RELIABILITY OF POWER CONNECTIONS

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RELIABILITY OF POWER CONNECTIONS

- Reliability requirements
- Basic feature of electrical contacts
- Connector design
- Degradation of electrical contacts
- Mitigating measures
- New trends in electrical contact design
ELECTRICAL CONTACT REQUIREMENTS

- **Electrical**: low power losses, no signal distortion, no overheating;
- **Mechanical**: stable contact force during closing and opening, high wear resistance;
- **Ecological**: resistance to environment factors, minimal pollution to the environment under fabricating, operating, and recycling conditions;
- **Ergonomic**: simplicity of design and fabrication, simple maintenance repair and replacement, possibility of combining units;
- **Economical**: minimal content of noble and deficient non-ferrous metals.
FACTORS AFFECTING CONTACT RELIABILITY

PERFORMANCE FACTORS

INTERNAL
- MECHANICAL LOAD
- MOTION (sliding, slip)
- VOLTAGE
- CURRENT
- VIBRATION
- WEAR DEBRIS
- SURFACE ACTIVATION
- CHEMICAL INTERACTION
- REAL CONTACT AREA
- CONTACT RESISTANCE
- CONDUCTING CONTACT AREA

EXTERNAL
- TIME
- TEMPERATURE
- ENVIRONMENT
- CREEP
- MATERIAL PROPERTIES
- SURFACE LAYER
- FРИTTING
- HEATING

ELECTRIC CONTACT RELIABILITY
FACTORS AFFECTING CONTACT RELIABILITY

DESIGN-TECHNOLOGICAL FACTORS

- INTERCONTACT MEDIUM
- CONTACT COATINGS (mechanical/electrical properties, thickness)
- CONTACT MATERIALS (mechanical/electrical properties)
- CONTACT SURFACE TOPOGRAPHY
- CONTACT GEOMETRY

EFFECT OF CONTACT SPOTS INTERACTIONS

SIZE OF SINGLE CONTACT SPOT

NUMBER OF CONTACT SPOTS

NOMINAL CONTACT AREA

CONDUCTING CONTACT AREA

REAL CONTACT AREA

CONSTRUCTION RESISTANCE

FILM RESISTANCE

CONTACT RESISTANCE

ELECTRICAL CONTACT RELIABILITY
BASIC FEATURES OF ELECTRICAL CONTACTS

- Surface Topography
- Contact Area
- Electrical Current at an Interface
- Constriction Resistance
- Influence of Mechanical Load
- Effect of Surface Roughness on Contact Resistance
BASIC FEATURES OF ELECTRICAL CONTACTS

• Surface Topography
BASIC FEATURES OF ELECTRICAL CONTACTS

• Electrical Current at Interface
BASIC FEATURES OF ELECTRICAL CONTACTS

• Constriction Resistance

\[ R_{ab} = R_c + R_f + R_b \]

\[ R_c = \frac{\rho}{2a} = \rho \sqrt{\frac{H}{F}} \]

\[ R_f = \frac{\sigma_f}{n \pi a^2} \]

\[ R_b = T_s^2 - T_b^2 = \frac{U^2}{4L} \]

\[ T_s \] - SUPERTEMPERATURE (Temperature of a-spot)

\[ T_b \] - BULK TEMPERATURE

\[ L \] - Wiedeman-Franz Lorenz Number = 2.45 \times 10^{-8} (V/k)
CONNECTOR DESIGN

Types of Power Connectors

- **Mechanical Connectors**
  - Split Bolt Connector
  - Parallel Groove
  - Bolted Wise Connector
  - Set Screw Lug

- **Compression Connectors**
  - H-Tap Connector
  - Compression Sleeve
  - Terminal Lug

- **Insulation Piercing**
- **Wedge Connectors**
  - Fired Wedge
  - Bolt Driven Wedge

- **Bolted Connectors**
- **Welded Connectors**
  - Exothermic
  - Friction Welded
CONNECTOR DESIGN

Types of Power Connectors

- Compression Sleeve
- "6" Compression
- "H" Compression
- Two-Bolt Parallel Grove
- Bolted Vise
- Bolt-Driven Wedge
- Fired Wedge
- Set-Screw Lug
- Insulation Piercing
- Split-Bolt
- Cable Tap
- Terminal Lug
### Comparison of different connection techniques

<table>
<thead>
<tr>
<th>TYPE OF CONNECTION</th>
<th>MECHANICAL PROPERTIES</th>
<th>ELECTRICAL PROPERTIES</th>
<th>INSTALLATION</th>
<th>REMOVAL</th>
<th>APPLICATION</th>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>OVERHEAD UNDERGROUND TAPPING</td>
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<tr>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>OVERHEAD UNDERGROUND</td>
</tr>
<tr>
<td></td>
<td>++</td>
<td>+</td>
<td>±</td>
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<td>UNDERGROUND</td>
</tr>
<tr>
<td></td>
<td>±</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>OVERHEAD UNDERGROUND TAPPING</td>
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<td></td>
<td></td>
<td></td>
<td>OVERHEAD UNDERGROUND TAPPING</td>
</tr>
</tbody>
</table>
Advantages

• Inherent resilience of the connector components permits follow-up of creep and reduces the stresses due to thermal expansion that tend to cause excessive creep.

• Ease of installation (sockets, wrenches, screwdrivers, etc) and removal, simple to use, require minimal training to install properly.

• Can be disassembled without damage to the connection components and may be reusable if in good condition.

• Electrical performance of mechanical connectors meets or exceeds the industry requirements for which they are designed, thus not compromising the performance.
CONNECTOR DESIGN

Mechanical Connectors

Disadvantages

• Specific torque requirements must be followed to provide the proper clamping force needed for a sound electrical connection.

• Inconsistency of forces applied over identical mechanical installations is not generally repeatable due to use of uncalibrated torque wrenches.

• Because of relatively low mechanical holding strength, these connectors cannot be used as full tension connections and in areas of high vibration; more maintenance and periodic inspection may be required.

• Owing to their geometry, installing mechanical connectors on insulated conductors is usually difficult and awkward.
COMPRESSION CONNECTORS

Advantages

- Low cost, relatively reliable performance, use of recommended tools and/or dies removes the human element during installation.
- Connector construction provides better conductor encirclement while retained oxide inhibiting compound protects the contact area from the atmosphere, thus assuring a maintenance free connection.
- High localized and consistent forces imparted by the installation tool break down the oxides and establish contact points (a-spots) for reduced contact resistance and electrically and mechanically sound connection.
- The softness of compression connector material relative to the conductor prevents spring back and contact separation.
- Due to their geometry, compression connectors are considerably easier to insulate or tape than mechanical connectors.
- These connectors are most suitable in areas of wind, vibration, ice build-up and other stress-associated tension applications.
CONNECTOR DESIGN

Compression Connectors

Disadvantages

- Proper installation tooling for a compression system program involves potentially high capital investments due to a large variety of different types of compression tooling to select from.

- Accurate die and tool selection is essential for proper installation of a compression connection.

- Due to the need for specific tools and dies to install a compression connection, installers must be trained how to use the proper techniques and maintain these tools.

- In some compression connections, manually operated tools require greater physical exertion to install, thus when installing numerous connections, installers can become fatigued and possibly not complete the specified number of crimps.
CONNECTOR DESIGN

Wedge Connectors

Fired Wedge Connector

Mechanical Wrench Lock Connector
CONNECTOR DESIGN

Wedge Connectors

Advantages

• Powder actuation provides consistent, uniform performance and requires low physical exertion from an operator to complete a connection.

• Rapid mechanical wiping action as the wedge is driven between the conductors breaks down surface oxides and generates superior contact points thus reducing overall contact resistance.

• Installation is accelerated with the use of lightweight, portable tooling with simplified loading and engaging mechanisms.

• The spring effect of the 'C' body maintains constant pressure for reliable performance under severe load and climatic conditions whereas a large connector mass provides better heat dissipation.

• Electrical performance of fired-on wedge connectors are excellent due to the low contact resistance developed during installation.
CONNECTOR DESIGN

Wedge Connectors

Disadvantages

• Dedicated nature of powder actuation require full support from the user in terms of training, maintenance and service.

• Precautions and specially trained and qualified installers are required for safe and proper installation of wedge connections.

• Mechanical wedge connectors installed with wrenches, require more physical exertion for installation, show more inconsistent performance due to discrepancies caused by contaminants on the hardware and wide tolerances of shear-off bolts.

• Mechanical wedge spring bodies are typically manufactured by casting which produces much less spring action to maintain the connection.

• Wedge connectors are restricted to non-tension, out-door applications and suited only for a limited range of conductors.
CONNECTOR DESIGN

Types of Power Connectors

INSULATION PIERCING CONNECTOR
CONNECTOR DESIGN

Insulation Piercing Connectors

Advantages

• Low installation costs since no special tooling is required as they can be installed with a basic wrench.

• No insulation stripping or application of oxide inhibitor is required when making connections to insulated conductors.

• These connectors incorporate contact teeth designed to penetrate conductor insulation and make electrical contact, and are pre-filled with an oxide inhibiting compound to fill voids where contamination may enter.

• Insulation piercing connectors are insulated and require no tape or special cover once the connection is made.

• Relatively safe and easy installation on energized conductors.
**Disadvantages**

- **Limited scope of applications; recommended for low voltage (600V and below) secondary distribution applications where insulated conductors are employed.**

- **The nature of the connection device limits their application to functions such as taps, although some parallel splices can also be made.**

- **These connectors are intended for use in non-tension applications only and should never be used on bare conductors.**

- **These connectors may not be suitable for conductors with very thick, very thin, or very hard insulation materials as they could damage the conductor or not make electrical contact at all.**
Exothermic (Thermite) Connectors

- Exothermic welding is a process in which an electrical connection is made by pouring superheated, molten copper alloy on and around the conductors to be joined.

- The process requires no external source of heat or current and is completed within few seconds in a semi-permanent graphite mold in which the molten copper alloys causes the conductors to melt.

- The result of a reaction between a metal oxide and aluminum is liquid metal that acts as the filler metal and flows around the conductors making a molecular weld.

- The following chemical reaction occurs in the welding of copper conductors:

\[ 3Cu_2O + 2Al = 6Cu + Al_2O_3 + \text{Heat (1060 kJ)} \]

- The thermite welding is extensively used for making grounding connections between copper conductors.
CONNECTOR DESIGN

Exothermic (Thermite) Connectors

Advantages

• Excellent current-carrying capacity equal to or greater than that of the conductors, high stability during repeated short-circuit current pulses, excellent corrosion resistance and mechanical strength.

Disadvantages

• Cost, lack of repeatability, numerous mold requirements, potential down-time caused by inclement weather or wet conditions, safety risks to personnel and equipment.

• The intense heat damages both the conductor and its insulation, anneals the conductor so that exothermic connections can not be used in tension applications.

• The resultant weld material exhibits lower conductivity and physical properties than the conductor, being similar to cast copper.
Friction Welded Connectors

- Friction welding is a solid-state welding process in which the heat for welding is produced by direct conversion of mechanical energy to thermal energy at the contact interface without the application of external electrical energy or heat from other sources.

- Friction welds are made by holding a non-rotating work-piece in a contact with a rotating work-piece under constant or gradually increasing pressure until the interface reaches welding temperature and then the rotation is interrupted to complete the weld.

- The frictional heat developed at the interface rapidly raises the temperature of the work-pieces, over a very short axial distance approaching but bellow the melting range.

- During the last stage of welding process, atomic diffusion occurs while the interfaces are in contact, allowing a metallurgical bond to form between the two materials.
CONNECTOR DESIGN

Friction Welded Connectors

FRICTION WELDED HEXAGONAL COMPRESSION  DEEP STEPPED INDENTATION

FRICTION WELDED DEEP STEPPED INDENTATION CONNECTOR  DEEP STEPPED INDENTATION CONNECTOR
DEGRADATION OF ELECTRICAL CONTACTS

- Oxidation
- Corrosion
- Fretting
- Stress Relaxation / Creep
- Differential Thermal Expansion
- Formation of Intermetallics
DEGRADATION OF ELECTRICAL CONTACTS

Degradation Mechanisms

- THERMAL EXPANSION
- TEMPERATURE RISE
- INTERMETALLICS
- FRETTING
- THERMOELASTIC RATCHETING
- RESISTANCE RISE REDUCTION OF CONTACT ZONE
- CREEP
- STRESS RELAXATION
- OXIDATION CORROSION
# Degradation of Electrical Contacts

## Oxidation

<table>
<thead>
<tr>
<th>METAL</th>
<th>AMBIENT</th>
<th>PRODUCT</th>
<th>Characteristic Features</th>
<th>Thickness (nm) at 10³h</th>
<th>Thickness (nm) at 10⁵h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Air</td>
<td>Cu₂O</td>
<td>Oxide forms immediately</td>
<td>20°C 2.2</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature-dependent</td>
<td>100°C 15.0</td>
<td>130.0</td>
</tr>
<tr>
<td>Sn</td>
<td>Air</td>
<td>SnO</td>
<td>Initially slow growth rate</td>
<td>20°C 4.2</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weak temperature-dependence</td>
<td>100°C 25.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Ni</td>
<td>Air</td>
<td>NiO</td>
<td>Self-limiting</td>
<td>20°C 1.6</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weak temperature-dependence</td>
<td>100°C 3.4</td>
<td>34.0</td>
</tr>
<tr>
<td>Al</td>
<td>Air</td>
<td>Al₂O₃</td>
<td>Oxide forms immediately (2nm in secs)</td>
<td>Self-limiting growth</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Humidity &amp; Temperature-dependent</td>
<td>Very hard &amp; insulating</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>Sulfur</td>
<td>Ag₂S</td>
<td>Depends of sulfur-vapor concentration</td>
<td>Humidity-dependent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ozone</td>
<td>Ag₂O</td>
<td>Remains thin and decomposes at 200°C</td>
<td>No effect on contact</td>
<td></td>
</tr>
</tbody>
</table>
DEGRADATION OF ELECTRICAL CONTACTS

Corrosion

- Atmospheric corrosion
- Crevice Corrosion
- Pitting Corrosion
- Galvanic corrosion
DEGRADATION OF ELECTRICAL CONTACTS

Galvanic corrosion

- Galvanic corrosion is one of the most serious degradation mechanisms.

- In case of Al*Cu joints, Al (anodic component) dissolves and deposits on Cu electrode forming complex hydrated Al oxide with evolution of hydrogen at the Cu cathode.

- Humidity is the most important parameter influencing corrosion
DEGRADATION OF ELECTRICAL CONTACTS

Galvanic corrosion

![Diagram showing the effect of electrolyte and grease on metal contacts](image-url)
DEGRADATION OF ELECTRICAL CONTACTS

Dust Corrosion

RELATIVE HUMIDITY (%)

DUST CORROSION RATIO (%)

$pH = 5.5$

$pH = 7.5$

Corrosion products

dust particle

MBI

33
DEGRADATION OF ELECTRICAL CONTACTS

Fretting

- Fretting is an accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movement.
- The motion can be produced by mechanical vibrations, differential thermal expansion, load relaxation, junction heating etc.
- Due to limited amplitude of fretting, wear debris and oxides accumulate in the contact zone forming a thick insulating layer which leads to a dramatic increase in contact resistance.
DEGRADATION OF ELECTRICAL CONTACTS

Schematic of kinetics, initiation and spreading of fretting damage.
DEGRADATION OF ELECTRICAL CONTACTS

- Effect of Fretting on Contact Resistance

![Graphs showing the effect of fretting on contact resistance for different material pairs: Cu * Cu, Al * Cu, Al * Cu(Sn), and Al (Ni) * Cu(Ni).](image)
DEGRADATION OF ELECTRICAL CONTACTS

- Examples of Fretting Damage of Contact Zone
  Al (wire) – Sn Plated Cu Plate Side
DEGRADATION OF ELECTRICAL CONTACTS

• Examples of Fretting Damage in Electrical Connections
DEGRADATION OF ELECTRICAL CONTACTS

Examples of Fretting Damage in Electrical Connections

Cross section of a typical rotor slot

Fretting wear damage of rotor slot insulation
DEGRADATION OF ELECTRICAL CONTACTS

Examples of Fretting Damage in Electrical Connections
DEGRADATION OF ELECTRICAL CONTACTS

- Fretting Damage in Electrical Connections

<table>
<thead>
<tr>
<th>FRETTING TIME (S)</th>
<th>RESISTANCE (Ω)</th>
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<tbody>
<tr>
<td>10^0</td>
<td>10^7</td>
</tr>
<tr>
<td>10^1</td>
<td>10^6</td>
</tr>
<tr>
<td>10^2</td>
<td>10^5</td>
</tr>
<tr>
<td>10^3</td>
<td>10^4</td>
</tr>
<tr>
<td>10^4</td>
<td>10^3</td>
</tr>
<tr>
<td>10^5</td>
<td>10^2</td>
</tr>
<tr>
<td>10^6</td>
<td>10^1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NUMBER OF FRETTING CYCLES</th>
<th>AC CONTACT RESISTANCE (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^0</td>
<td>0.00</td>
</tr>
<tr>
<td>10^1</td>
<td>0.01</td>
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<tr>
<td>10^2</td>
<td>0.02</td>
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<tr>
<td>10^3</td>
<td>0.03</td>
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<tr>
<td>10^4</td>
<td>0.04</td>
</tr>
<tr>
<td>10^5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

DC CURRENT

AC CURRENT

MBI
DEGRADATION OF ELECTRICAL CONTACTS

- Fretting Damage in Electrical Connections

AFTER 40,000 CYCLES

 INITIAL

AC CURRENT
DC CURRENT
DEGRADATION OF ELECTRICAL CONTACTS

Effect of Fretting on Power Quality
DEGRADATION OF ELECTRICAL CONTACTS

Differential Thermal Expansion

- Aluminum expands at a greater rate than Cu or steel when exposed to higher temperatures resulting in the shearing of metal-contact bridges or plastic deformation.

- Thermoelastic ratcheting occurs in a bolted Al-Cu joint with a steel bolt due to excessive tightening of the bolt which causes plastic deformation of Al.

- Repeated heating-cooling cycles loosens the joint, increases the contact resistance and joint temperature.
DEGRADATION OF ELECTRICAL CONTACTS

Differential Thermal Expansion

Diagram showing the process of compression and the effect of differential thermal expansion between copper (Cu) and aluminum (Al) wires.
DEGRADATION OF ELECTRICAL CONTACTS

Formation of Intermetallics in Al-Cu Joints

- In Al-Cu joints intermetallics can form relatively rapidly at temperatures generally accepted as normal operating and overload temperatures on the network.

- Electrical and mechanical properties of Al-Cu contact are significantly impaired by formation and growth of intermetallics.

- Intermetallics increase the significantly brittleness and the contact resistance of a joint.
DEGRADATION OF ELECTRICAL CONTACTS

- Formation of Intermetallics in Al-Cu Joints

Thermal Gradient

Electric Field Gradient
DEGRADATION OF ELECTRICAL CONTACTS

• Deleterious Effect of Intermetallics
DEGRADATION OF ELECTRICAL CONTACTS

- Deleterious Effect of Intermetallics in Tin-Plated Cu
DEGRADATION OF ELECTRICAL CONTACTS

**Creep (Cold flow)**
- Occurs when a metal is subjected to a constant external force
- Manifested by a dimensional change
- Higher for aluminum than for copper
- Stress-, time- and temperature-dependent

**Stress relaxation**
- Manifested by a reduction in the contact pressure
- Higher for aluminum than for copper
- Stress-, time- and temperature-dependent

**Electroplasticity**
- Manifested by an increased ductility
- Increases creep / stress relaxation rates
DEGRADATION OF ELECTRICAL CONTACTS

Stress Relaxation / Creep

Diagram showing the relationship between residual load (in kPa) and time (in hours) for various materials under stress relaxation conditions. The y-axis represents residual load ranging from 0 to 35 kPa, and the x-axis represents time ranging from $10^{-4}$ to $10^8$ hours. The graph includes lines for different materials such as Al - 0.45 Mg, Al - 0.2Cu - 0.1Mg, Cu - annealed, Al - 0.7Fe - annealed, Al - Cu clad annealed, EC Al - annealed, EC Al - 1/2 hard, and EC Al - full hard. The initial load is 30 kPa, and the tests are performed at room temperature.
DEGRADATION OF ELECTRICAL CONTACTS

Stress Relaxation / Creep

![Graph showing stress relaxation and stress relaxation rate with and without current.](image-url)
PALLIATIVE MEASURES

• Surface Preparation
• Connector Design
• Contact Area / Pressure
• Mechanical Contact Aids
• Coating / Plating
• Lubrication
• Installation Practices
• **Surface Topography**

Surface topography of a metal abraded by a file (A) and a metal brush (B)
PALLIATIVE MEASURES

- Effect of Surface Roughness
PALLIATIVE MEASURES

- Effect of Contact Area (Serrations)
PALLIATIVE MEASURES

- Effect of Contact Area

Contact resistance of joint configuration (B) is 20-30% lower than that of (A) and is mechanically more stable.
PALLIATIVE MEASURES

• Effect of Contact Area

Contact resistance of slanted busbars (A) is 1.3 – 1.5 times lower than that of non slanted busbars (B).
PALLIATIVE MEASURES

- Use of transition washers
Recommended installation practice for bolted Al-Al joints with all aluminum hardware.
Recommended installation practice for bolted joints:
Al-Al, Cu-Cu, Al-Cu with steel hardware.
Recommended installation practices for bolted Cu-Cu joints with all copper hardware
PALLIATIVE MEASURES

- Effect of Mechanical Contact Load
PALLIATIVE MEASURES

- Coatings / Plating
- Industrial Pollution
PALLIATIVE MEASURES

Coatings / Plating

- Saline Environment

![Graph showing resistance rise for different materials in lubricated and nonlubricated conditions]
PALLIATIVE MEASURES

Lubrication

Basic Properties of Lubricants Intended for Electrical Contacts

- Thermal Stability
- Spreading Tendency
- Resistance to Oxidation
- Resistance to UV Radiation
- Ability to Protect Contact Zone
- Corrosion Inhibition

- Dispensability for Dust and Wear Particles
- Applicability
- Stability to Polymerization
- Reactivity with Ambient Vapors
- Viscosity
PALLIATIVE MEASURES

Effect Lubrication on Contact Voltage of Al-Cu Contacts Under Fretting Conditions

**NON-LUBRICATED**

**LUBRICATED**

Slip Amplitude: 25 microns  
Frequency: 0.0033 Hz  
Load: 2 N
PALLIATIVE MEASURES

Lubrication

Al * Cu (MOBIL GREASE)
Cu * Cu (SENSYN SLM-10924)

FRETTING TIME (S)

RESISTANCE (Ω)

10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
MONITORING AND DIAGNOSTIC TECHNIQUES

- Ageing is the continuous time dependent degradation of materials due to normal service conditions.

- All power equipment materials undergo ageing and lose, partially or totally, their designed function.

- Ageing degradation of power components, such as connectors and disconnect switches, if not effectively monitored and controlled, may impair their performance characteristics and thus a reduction of the reliability of associated power systems.

- Effective control of ageing degradation of power components requires timely detection and mitigation of the degradation.
Monitoring and diagnostic techniques should:

- Detect deterioration or damage affecting structural integrity of power equipment.
- Determine and characterize the extent and severity of deterioration.
- Assess the deleterious effect of deterioration on the performance of the power equipment.
- Initiate mitigating or corrective actions to restore the operational capabilities of the power equipment.
MONITORING AND DIAGNOSTIC TECHNIQUES

Techniques and methods used to monitor and diagnose the condition of power components

- Thermal measurements
- Resistance measurements
- Force measurements
- Torque measurements
- Ultrasonic measurements
Monitoring and Diagnostic Techniques

Thermal measurements include:

- Infrared thermal systems
  - Infrared thermometers
  - Infrared focal plane area cameras
- Temperature stickers
- Remote temperature sensors
- Shape-memory alloy indictors
MONITORING AND DIAGNOSTIC TECHNIQUES

Infrared thermometers

Handheld IR thermometers

Fixed-type IR thermometers
MONITORING AND DIAGNOSTIC TECHNIQUES

Infrared focal plane area cameras

Mikron MikroScan 7600 PRO

FLIR ThermaCAM® P60 IR Camera

Electrophysics EZTHERM PRO
MONITORING AND DIAGNOSTIC TECHNIQUES

Examples of overheated power components
(Courtesy of Boldstarinfrared)

Overheated bolted connection
Overheated of disconnect switch
MONITORING AND DIAGNOSTIC TECHNIQUES

Temperature stickers (Labels)

TEMPERATURE CHANGE INDICATED BY COLOR CHANGE FROM WHITE TO BLACK
MONITORING AND DIAGNOSTIC TECHNIQUES

Example of temperature stickers (Labels)
(Courtesy of Manitoba Hydro)
Remote temperature sensors

PhoneDucer (www.elwoodcorp.com)
MONITORING AND DIAGNOSTIC TECHNIQUES

Resistance measurements

Tinsley 5898 Portable 200A Precision Micro-Ohmmeter
Megger DLRO10X Digital Resistance Ohmmeter
Resistance measurements

Microohmmeter DRM-40, probe and a close-up of resistance measurement of the welded joint. (Courtesy of ndb Technologies Inc.)
MONITORING AND DIAGNOSTIC TECHNIQES

Resistance measurements

Ohmstik and Qualstik devices (Courtesy of Sensorlink)
MONITORING AND DIAGNOSTIC TECHNIQUES

Resistance measurements

In-field measurement of joint resistance using Ohmstik
(Courtesy of Transpower of New Zealand)
MONITORING AND DIAGNOSTIC TECHNIQUES

Force monitoring

Schematic of Strainsert instrumented bolts
MONITORING AND DIAGNOSTIC TECHNIQUES

Ultrasonic measurements

- Ultrasonic detectors provide a method of detecting sounds greater than 20 kHz.
- Loose electrical connections emit characteristic sounds that are beyond the range of the human ear.
- The ultrasonic detector provides a method of converting inaudible sounds to sounds and tones that match our hearing capabilities.
- Flashovers across an insulator make crackling sounds that are detectable even when there are no visible signs of arcing.
MONITORING AND DIAGNOSTIC TECHNIQUES

Ultrasonic measurements

Ultrasonic detector Ultraprobe 10000 Digital Ultrasonic Inspection System, display panel and data views (Courtesy of UE Systems).
MONITORING AND DIAGNOSTIC TECHNIQUES

Shape-Memory Alloys (SMA)

- The shape-memory effect (SME) refers to the ability of certain materials to “remember” and restore their shape upon heating, even after being initially severely deformed.

- When cooled below its transformation temperature (martensite), SMA has a very low yield strength and can be deformed quite easily into a new shape.

- When heated above its transformation temperature, SMA undergoes a change in crystal structure which causes it to return spontaneously to its original shape (austenite).

- During this isotropic transformation process, as the atoms shift back to their original positions, a substantial amount of energy is released.

- A single cube of shape-memory alloy can exert enough force to move an object weighing 4650 kg!
MONITORING AND DIAGNOSTIC TECHNIQUES

Schematic of Shape-Memory Effect

Fig. 3 One-way shape-memory effect.

Fig. 4 Schematic of two-way effect.
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*Shape-Memory Alloy Temperature Hot-spot Indicators*
MONITORING AND DIAGNOSTIC TECHNIQUES

Shape-Memory Alloy Temperature Hot-spot Indicators
MONITORING AND DIAGNOSTIC TECHNIQUES

**Desired Features of Wireless (Remote) Sensors**

- Low installation costs.
- Easy-to-use products allowing simplified maintenance and eliminating process problems.
- Fault-tolerant technology.
- Zero defects and 100% reliability from wireless products.
- Easy interrogation at any time without interfering with its environment.
- Accurate measurements and low power consumption to ensure long operating life.
MONITORING AND DIAGNOSTIC TECHNIQUES

Desired Features of Wireless (Remote) Sensors

Wireless Telemetry Solutions

- **Cellular systems**
  - Available GSM modules.
  - Using existing cellular infrastructure (where available).
  - Range within GSM network.
  - Low power consumption.

- **Dedicated wireless telemetry systems and networks**
  - Available industrial communication modules and base stations (complying with local regulations).
  - Local networking and data acquisition.
  - Independent of other networks, no additional costs.
  - Possibility of long distance monitoring and/or data acquisition using existing communication infrastructure.
MONITORING AND DIAGNOSTIC TECHNIQUES

Areas of concern with wireless sensors

- Cost.
- Size (Miniaturization).
- Power supply (Battery lifetime).
- Reliability.
- Distance of transmissions.
- Carrier frequency.
- Wireless protocol for multiple sensor nodes.
- Compliance with FCC regulations.
MONITORING AND DIAGNOSTIC TECHNIQUES

Wireless Temperature Monitoring Systems

SQUARE D On-Line monitoring systems for LV, MV electrical systems

- Switchgear
- Circuit Breakers
- Capacitor Banks
- Transformers
- Motors
- Busways
- Cables
- HV and EHV electrical equipment
- Apparatus from any OEM
MONITORING AND DIAGNOSTIC TECHNIQUES

**Wireless Temperature Monitoring Systems**

**Omega Wireless Sensor**

- Operates on UHF.
- Carrier Frequency: 450 to 470 MHz
- Transmits Strain Gage, Voltage and Thermocouple Signals
- Transmitters powered by a 12V battery;
- Receivers powered by 110Vac
- Range up to 3.2 km.
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Wireless Temperature Monitoring Systems

Block Diagram of The Wireless Temperature Transmitter

CdTe Probe

Driver

Amplifier

BPF

ADC

RF Module

MBI
Wireless Temperature Monitoring Systems

Possible System Configuration

- Radio Link to Remote System
- RF Transceiver
- Local Control Station
- Control Center
- Existing Networks
- Wireless Transmitter
- Transformer Station
- Temperature Sensor(s)
- Heat Source
MONITORING AND DIAGNOSTIC TECHNIQUES

Wireless Temperature Monitoring Systems

Power Donut2 (Courtesy USi, )

- Power Donut2 is designed for data acquisition and data logging applications on high voltage, overhead conductor systems.
- Power Donut is complete and self-contained unit powered directly from the conductor E-H field.
- Three communications options are available: FHSS (900 MHz / 2.4 GHz), GSM and GPRS Cell phones.
- Data output: current, voltage, conductor temperatures, conductor tension and sag, MW, MVars, MWhrs, MVarhs.
- Stores data on-board using flash RAM memory system.
- It can be installed live - from a bucket truck without taking the circuit out of service.
- Each data acquisition point can have three alarm levels: notification, early warning and alarm (reported in real time).
MONITORING AND DIAGNOSTIC TECHNIQUES

Wireless Temperature Monitoring Systems

Power Donut2

32 cm/12.6 in
14 cm/6.1 in
10 kg/22 lb

** This Information is Proprietary to USi, Armonk, NY **
MONITORING AND DIAGNOSTIC TECHNIQUES

Wireless Temperature Monitoring Systems

Power Donut2 -- The Clearance Monitoring Application

** This Information is Proprietary to USI, Armonk, NY **
NEW TRENDS IN CONNECTION DESIGN

Applications of Shape-Memory Alloys

Connectors

Principle of shape-memory alloy coupling (Cryofit)
NEW TRENDS IN CONNECTION DESIGN

Applications of Shape-Memory Alloys

Connectors

Cryocon and Souriau pin-and-socket connector
NEW TRENDS IN CONNECTION DESIGN
Applications of Shape-Memory Alloys

Shape-memory alloys disc-spring (Belleville) washer

APPLIED FORCE (kg)

DEFLECTION (mm)
NEW TRENDS IN CONNECTION DESIGN

Composite materials (metallic foams)

• Metal composites can be broadly defined as a metal matrix with voids between two layers of cladding material.

• The density of void space can vary widely from less than 50% up to 90% of the material volume.

• Light weight, high volume, low cost, multiple applications

Bare foam

Reinforced foam

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<tr>
<th>TITANIUM</th>
<th>ALUMINUM + SIC HARD WIRES</th>
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NEW TRENDS IN CONNECTION DESIGN

Composite materials (metallic foams)

Precursor/Dense Materials  Shaped Aluminum Composite and Sandwich Structures
NEW TRENDS IN CONNECTION DESIGN

Properties of Al composite materials

• Ultra lightweight.
• High specific strength.
• High stiffness to weight ratio (up to 2 x aluminium).
• Excellent impact, vibration and energy absorption.
• Good fire retardant.
• Good sound absorption.
• Low thermal conductivity.
• Low density.
• Less hygroscopic.
• Good corrosion resistance.
• Fully recyclable.
NEW TRENDS IN CONNECTION
DESIGN

Properties of Al composite materials

Force-displacement and stress-strain characteristics of aluminium foam composite materials
NEW TRENDS IN CONNECTION DESIGN

Applications of Al composite materials

- **Transportation**
  - *Automotive*
  - *Ships*
  - *Airplanes*
  - *Railroads*
- **Security**
  - *Military*
  - *Public / Personal*
- **Construction**
- **Acoustic applications**
- **Power**

Composite (foam) material used as A transition washer
• **Surface Roughness**
  – An appropriately selected surface roughness is essential for acceptable connector performance

• **Mechanical Force**
  – Minimum mechanical force is essential for acceptable connector performance

• **Formation of Intermetallics**
  – Should be avoided

• **Fretting**
  – Minimize or eliminate micro-motion at electrical interfaces.

• **Lubrication**
  – Essential for acceptable connector performance

• **Surface Preparation**
  – Appropriate surface preparation of conductors and contact surfaces is essential for acceptable connector performance

• **Area of True Contact**
  – Generally very small

• **Connector Technologies**
  – Connector performance depends on connector technology and design

• **Connector Degradation**
  – Connector degradation may have a highly deleterious effect on the operating cost of power network.
Imagination is more important than knowledge

A. Einstein