ELECTRICAL-THERMAL OPTIMIZATION OF END CORONA PROTECTION SYSTEMS ON LARGE ROTATING MACHINES BY USE OF NUMERICAL OPTIMIZATION ALGORITHM BASED ON FEM

C. Staubach[1], S. Kempen[1], F. Pohlmann[1] and F. Jenau[2]
[1]Siemens AG Energy
Rheinstr. 100, 45478 Muelheim / Ruhr, Germany
[2]TU Dortmund
Friedrich-Woehler-Weg 4, 44227 Dortmund, Germany

Abstract: Due to highly nonlinear material characteristics the design of end corona protection systems (ecp-system) is a difficult and time consuming process. In order to accelerate this process a finite element model is developed. The model takes the nonlinear electrical and thermal coupled material properties into account. Furthermore it is able to calculate the electric and thermal behavior of a painted or taped ecp-system. The goal of this work is to present strategies to determine optimal ecp-configurations for a minimization of the electrical as well as the combined electrical-thermal stress caused by the potential grading. Effects of changing these system parameters (ecp-length, material properties) with regard to the electrical field strength and resulting temperature distribution are presented by means of fem-calculations. In a next step the theoretical performance limits received by the fem-model of 1 – 4 layer ecp-systems are determined, compared and quantified. Therefore several numerical, global bounded optimization algorithms are implemented in the fem-model. As a result one of these algorithms is a self developed, partial swarm based simplex optimization (PSBSO), which obtains the best results for this special optimization problem.

1 INTRODUCTION

Groundwall insulation, internal potential grading (IPG), outer corona protection (OCP), and end corona protection (ECP) are typical components of the insulation system of stator winding coils of large turbine-generators.

A triple junction region is developed at the exit point of the stator bars out of the stator core. The resulting tangentially stressed interfaces represent marked weak points in an insulation system.

In order to prevent this, capacitative-resistive potential grading is implemented in the area of the end of the outer corona protection to reduce the increase in field strength. The capacitative part results from the groundwall insulation, while the resistive part is realized by semi conductive varnishes or impregnated tapes normally based on silicon carbide. The feature of these conductive varnishes or tapes is the in part highly nonlinear resistance characteristic which allows no analytical solution of the describing partial differential equations [1,2,3]. However to increase the efficiency of the ECP a numerical model is needed to perform numerical optimization algorithm. Beside the effect of reducing electrical-thermal stress caused by the ECP to avoid potential failure of a generator, the total ecp-length can also be shortened with optimization without exceeding the electrical and thermal stress limits. These results in additional degrees of freedom for the generator, respectively the end windings design.

A possible optimization/decreasing of the groundwall insulation thickness cause an increase of the capacitive currents which results also in a necessity of ecp-optimization.

2 FINITE ELEMENT MODEL

The most important part in the numerical optimization is the finite element model itself. All the optimization results are depending on the accuracy of the models calculation results. Because of probabalistic restarts of most of the optimization algorithm an additional requirement is a preferably short calculation time.

A three dimensional, full parameterized model was developed, which consist of up to 9 ecp-layers on a rectangular cross-section and takes effects like forced cooling with air or hydrogen into account. The strong electrical and weaker thermal coupling caused by the ecp-material is considered by to nested recursion loops [1]. Normally a harmonic quasi-static analyze is performed, in this case harmonics of higher order are neglected. Recent works have been published that there is still a very good correlation between calculation and measurement results [1,4].

The dependence on temperature and electrical field strength of the specific resistance of the ecp-material is implemented either with three dimensional tables of measuring results or with an analytical regression fit (see Chapter 4).

With a modern desktop pc (QuadCore, 16 GB RAM, 64 Bit) it is possible to perform one calculation cycle in about 30 to 120 seconds, depending mainly on the inhomogeneity exponents α (see Chapter 4) and chosen convergence criteria.

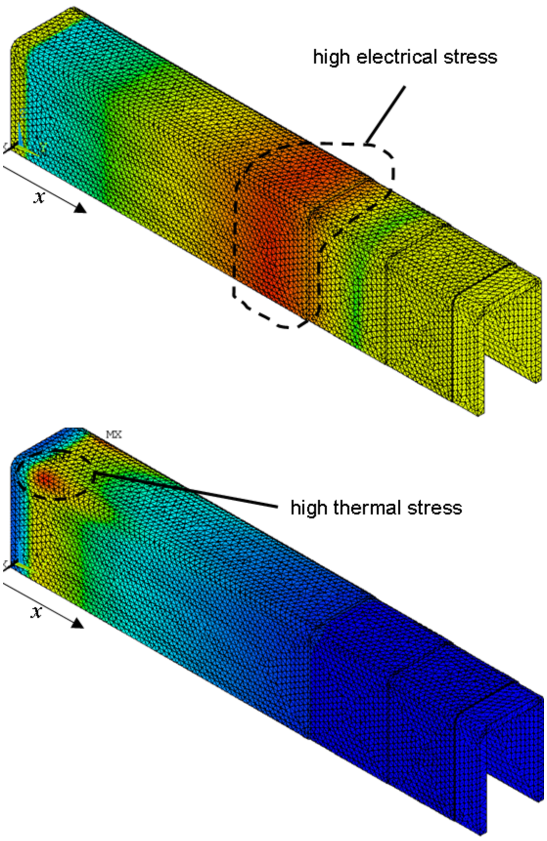


Figure 1: False-color plots of tangential field strength $E_{tan}[x]$ (top) and temperature distribution v (bottom) calculated numerically

Figure 1 shows a model of real stator bar geometry with groundwall insulation, outer and end corona protection (OCP resp. ECP). In this example the half-section is presented due to symmetry effect reducing the calculation time. The copper bar itself is not modeled. Although false-color plots are an adequate possibility for a rough estimation of electrical and thermal distribution, detailed qualitative determination are easier to perform with path plots. In the following discussions we will speak about electrical and thermal stress which is the point of interest to quantify the efficiency of the potential grading system.

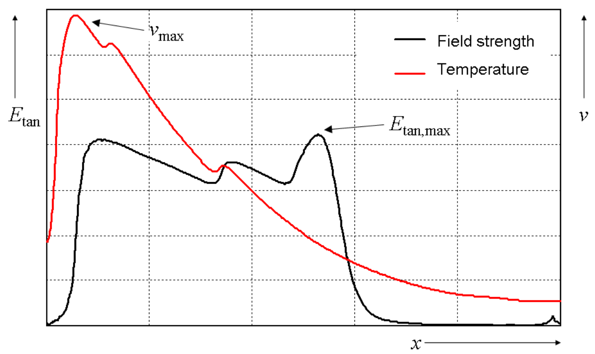


Figure 2: Example of path plots of tangential field strength E_{tan} and temperature v along the insulation surface according to the x-axis in figure 1

Figure 2 shows the tangential field strength E_{tan} and the temperature v along the insulation surface (x-axis in figure 1). The electrical stress is quantified by $E_{tan,max}$ the thermal stress by v_{max}.

3 ELECTRICAL-THERMAL DESCRIPTION OF ECP-MATERIAL

Besides varying the geometrical configuration (ecp-layer length and number) the goal of the numerical optimization is to quantify the best ecp-material properties. Therefore an analytical model is necessary which describes the electrical and thermal behavior with high accuracy.
In regard to the electrical characteristics two classes of equations have been developed. The common power-law model (see equation 2) gives the relation between the specific resistance ρ and the applied field strength $|E|$ [5,6,7].
Both constants, n as well as k, are specific material parameters.

$$\rho = k \cdot E^{n} \qquad (2)$$

The second class of equation is the exponential model

$$\rho = k \cdot e^{n \cdot E} \qquad (3)$$

which correlates very well with measurement results especially for silicon carbide (sic) [8,9,10].
In this work we suggest a variation of power-law model (equation (2)) which takes into account theoretical switching field strength E_G where the constant specific resistance ρ_0 of a semiconductor starts to decrease nonlinear.

$$\rho(E) = \begin{cases} \rho_0 & E < E_G \\ \rho_0 \left(\dfrac{E}{E_G}\right)^{1-\alpha} & E \geq E_G \end{cases} \qquad (4)$$

In addition it handles more friendly specific resistances for small electrical fields which are significant in numerical calculations.
The thermal dependence of the ecp-material is described with the so called Beta-equation for high-temperature-conductors [11].

$$\rho(T) = \rho(T_0) \cdot e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} \qquad (5)$$

The material constant B is set to a value determined out of comprehensive measurements on sic.

$$\rho(T,E) = e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} \cdot \begin{cases} \rho_0(T_0) & E < E_G \\ \rho_0(T_0) \left(\dfrac{E}{E_G}\right)^{1-\alpha} & E \geq E_G \end{cases} \qquad (6)$$

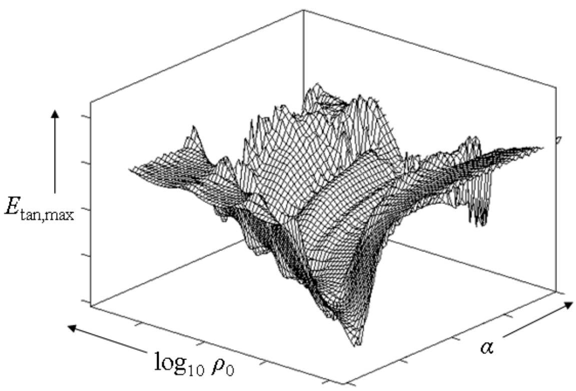
The combination of the electrical and thermal equations (4) and (5) is presented in the following equation with the specific resistance $\rho_0(T_0)$ at absolute temperature T_0, the inhomogeneity exponent α and the switching field strength E_G as degrees of freedom (DoF) for optimization.
All the presented results of electrical and electrical-thermal optimization are based on this equation.

4 NUMERICAL OPTIMIZATION ALGORITHMS

Several problems have to be solved with regard to a numerical optimization based on fem-simulation. Due to the developed multiple coupled electrical-thermal FEM-model (see chapter 2) and the resulting calculation time the optimization procedure has to be efficient as well as effective.
Therefore several strategies for optimization were tested for this special problem. A challenge is to take the strong exponential effect of the parameter α into account. As a result of the investigation a new optimization routine called PSBSO (particle swarm based simplex optimization) is introduced. This routine combines the positive features of particle swarm optimization (PSO) [12] and globalized bounded nelder-mead algorithm (GBNM) [13], which are bordering by PSO and finally finding the location of the global optimum by GBNM.
The capability of the optimization routine PSBSO is verified for a single layer ecp-system with fixed length, variable inhomogeneity exponent α and specific resistivity ρ_0. For this configuration it is possible to compare the results obtained by PSBSO with brute force (BF) iteration. In example to determine the plot in figure 3 with BF both parameters, α as well as ρ_0 are discretized in 100 values. With a total of 10000 material-combinations the total calculation time is about 170 hours. The global minimum for the ecp-configuration with the lowest value of the electrical stress Min $\{E_{tan,max}\}$ along the insulating surface can be found this way.
Results of PSBSO fall below these value for the first time after about 750 iterations or about 12 hours. The advantage of an optimization routine like PSBSO compared to BF becomes apparent, if the DoF are increased. Assuming a total of 27 DoF (9 ecp-layer), each discretized in 100 values, the calculation with BF would take about $1.6{\cdot}10^{46}$ years.

5 ELECTRICAL OPTIMIZATION

For electrical optimization of the potential grading system a fundamental knowledge about the electrical and thermal behavior with regard to material parameter variation is essential.
This can be realized especially for 1-layer ecp-systems where the DoF are restricted to the 2-3 material parameters of the grading material.



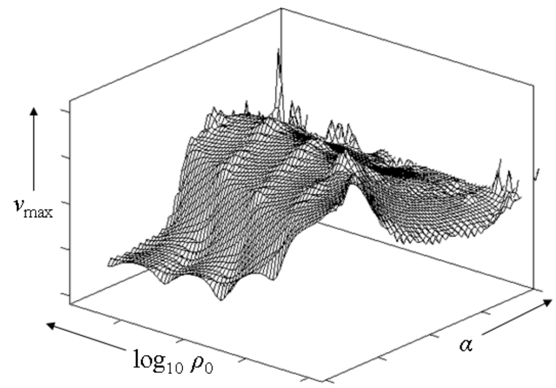


Figure 3: Qualitative surface plots of max. electrical stress $|E_{tan,max}|$ (top) and thermal stress v_{max} (bottom) over inhomogeneity exponent and specific resistance

If not mentioned in particular all the following calculation results are determined for fixed copper bar geometry, groundwall insulation thickness, total ecp-system length, switching field strength E_G, thermal conductivity and heat transfer coefficient.

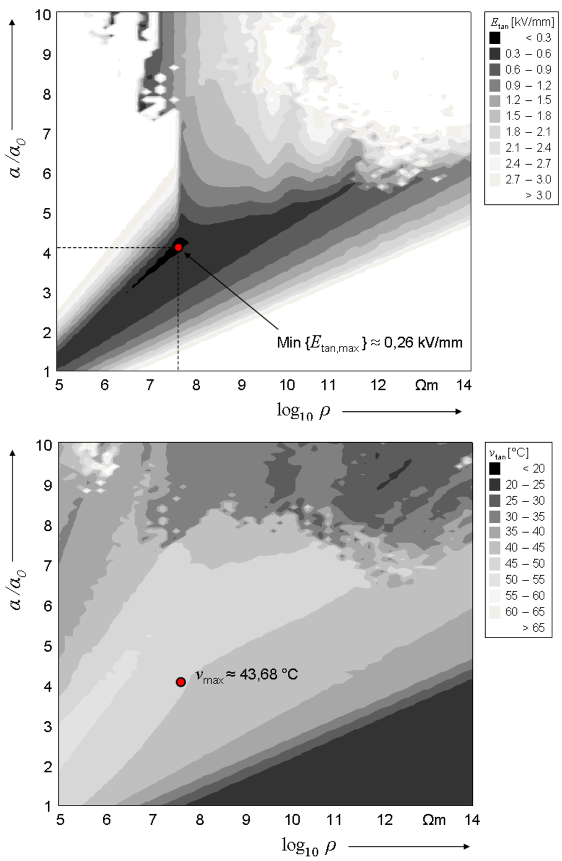


Figure 4: Exemplary scatter-plots obtained with bf-algo-rithm for ectrical stress $E_{tan,max}$ (top) and thermal stress v_{max} (bottom) distribution depending on the material parameters (highlighted are the global minimum of the electrical stress Min$\{E_{tan,max}\}$ and the corresponding temperature)

Figure 3 (top) shows a three dimensional surface plot with the resulting maximum value of tangential field strength $|\underline{E}_{\mathrm{tan,max}}|$ depending on specific resistance ρ_0 and inhomogeneity exponent α obtained with BF. igure 3 (bottom) illustrates the corresponding maximum ecp-temperatures v_{max}.
The region with low electrical stress is visible. The resistive grading works for these material-combinations very well but is also characterized by high maximum ecp-temperatures v_{max}. However a better imagination may be provided by two dimensional contour-plots. The corresponding type of plots is seen in figure 4.
To give an estimation about the combined electrical and thermal stress scatter-plots with v_{max} over $E_{\mathrm{tan,max}}$ shown in figure 5 are a good means. The axis are standardized to E_0 = 1 kV/mm and v_0 = 1 °C respectively. Each dot symbols an actual combination of an ecp-material. In regard to the electrical stress only ecp-configuration with $E_{\mathrm{tan,max}} \leq 0.9$ kV/mm are highlighted. The determined global electrical minimum Min $\{E_{\mathrm{tan,max}}\}$ with BF-algorithm is clear visible. To take the nonlinear effect of increasing the applied voltage into account the scatter-plots are presented for 30 kV respectively 60 kV (RMS).
According to [14] the inception field strength E_{PD} for partial discharges on tangential stressed insulation surface is approximately 0.65 kV/mm.

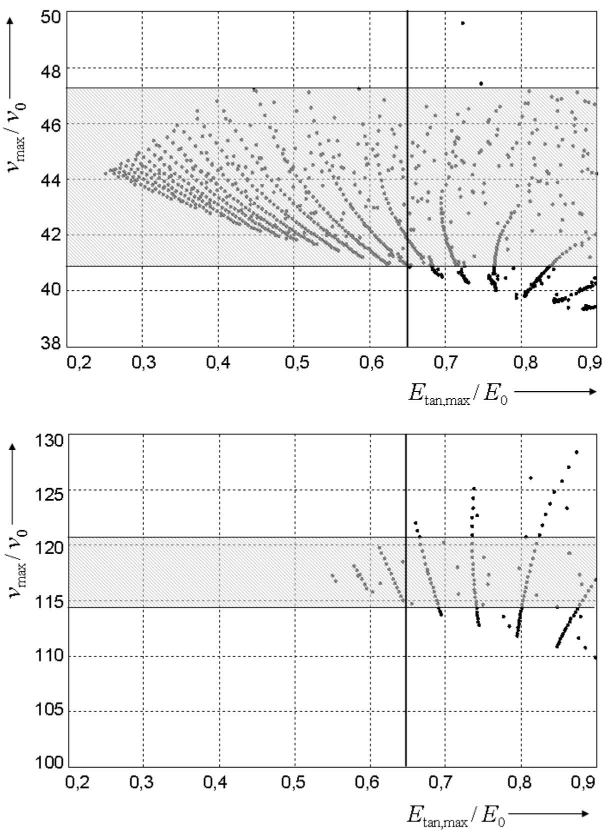


Figure 5: Standardized scatter-plots with resulting electrical and thermal stress relation for 1-layer ecp-configurations obtained with bf-algorithm (30 kV top; 60 kV bottom)

In the case of an applied higher voltage the absolute values of $E_{\mathrm{tan,max}}$ increases as well as the resulting ecp-temperatures v_{max}. Only a couple of ecp-confiur-tions calculated with bf-algorithm still fall below the inception field strength E_{PD}.
The possibility to control the thermal stress via material characteristic for field strength below E_{PD} is restricted to about $\Delta v_{\mathrm{max}} \approx 6$ K (30 kV) respectively $\Delta v_{\mathrm{max}} \approx 8$ K (60 kV) for assumed free convection (see marked areas in figure 5).

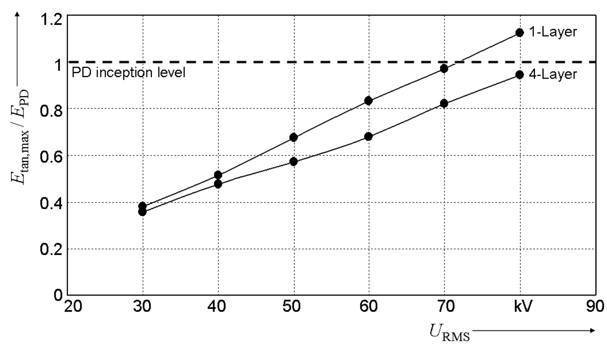


Figure 6: Calculated minimal electrical stress $E_{\mathrm{tan,max}}$ (standardized to E_{PD}) for optimized ecp-configurations and different applied voltages (fixed total ecp-length, groundwall insulation thickness)

Finally in figure 6 the electrical stress $E_{\mathrm{tan,max}}$ related to E_{PD} is highlighted for different applied voltages up to 80 kV (RMS). The values are the minima determined by means of the optimization algorithm PSBSO for 1-layer respectively 4-layer ecp-configurations. This pointed out that theoretical for ideal ecp-properties the electrical stress on the insulation surface for different number of layers differs only slightly.
However if ideal ecp-materials are not available the geometrical aspect of several layers with regard to minimize electrical stress increases. Recent numerical calculations pointed out that in regard to the variance of ecp-properties provided by suppliers the effect on resulting electrical stress is decreased by increasing layer numbers.

6 ELECTRICAL-THERMAL OPTIMIZATION

The scatter-plots shown in figure 5 point out that within an electrical stress beneath the inception field strength it is possible to influence the resulting thermal stress v_{max}. Although this effect is very limited in the case of 1-layer ecp-system the question may arise what happens if the number of ecp-layers is increased.
To analyze this issue comprehensive optimization calculations were performed based on the fem-model. Due to the structure of the implemented optimization algorithm PSBSO it is possible to provide scatter-plots with the resulting electrical and thermal stress relations of the local optimum ecp-configuration based on probabalistic restart iterations. The scatter-plots shown in figure 7 are determined for an applied voltage of 60 kV (RMS),

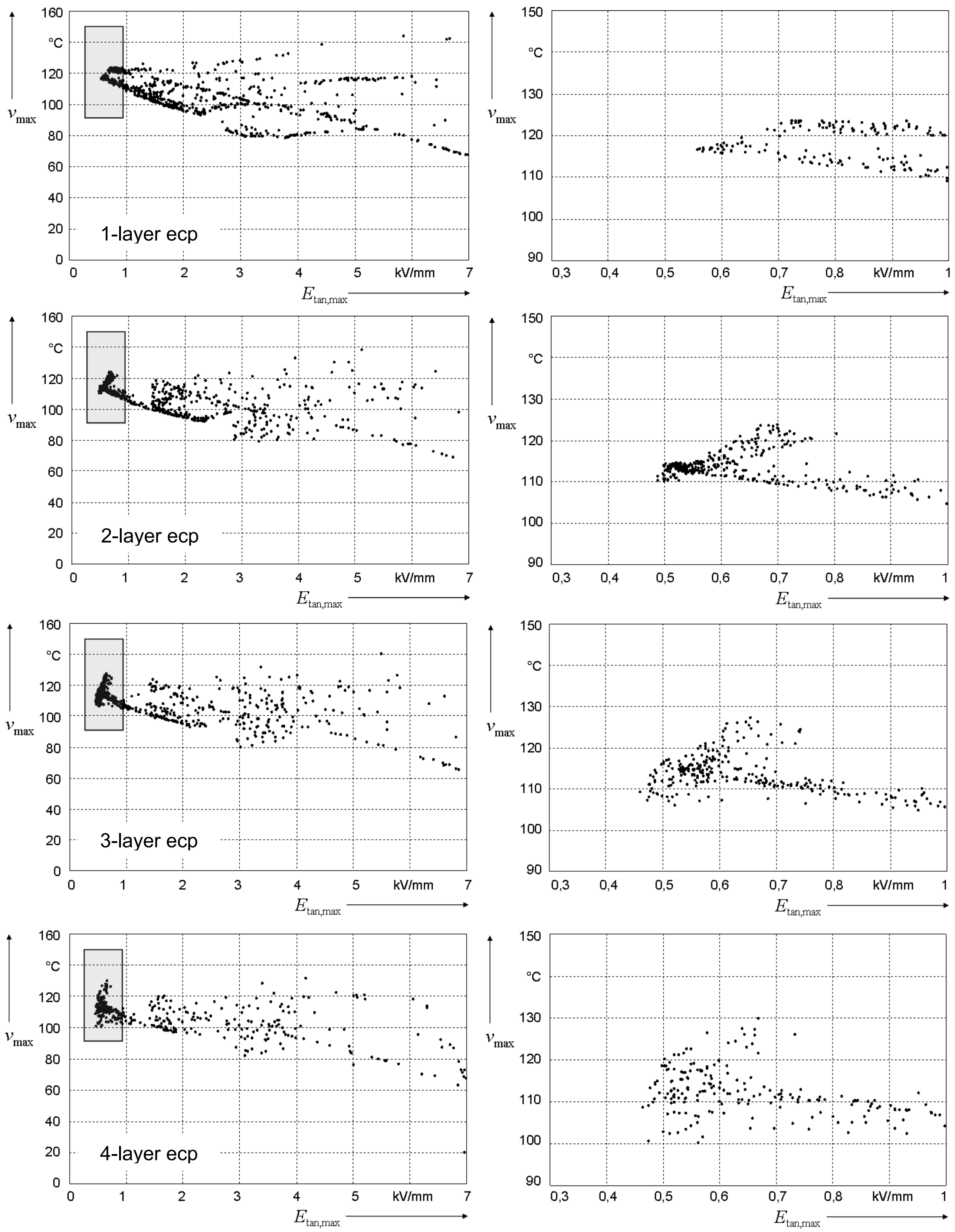


Figure 7: Scatter-plots of ecp-configurations with electrical $E_{tan,max}$ and thermal v_{max} stress relation obtained with numerical optimization PSBSO based on FEM (1000 probalistic restarts, 60 kV (RMS); from 1-layer-configuration (top) up to 4-layer-configuration (bottom)

which is in the region of values for high voltage testing on large rotating machines. The plots for 1-layer-configurations (top) to 4-layer-configurations (bottom) present on the left hand side the global electrical and thermal stress region on the right hand side a detailed view is illustrated. Although the scatter-plot for the 1-layer ecp-system is calculated by means of PSBSO the pattern equals figure 5 very well.

These calculations illustrate that within an electrical stress beneath the inception field strength it is possible to influence the resulting thermal stress v_{max}. For assumed free convection it is possible to to adjust v_{max} in a range of $\Delta v_{max} \approx 30$ K (60 kV)

7 SUMMARY AND OUTLOOK

The paper gives an impression about the electrical and thermal behavior of ecp-systems related to variable material characteristics. With the help of artificial and efficient numerical optimization algorithms it is possible to perform electrical and electrical-thermal stress reducing on the multiple coupled ecp-systems.

In the case of electrical optimization the best ecp-material characteristic depends strongly on applied voltage and total ecp-length.

The possibility of a combined electrical and thermal optimization increases with an increasing number of ecp-layers.

In regard to pure electrical stress optimization by adjusting the geometrical configuration qualification of a new modified ecp-configuration on a global vacuum pressure impregnated generator with 21 kV rated voltage and about 542 MVA output was passed successfully.

To perform further combined electrical-thermal optimization on ecp-configurations new semiconducting materials with variable material characteristics have to be developed.

Regarding to new ecp-materials a R&D project is currently running and first ecp-configurations with calculated ideal material parameters ρ_0 and α (top-down-approach) are tested.

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