Electrical Stress & Reduced Equipment Life

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.

Elevated Voltages and Reduced Equipment Life

The relationship between elevated voltages, reduced equipment life, and the Arrhenius law activation energy is crucial in understanding the impact of electrical stress on the degradation of motors, transformers, and electronic systems. In this Application Note, we explore this interplay through specific numerical examples for each type of equipment.

Arrhenius Law and Activation Energy

The Arrhenius equation is used to model how temperature affects degradation:

$$k = A e^{\frac{-E_a}{RT}}$$

Where:

K	Degradation rate
A	Pre-exponential factor (related to the frequency of degradation processes)
E_a	Activation energy (in Joules per mole)
R	Gas constant (8.314 J/mol·K)
T	Absolute temperature (Kelvin)

The equation shows that even small increases in temperature lead to exponentially higher degradation rates.

The degradation rate doubles for every 10°C increase in temperature, a general rule used in reliability engineering.

Impact of Elevated Voltages and the Arrhenius Law

In all equipment types (motors, transformers, electronics), higher voltages lead to increased losses (following **$P \propto V^2$**), which results in elevated temperatures and accelerates degradation. The Arrhenius law predicts how this temperature rise impacts lifespan.

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Case 1: Motors

Problem A motor operating at **415 V** experiences overheating due to a **10% voltage increase** (to **456 V**). Assume the winding insulation has an activation energy E_a = 1.0 eV (96,500 J/mol). Under normal conditions, the motor operates at **75°C (348 K)**, but the voltage increase raises the temperature to **85°C (358 K)**. Reference [1].

Calculation Using the Arrhenius equation:

$$\frac{k_2}{k_1} = e^{\frac{96,500}{8.314}\left(\frac{1}{348}-\frac{1}{358}\right)}$$

$$\frac{k_2}{k_1} = e^{\left(96,500\times-8.04\times10^{-5}\right)} = e^{7.76} \approx 2,350$$

Thus, the degradation rate increases by a factor of 2,350, significantly reducing the motor's life.

Case 2: Transformers

Problem A distribution transformer is rated for 11 kV and typically operates with an oil temperature of 60°C (333 K). A 5% voltage increase causes an additional 10°C rise to 70°C (343 K). Transformer insulation has an activation energy E_a = 0.9 eV (87,000 J/mol). Reference [2].

Calculation Using the Arrhenius equation:

$$\frac{k_2}{k_1} = e^{\frac{87,000}{8.314}\left(\frac{1}{333}-\frac{1}{343}\right)}$$

$$\frac{k_2}{k_1} = e^{\left(87,000\times-8.67\times10^{-5}\right)} = e^{7.54} \approx 1,900$$

The transformer's insulation degradation accelerates by 1,900 times, severely affecting its life expectancy.

Case 3: Electronic Systems

Problem A semiconductor chip operates at **1.2 V**, with a normal temperature of **40°C (313 K)**. A **10% voltage increase** causes the temperature to rise to **50°C (323 K)**. Electromigration, the primary cause of degradation in chips, has an activation energy E_a = 0.7 eV (67,500 J/mol). Reference [3].

Calculation Using the Arrhenius equation:

$$\frac{k_2}{k_1} = e^{\frac{67,500}{8.314}\left(\frac{1}{313}-\frac{1}{323}\right)}$$

$$\frac{k_2}{k_1} = e^{\left(67,500\times-9.8\times10^{-5}\right)} = e^{6.62} \approx 750$$

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The degradation rate due to electromigration increases by **750 times** with this temperature rise.

Summary of Numerical Results

Equipment Type	Normal Temp	Elevated Temp	Activation Energy (eV)	Life Reduction Factor
Motor	75°C	85°C	1	2,350
Transformer	60°C	70°C	0.9	1,900
Electronic System	40°C	50°C	0.7	750

Conclusion

Elevated voltages in motors, transformers, and electronic systems increase power dissipation, raising operating temperatures. According to the Arrhenius law, these temperature rises cause an exponential increase in degradation rates, significantly reducing equipment life. Accurate voltage regulation and thermal management are critical for extending equipment lifespans and ensuring operational reliability.

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

References

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