Elevated Voltage and MTBF

Voltage as a Service (VAAS)TM is an energy-saving service solution for regulating and optimizing the voltage supplied to electrical equipment to the optimal level for efficient operation. The purpose of VAAS is to reduce energy consumption, lower electricity bills, and decrease carbon emissions by ensuring that electrical devices operate at their most efficient voltage level.

Relationship Between Elevated Voltage and MTBF

The MTBF reduction due to voltage stress can be modelled using the Arrhenius equation, which relates temperature to failure rate:

$$MTBF_2 = MTBF_1 \times e^{\frac{-E_a}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)}$$

Where:

$MTBF_1$	Initial MTBF at baseline conditions
$MTBF_2$	New MTBF after temperature increase
E_a	Activation energy (in J/mol)
R_R	Gas constant (8.314 J/mol·K)
T_1, T_2	Temperatures before and after voltage increase (in Kelvin)

Elevated voltage increases operating temperatures, reducing MTBF due to **exponential acceleration of failure mechanisms**.

Case 1: Motors

Problem A motor operating at 415 V and an initial MTBF of 10,000 hours at 75°C (348 K). An 8% overvoltage (to 448 V) raises winding temperature to 85°C (358 K). Assume the winding insulation has an activation energy E_a = 1.0 eV (96,500 J/mol).

Calculation Using the Arrhenius equation:

$$MTBF_2 = 10,000 \times e^{\frac{-96,500}{8.314}\left(\frac{1}{348}-\frac{1}{358}\right)}$$

$$MTBF_2 = 10,000 \times e^{-7.76} \approx 10,000 \times 0.00042 \approx 42\,\text{hours}$$

MTBF drops from 10,000 hours to 42 hours due to the elevated voltage.

Case 2: Transformers

Problem A distribution transformer is rated for 11 kV operates with an initial MTBF of 20 years at 60°C (333 K). A 5% overvoltage raises the temperature to 70°C (343 K). Insulation in the transformer has an activation energy of E_a = 0.9 eV (87,000 J/mol).

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Calculation Using the Arrhenius equation:

$$MTBF_2 = 20 \times 365 \times e^{\frac{-87,000}{8.314}\left(\frac{1}{333} - \frac{1}{343}\right)}$$

$$MTBF_2 = 7,300 \times e^{-7.54} \approx 7,300 \times 0.00053 \approx 3.87\,\text{days}$$

With the voltage increase, the transformer's MTBF drops from 20 years to less than 4 days.

Case 3: Electronic Systems

Problem A semiconductor chip with an initial MTBF of 500,000 hours operates at 1.2 V and 40°C (313 K). A 10% voltage increase (to 1.32 V) causes the temperature to rise to 50°C (323 K). The activation energy for electromigration in semiconductors is E_a = 0.7 eV (67,500 J/mol).

Calculation Using the Arrhenius equation:

$$MTBF_2 = 500,000 \times e^{\frac{-67,500}{8.314}\left(\frac{1}{313} - \frac{1}{323}\right)}$$

$$MTBF_2 = 500,000 \times e^{-6.62} \approx 500,000 \times 0.00134 \approx 670\,\text{hours}$$

The MTBF drops from 500,000 hours to 670 hours due to the overvoltage.

Summary of Numerical Results

Equipment Type	Initial Voltage	Overvoltage (%)	Initial MTBF	New MTBF
Motor	415 V	8%	10,000 hours	42 hours
Transformer	11 kV	5%	20 years	3.87 days
Electronic System	1.2 V	10%	500,000 hours	670 hours

Conclusion

Elevated voltage has a dramatic impact on the MTBF of motors, transformers, and electronic systems. Even small over-voltages increase operating temperatures, which exponentially accelerate degradation processes such as insulation wear, metal fatigue, and electromigration. As shown in the numerical examples, MTBF can drop by several orders of magnitude due to these effects, emphasizing the importance of voltage regulation and thermal management to ensure equipment reliability.

Therefore, controlling supply voltages with the assistance of Voltage as a Service (VAAS) is critical to ensuring long equipment lifetimes.

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