Causes of Reduced Equipment Life

Voltage as a Service (VAAS)™ 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 can be illustrated through quantitative examples and well-referenced studies. In this Application Note, we explore this interplay in detail.

Overview

When the voltage supplied to electrical equipment exceeds its design limits, the following impacts are observed:

- Increased power dissipation (since power ∝ voltage²)
- Elevated operating temperature, especially in resistive and semiconductor components.
- Accelerated material degradation, such as insulation wear and electromigration.

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.

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Linking Elevated Voltages, Heat, and Arrhenius Law

- **Elevated voltages** cause **higher operating temperatures**, increasing the reaction rates of physical and chemical degradation processes in the equipment's materials (e.g., insulation breakdown, metal fatigue, polymer degradation).
- The **Arrhenius law** describes this behaviour: As temperature rises, the activation energy barrier is overcome more frequently, leading to **faster material degradation**.
- **Result**: Operating equipment under higher voltages, which generates more heat, directly shortens its lifespan because the degradation processes accelerate exponentially according to Arrhenius principles.

Quantitative Example

Consider the case of motor windings insulation, where the activation energy is approximately 1 eV (96.5 kJ/mol). If the motor operates at a higher voltage, the increased current results in elevated temperature, raising the winding's temperature from **25°C (298 K)** to **45°C (318 K)**.

Using the Arrhenius equation to compare the degradation rates:

$$\frac{k_2}{k_1} = e^{\frac{E_a}{R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)}$$

Substitute E_a = 96,500 J/mol, T_1 =298 K, and T_2 = 318K :

$$\frac{k_2}{k_1} = e^{\frac{96{,}500}{8.314}\left(\frac{1}{298}-\frac{1}{318}\right)}$$

$$\frac{k_2}{k_1} = e^{\frac{96{,}500}{8.314}\cdot(-0.000336)} \approx e^{3.91} \approx 50$$

Thus, the degradation rate increases by a factor of 50 when the temperature rises from 25°C to 45°C.

Impact of Voltage on Temperature and Degradation

Using Joule's law, the power loss in a resistive component (like a transformer or cable) is:

$$P \propto V^2$$

If voltage increases by 10%, the power dissipation increases by:

(1.1)^2 = 1.21 , ie: a 21% increase

This additional heat can raise the temperature of the device, accelerating degradation according to the Arrhenius equation.

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Empirical Evidence from Research

Several studies and standards have established the connection between elevated voltage, increased temperature, and equipment life:

1. **Transformer insulation aging**: Research shows that every 6°C **increase** in operating temperature cuts the lifespan of insulation by half [1].

2. **Electronics and semiconductors**: Elevated voltages accelerate **electromigration** in semiconductors, including microprocessors, leading to failure. Studies confirm that higher supply voltages significantly increase **mean-time-to-failure (MTTF)** reduction rates [2], [3].

3. **IEEE C57.91 Standard**: This standard provides guidelines for **transformer life expectancy**, showing that elevated temperatures from excessive voltage shorten the service life exponentially [4].

Conclusion

The relationship between elevated voltages, reduced equipment life, and the Arrhenius law centres around heat generation and accelerated degradation.

Elevated voltages lead to higher power dissipation and increased operating temperatures, which, in turn, accelerate material degradation.

The Arrhenius law quantifies this effect, showing that degradation rates increase exponentially with temperature. In real-world scenarios, maintaining appropriate voltage levels is essential for extending equipment life and avoiding premature failures.

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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2. Black, J. R. “Electromigration—A Brief Survey and Some Recent Results.” *IEEE Transactions on Electron Devices*, vol. 16, no. 4, 1969, pp. 338–347.

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