General Equation to Determine Design Rules for Mitigating Partial Discharge and Electrical Breakdown in Power Module Layouts

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Partial Discharge

https://www.youtube.com/watch?v=Q5xGicxtNM

End-Winding  Cables  Transformers  DBC test coupon

Cable joints
Existing PD Models

- **Electrical Point of View**
  Three-capacitor (ABC) model

- **Field Point of View**
  - Pederson’s model – considers volume and surface charge density
  - Conductance model – considers current density
  - Niemeyer’s model – considers avalanche and streamer propagation
  - Plasma model – fluid equations
  - Numerical simulation model – temporal and spatial distribution

- **Other models**
2D Simulations

Model geometry

Parameter range:
- Trace gap: 0.5mm to 5.0mm
- $\varepsilon_r$: 1 to 10
- Voltage: 5kV to 30kV

Metal traces, 0.125 mm thick
Ceramic Isolation, 0.625 mm thick

Partial Discharge
Existing Models
2D Simulations
3D Simulations
Design Rule Implementation in PowerSynth
Effect of Filleting
2D Simulations

Model geometry

Parameter range:
- Trace gap: 0.5mm to 5.0mm, step size: 0.5mm
- \( \varepsilon_r \): 1 to 10, step size: 1
- Voltage: 5kV to 30kV, step size: 5kV

E-field distribution

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2D Simulations

Model geometry

Parameter range:
Trace gap: 0.5mm to 5.0mm
step size: 0.5mm
\( \varepsilon_r \): 1 to 10
step size: 1
Voltage: 5kV to 30kV
step size: 5kV

Power curves

E-field vs. trace gap for corner cases of the parametric sweep of voltage and relative permittivity at a point close to the triple point

- \( y = 8.9 \times 10^7 x - 6.3 \times 10^{-1} \) with \( R^2 = 1.0 \times 10^0 \)
- \( y = 7.9 \times 10^7 x^{5.5} - 6.3 \times 10^{-1} \) with \( R^2 = 1.0 \times 10^0 \)
- \( y = 1.5 \times 10^7 x^{5.3} - 6.3 \times 10^{-1} \) with \( R^2 = 1.0 \times 10^0 \)
- \( y = 1.3 \times 10^7 x^{5.5} - 6.3 \times 10^{-1} \) with \( R^2 = 1.0 \times 10^0 \)
2D Simulations

General form of equation

\[ E = f(v, \varepsilon_r) x^{-g(v, \varepsilon_r)} \]

Where

- \( E \) is the electric field in kV/mm,
- \( v \) is the voltage in kV,
- \( x \) is the gap between traces A and B in mm,
- \( \varepsilon_r \) is the relative permittivity of the encapsulating material
- \( f \) and \( g \) are functions of \( v \) and \( \varepsilon_r \).

Power curves

E-field vs. trace gap for corner cases of the parametric sweep of voltage and relative permittivity at a point close to the triple point

Partial Discharge
Existing Models
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2D Simulations

General form of equation

\[ E = \frac{v}{5} f_{5kV}(\epsilon_r) x^{-g(v, \epsilon_r)} \]

Where

- \( E \) is the electric field in kV/mm,
- \( v \) is the voltage in kV,
- \( x \) is the gap between traces A and B in mm,
- \( \epsilon_r \) is the relative permittivity of the encapsulating material
- \( f \) and \( g \) are functions of (\( v \) and) \( \epsilon_r \).

Coefficient, \( \frac{v}{5} f_{5kV}(\epsilon_r) \) in mC/m²

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<tr>
<th>( \epsilon_r )</th>
<th>5 kV</th>
<th>10 kV</th>
<th>15 kV</th>
<th>20 kV</th>
<th>25 kV</th>
<th>30 kV</th>
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Exponent, \( g(v, \epsilon_r) \)

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3D Simulations

General form of equation

\[ Q_S = f(v, \varepsilon_r) \times' - g(v, \varepsilon_r) \]

\[ \rightarrow Q_S = \frac{v}{2.5} f(\varepsilon'_r) \times' - g(\varepsilon'_r) \]

Where

- \( Q_S \) is the surface charge density in mC/m²,
- \( v \) is the voltage in kV,
- \( x' \) is the ratio of the gap between traces A and B, and the gap between traces A and C.
- \( \varepsilon'_r \) is the relative permittivity of the encapsulating material relative to the relative permittivity of the ceramic,
- \( f \) and \( g \) are functions of \( \varepsilon'_r \).

Model geometry

A: Variable voltage Cu trace
B: 0 V Cu trace
C: 0 V back side Cu trace
D: Balloon boundary region
E: Encapsulant material
F: Ceramic (Al₂O₃)
TP: Triple point
MP: Measurement point
Ceramic thickness: 1mm
Metal thickness: 0.3mm

Effect of Filleting

Partial Discharge
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Design Rule
Implementation in PowerSynth
3D Simulations

Power curves

Surface charge density vs. trace gap for corner cases of the parametric sweep of voltage and relative permittivity

\begin{align*}
\text{Coefficient, } [\gamma/2.5 f(\varepsilon'_r)] \text{ in mC/m}^2 \\
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\varepsilon_r & \varepsilon'_r & 2.5 \text{ kV} & 5 \text{ kV} & 7.5 \text{ kV} & 10 \text{ kV} & 15 \text{ kV} & 20 \text{ kV} \\
\hline
1 & 0.102 & 0.047 & 0.097 & 0.150 & 0.190 & 0.290 & 0.390 \\
2 & 0.204 & 0.093 & 0.190 & 0.280 & 0.370 & 0.560 & 0.740 \\
3 & 0.306 & 0.130 & 0.270 & 0.400 & 0.530 & 0.800 & 1.100 \\
4 & 0.408 & 0.170 & 0.340 & 0.520 & 0.690 & 1.000 & 1.400 \\
7 & 0.714 & 0.280 & 0.550 & 0.830 & 1.100 & 1.700 & 2.200 \\
10 & 1.020 & 0.370 & 0.750 & 1.100 & 1.500 & 2.200 & 3.000 \\
\hline
\end{array}
\end{align*}

\begin{align*}
f &= 0.35\varepsilon'_r + 0.02 \\
g &= 0.20\varepsilon'_r + 0.40
\end{align*}
3D Simulations

General form of equation

\[ Q_s = \frac{v}{2.5} f(\varepsilon'_r) x^{-g(\varepsilon'_r)} \]

\[ \Rightarrow x = e^{\left(\frac{1}{g} \ln\left(\frac{\frac{v}{2.5} f(\varepsilon'_r)\frac{1}{Q_s}}{1}\right)\right)} \]

\[ \Rightarrow x = e^{\left(\frac{1}{g} \ln\left(\frac{\frac{v}{2.5} f(\varepsilon'_r)\frac{1}{\varepsilon_0\varepsilon_r E*10^9}}{1}\right)\right)} \]

\[ \Rightarrow x = e^{\left(\frac{1}{0.20 \varepsilon_r + 0.40} \ln\left(\frac{\frac{v}{2.5} (0.35 \varepsilon'_r + 0.02)\frac{1}{\varepsilon_0\varepsilon_r E*10^9}}{1}\right)\right)} \]

where

- \( Q_s \) is the surface charge density in mC/m²,
- \( E \) is the electric field in kV/mm,
- \( v \) is the voltage in kV,
- \( x \) is the ratio of the gap between traces A and B, and the gap between traces A and C. For ceramic thickness = 1mm, \( x \) gives trace-gap A-B in mm.
- \( \varepsilon'_r \) is the relative permittivity of the encapsulating material relative to the relative permittivity of the ceramic,
- \( f \) and \( g \) are functions of \( \varepsilon'_r \).
Implementation in PowerSynth

Manufacturing Design Kit (MDK) and Design Rule Check (DRC)

Default layout vs. Layout with design rules applied

W: lateral width of trace
X: lateral trace gap
E: minimum enclosure
T: vertical thickness of a layer
D: device
P. trace: power trace; S. trace: signal trace
S: substrate attach or die attach

Partial Discharge
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Effect of Filleting
Effect of filleting sharp corners

E-field and $Q_s$ are almost halved

Partial Discharge
Existing Models
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Design Rule Implementation in PowerSynth
Effect of Filleting
Filleting reduces mechanical stress

**Bottom view**

- **Max stress** = 301 MPa
- Sharp

**Top view**

- **Max stress** = 247 MPa; 18% reduction.
- Fillet

**Effect of Filleting**

- Partial Discharge
- Existing Models
- 2D Simulations
- 3D Simulations
- Design Rule Implementation in PowerSynth
Effect of filleting sharp corners

Application of fillets in PowerSynth

\[ E = E_{\text{max}}; \text{gap} = 2.04 \text{ mm} \]

No fillet

\[ E = 0.65 E_{\text{max}}; \text{gap} = 2.04 \text{ mm} \]

1 mm fillets

\[ E = E_{\text{max}}; \text{gap} = 0.75 \text{ mm} \]

1 mm fillets

\[ \leftarrow \text{Gap can be reduced to about 40\% of the original gap if fillets are applied.} \]
Summary

- Partial discharge.
- 2D simulations of E-field focusing.
- 3D simulations of surface charge density.
- General equation developed for determining trace gap.
- Effect of filleting sharp corners.
- Implementation of trace-gap design rules and fillets in PowerSynth.
Coming up next...

- Enhancing the general equation with
  - Fillet factor,
  - Derating factor based on wet-etching profile of metal on ceramic,
  - Derating factor based on voltage profile, and
  - Metal thickness variation.

- Statistical analysis through partial discharge tests to determine a margin on design rules because PD is stochastic in nature.
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