A screenshot of the top portion of the developed COMSOL CaTr model with; (1) High voltage electrode, (2) Fiber Reinforced Plastic (FRP) body of the CaTr, (3) Circulating water, (4) Polyethylene insulation of the cable being tested, (5) inner semiconducting material of cable, (6) Copper conductor of the cable.

electric field and heat transfer. The electrical field distribution is described by using a two-dimensional field model, which is solved for nonlinear equations of electrical conductivity of water $E_q (1)$ and for the nonlinear equations of the polyethylene (XLPE) insulation of cable $E_q (3)$; [3], [4].

$$\sigma_i = \sigma_o' \{ \exp (\alpha' T + \beta' E_e) \} \quad (3)$$

where;

- σ_i - Electrical conductivity of XLPE cable insulation [S/m]
- σ_o' - Value of electrical conductivity of XLPE at 20°C [S/m]
- α' - Temperature dependency coefficient of polyethylene material [K⁻¹]
- β' - Electric field dependency coefficient
- E_e - Electric field as computed by COMSOL ($\cong ec.normE$) during simulation.

The mathematical formulation for the applied AC and DC electric field can be understood from the governing equations as follows,

$$\nabla \cdot J = Q \quad (4)$$

$$E = -\nabla V \quad (5)$$

$$J = \sigma E + J_e \quad \dots \quad DC \quad (6)$$

$$J = (\sigma + \epsilon_o \epsilon_r \frac{\partial}{\partial t}) E + J_e \quad \dots \quad AC \quad (7)$$

where;

J - Conduction current density
 Q - Charge density
 E - Electric field
 V - Applied potential
 ϵ_0, ϵ_r - permittivity of free space and relative permittivity respectively

$$J = \frac{1}{A} \frac{dQ}{dt} \quad \dots \quad \text{Heat flux} \quad (9)$$

$$J = -k \frac{dT}{dx} \quad \dots \quad \text{Fourier' Law} \quad (10)$$

The above equations represent parts of Maxwell's equations which are computed in this modelling for the material properties, characterizing the AC and DC electric fields [3]. This could be understood from the above equations *Eq (4) and Eq (5)* which are the independent electric field calculation equations. The *Eq (6)* represents the DC electric field having the field influential parameter of electrical conductivity (σ). *Eq (7)* represent AC electric field with the field influencing parameter being permittivity (ϵ) of the material. These equations are simulated for DC with a Stationary Study and for AC with a Time Dependent Study for one full wave 50 Hz cycle (20 ms). The aim hereby lies in verifying the theoretical expectation of AC electric field getting influenced by geometry and permittivity whereas DC electric field distribution, under steady state conditions, being influenced by electrical conductivity and space charge accumulation [3].

$$\rho C u \nabla T = \nabla \cdot (k \nabla T) + Q \quad (8)$$

The *Eq (8)* [6] describes the heat generation between domains, where; u is the velocity of the fluid (water) [m/s] and k is the thermal conductivity of water [W/(m·K)]. The heat source in this modelling is the heat dissipation occurring due to the electric current flowing in the cable and the losses in water, which are simulated by computing a parametric sweep for a temperature difference of 30°C between water and the reference ambient temperature of 20°C. This forms the basis for electric fields and temperature coupling.

4. Experimental Setup

The experimental technique chosen hereby is the development of an analogy between electrical and thermal effects using the following physical equations [6];

Equating the above two equations *Eq (9)* and *Eq (10)* for considering the path travelled by the heat from inside (i) of the cable to the outside (o) surface of the FRP body of CaTr, the following thermal resistance value (R_{th}) has been derived;

$$R_{th} = \frac{\ln(o/i)}{2 \pi k L} \quad (11)$$

On similar lines it can be further appreciated that;

$$\frac{dQ}{dt} = \frac{\Delta T}{R_{th}} \quad (12)$$

Eq (12) can be compared to the Ohm's Law of electricity studies; $I = V / R$ (here; $R \approx R_{th}$). Hence, the analogy that is understood and verified with COMSOL results is that the temperature gradient (ΔT) is equivalent to voltage (V) and the heat flux (dQ/dt) is equivalent to the current (I) flowing through the cable causing the heat flow [6].

The capacitive effect in case of AC is not seen in DC *Figure 4*; the indicated area. The adjacent zoomed-in temperature plot is the water temperature in the outer concentric area. This temperature is, as expected, higher than the other parts. Here, the incompressible nature of water is verified where most of the heat transfer takes place. The circulation of water provides an effective convective heat transfer and hence hardly any temperature rise on the outer surfaces of FRP is observed.

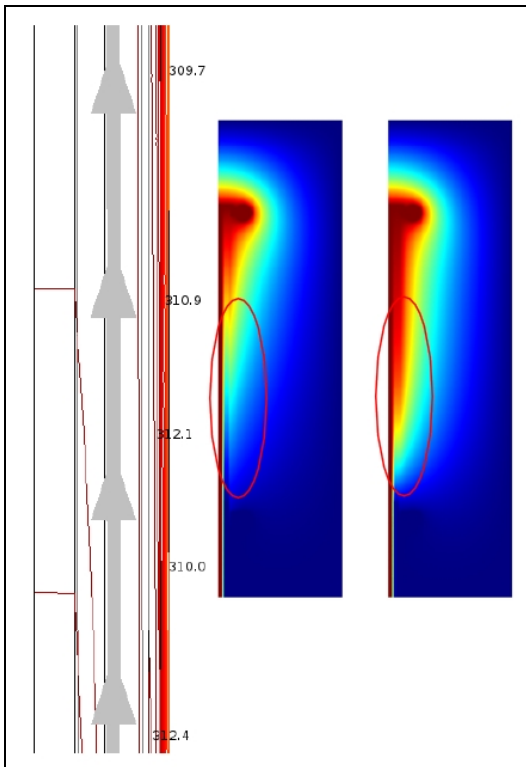


Figure 4. The Temperature plot showing the implementation and agreement with the derived electrical-thermal analogy; the center plot indicates the DC potential for the applied 500 kV voltage; the right plot indicates the AC potential for the applied 500 kV peak voltage (350 kV rms).

5. Results

Even though the modelling work presented hereby does not seek to compare the simulation outcome with experimental results, the results of the simulation are found to be in complete agreement with the practically observed behaviour of CaTr from the in-house high voltage experience and it is also found to be consistent with theoretical expectations, as presented in this work, within acceptable tolerances.

One important aspect in analyzing the results is the AC - DC electric field stress in the polyethylene insulation of the cable and across the FRP surfaces of CaTr as these two are the most damage prone areas due to the electric field stress. This can be seen from *Figure 5*.

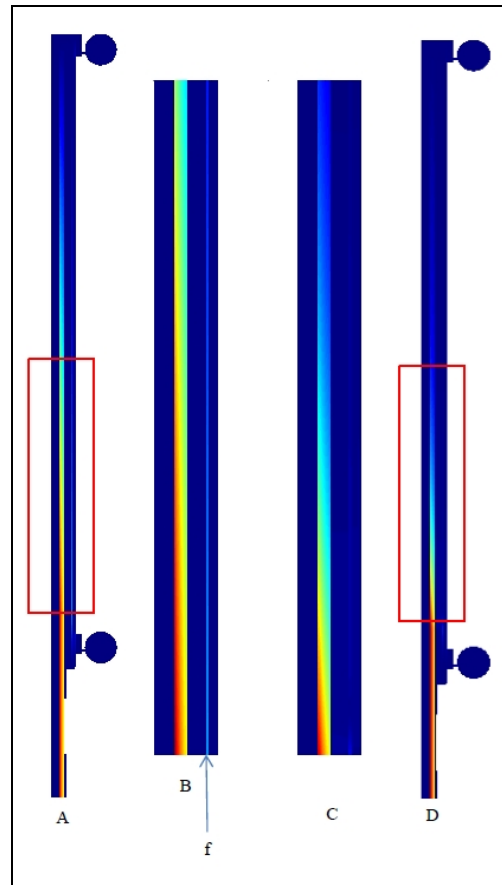


Figure 5. The Surface plot of the electric field clearly shows the difference in the DC (A) AC (D) influence on the polyethylene and FRP surfaces.

The *Figure 5* clearly shows that the influence of DC is severe, however, the electric field is found to be linearly distributed in both the cases. A further attempt to understand the influence of electrical conductivity of water can be seen in the *Figure 6*. The conductivity of water is seen to be pushing the electric field towards the surface with a comparatively lower conductivity i.e., FRP. Hence, we see that at the inner FRP (i.e., at the inner concentric FRP tube) the DC stress is higher compared to AC stress *Figure 5(B)* – arrow at 'f' shows this influence of DC on FRP which is not to be seen for AC; *Figure 5(C)*. However, at the outer FRP surface the effect is vice versa. Here, an attempt is made to verify the integral equation; $\int E \, ds = V$ and the AC potential is chosen to be the peak value. The y-axis in *Figure (6)* and *Figure (7)* indicates the normalized electric field stress [kV/cm].

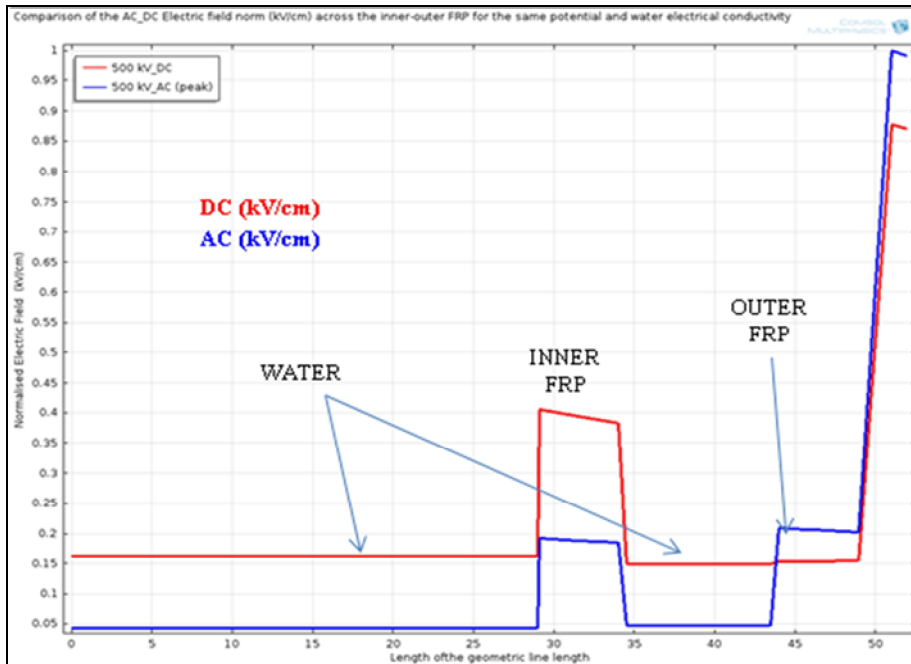


Figure 6. The Line Plot (graph) of the normalized electric field stress starting from the water in the inner concentric portion to inner FRP and finally to the outer FRP via the water in the outer loop.

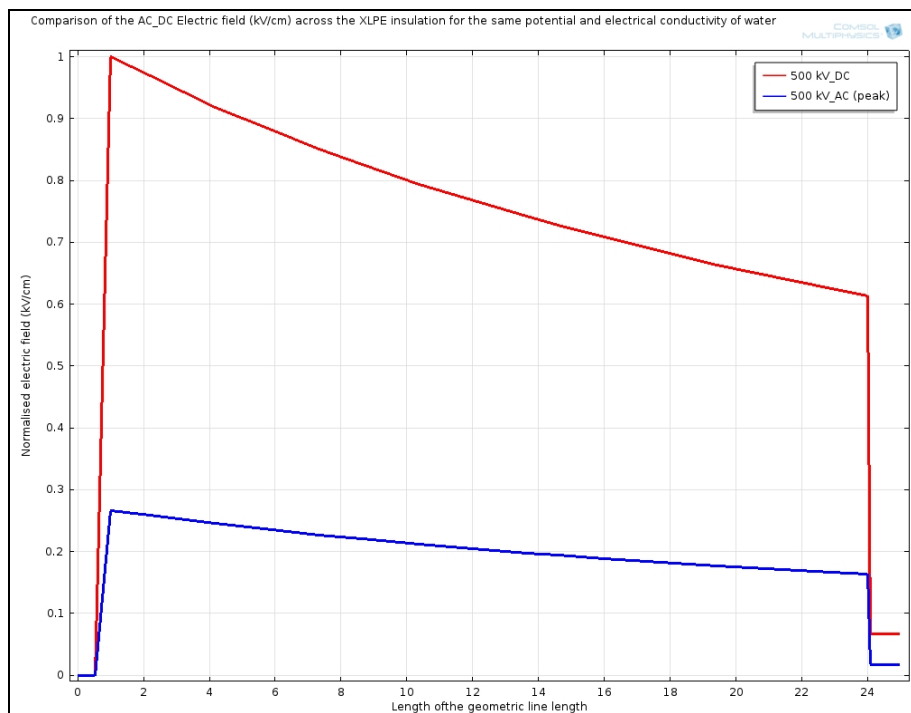


Figure 7. The Line Plot (graph) of the normalized electric field stress (kV/cm) across the polyethylene (XLPE) insulation of the cable.

6. Conclusion

A two dimensional Finite Element Method (FEM) model using COMSOL Multiphysics® has been developed for water controlled Cable Termination (CaTr) with a 3000 mm² XLPE Cable inside it. The electric field computation has been performed for both, AC and DC voltage stresses and a significant influence of the electrical conductivity of water has been observed. The physical effect of electric field distribution, in case of AC and DC, has been observed. These electric field effects have been verified with analytical derivations based on real-life physics and practical in-house high voltage experience. The simulated values have been found to match our requirements within acceptable tolerances.

The technical adaptability of scientific computation using FEM modelling and simulation tool, COMSOL Multiphysics®, has been demonstrated for its importance in the area of high voltage equipment design and optimization. Such methodology is supportive in updating and meeting the state-of-the-art requirements of the power industry, especially in high voltage engineering where the recent trend of increasing voltage levels and simultaneous decreasing device sizes push the technology limits to a new higher level, which in our case is the present shift of technology from AC to DC.

7. References

- [1] IEC 62067(2001-10), Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) - Test methods and requirements
- [2] Ralf Pietsch et al. Optimised cable end termination system with water conditioning unit, XIIIth International Symposium on High Voltage Engineering, Netherlands 2003, Smit (ed.) ISBN 90-77017-79-8
- [3] Alexander Eigner, Developments in Stress Control Systems in HV Cable Accessories, INMR World Congress 8-11 September 2013, Vancouver Canada

[4] Ralf Pietsch, On-site testing of extruded AC and DC cables above 36 kV and up to 500 kV - Some thoughts about the physics behind it, standards and test techniques, 2012 CIGRE Canada Conference, Montreal, Quebec, September 24-26, 2012

[5] HIGHVOLT Technical brochure of Water End Termination. Available for download at: <http://www.highvolt.de/desktopdefault.aspx/tabid-1163/>

[6] E. Marin, Characteristic dimensions for heat transfer, Lat. Am. J. Phys. Educ. Vol. 4, No. 1, Jan. 2010

8. Acknowledgements

I would hereby like to express my heartfelt gratitude to HIGHVOLT Prüftechnik Dresden GmbH, Germany for providing me with an opportunity to work on challenging high voltage design-engineering tasks while I am still about to complete my master's study from BTU Cottbus-Senftenberg, Germany. I would also like to extend my sincerest thanks to Dr. Ralf Pietsch, my mentor at HIGHVOLT, for his valuable guidance, expertise and for his practical knowledge sharing sessions in fulfilling my assignments and this presented work effectively.