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Circuit Protection Devices & Arc Fault Detection Schemes for Electrical Automotive Systems

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Introduction

- Circuit protection devices are used to provide protection against over/under-voltage, over-current and over-temperature conditions.

- The suitability of a device depends on many factors such as transient/steady state voltage conditions, current and power ratings etc.

- The absence of a protection device or an inappropriately selected protection device may result in failures which may be catastrophic.
Introduction
Introduction
What are we protecting against?

- **Current**
  - Short circuit current
  - Overload current

- **Voltage**
  - Over-voltage
  - Under-voltage
  - Transients

- **Temperature**
  - Excessive ambient temperature
  - Component heat dissipation
Current

- Usually relies on heat generated by excess current to open circuit
  - Fuses
  - Fusible links
  - Circuit breakers
  - PTCs
Fuses

Insulated end-caps to help prevent accidental contact with live parts.

Filler material

Before

Spring

After
Positive Temperature Coefficient (PTC)
Polymeric Positive Temperature Coefficient (PPTC)
Voltage

- Two categories of overvoltage circuit protection devices
  - Clamping/Foldback
    - MOVs
    - Diodes
    - TVSS
  - Crowbar
    - Gas discharge tubes
    - Thyristor surge suppressors
MOV

- Used to protect equipment from power line transients and surges
- Consists of metal oxide grains sintered into ceramic disks and encapsulated in an epoxy
- The MOV degrades over time due to the cumulative fusing of grains and the micro-cracking of the disks
Temperature

- Protection may or may not be re-settable
  - PTC
  - Bi-metal switches
  - Thermal Fuses
Bi-Metal Switches
Automotive Electrical Systems

12 V

42 V

360 V
So What is the Problem?

Arcing!!!
What is Arcing?

- The effect generated when electrical current bridges the air gap between two contacts or conductors

- Arcing may take two forms in a typical automotive environment:
  - Series Arcing
  - Parallel Arcing
Arc Faults

Parallel Arc Fault

Series Arc Fault

Ref: 42VDC Arc Faults: Physics and Test Methods, Engelbert Hetzmannseder, Joe Zuercher
Series Arcing

- Faults in series with the load
- Arcing currents less than nominal circuit currents
- Occurs on loose (lugs/terminals), broken (conductors) or otherwise high resistance segment in a single line
- Cannot be detected by using conventional short circuit or overload protection devices
- May result in low reliability and a fire hazard
Parallel Arc

- Faults in parallel with the load
- Arcing currents significantly higher than the nominal currents
- Occurs when damaged wires or wires exposed due to aging insulation touch system ground or auxiliary low voltage bus
- May/may not trip the fuse or breaker due to current limiting nature of the arc
- Potentially more dangerous than a series fault condition
Arc Physics

LTE (Local Thermal Equilibrium)
Very low opening speed

1.8mm
1.5mm
1.0mm
0.5mm

Resistive characteristic

Ref: 42VDC Arc Faults: Physics and Test Methods, Engelbert Hetzmannseder, Joe Zuercher
Arc-Fault Current Interrupters (AFCI)

- Required in all circuits that feed receptacles in bedrooms of dwelling units since 1999 by the National Electric Code.

- Advanced electronics inside an AFCI breaker detect sudden bursts of electrical current in milliseconds, long before a standard circuit breaker or fuse would trip.

- The 2008 NEC requires installation of combination-type AFCIs in all 15 and 20 amp residential circuits with some exceptions (laundries, kitchens etc.)
What about DC systems?

- **Series Arc Faults**
  - Plugging and unplugging connectors under load
  - Lose lugs
  - Breaks in wires

- **Parallel Arc Faults**
  - Simulation of cutting wires (point contact arc test)
  - Simulation of chafed wires (dry arc propagation test)
  - Influence of contamination (carbonized track test)
  - Water intrusion test of connectors
  - Impact of humidity & salt water (wet-arc propagation test)
  - Simulation of broken/dangling wire (dangling wire test)
Why can’t we use conventional circuit protection devices?


Series Arc Fault

Parallel Arc Fault
What is out there?

What do we want to do & why
Test Setup

Power Supply

Motor Controller

Motor

Coupling/Shaft

Copper Rod

Battery Bank

Load

Copper Rod

String pot

Oscilloscope

I

V
Test Setup
Test Setup
Test Setup
# Factors

<table>
<thead>
<tr>
<th>Factor Description</th>
<th>Main Factor Designation</th>
<th>Low Level (-)</th>
<th>Center Point</th>
<th>High Level (+)</th>
</tr>
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<tbody>
<tr>
<td>Circuit Inductance</td>
<td>A</td>
<td>0 H</td>
<td>500 mH</td>
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<td>10 A</td>
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<tr>
<td>Speed of separation</td>
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<tr>
<td>Copper Purity</td>
<td>E</td>
<td>50 %</td>
<td>75 %</td>
<td>95 %</td>
</tr>
<tr>
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Series Arcs

Arc Discharge Voltage Profile

Test Results

1100 µH

20 µH
Test Results

20 µH

3300 µH
Test Results – 3 mm/second
Test Results – 10 mm/second

The graph shows the relationship between inductance (uH) and the rate of change of current (dI/dt in mA/us) for a specific condition. As the inductance increases, the rate of change of current decreases.
Test Results

- The current waveform shows an initial drop in current when the arc is initiated.
- It may be possible to use this drop in current to detect the initiation of a series arcing event.
- The fall time of the current is dependant on the inductance as expected.
- Based on the testing performed, it appears that the minimum di/dt is approximately 2 mA/μs.
  - This figure is not dependant upon speed of separation or the magnitude of current.
## Next Steps

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Next Steps

- Determination of the effects of untested factors on the fall time
- Design, implementation and test of a simple circuit to provide series arc fault protection
- Scaling the measurement to higher voltages
- Identifying parameters and potential simpler solutions to parallel arc faults
Summary

- Series arcs may not always be detected by circuits because of the damping effect of the long wire harnesses.
- Circuit protection devices commonly available are not designed to detect series arcs specially in automotive applications.
- What is required is a detection mechanism as close to the location of the series arc as possible.
Summary

- Preliminary testing indicates that a minimum $\text{di/dt}$ of approximately 2 mA/µs will be observed at the initiation of the series arc.
- A time delay circuit with an integrator/comparator may be implemented to detect and take corrective action in the event of a series arc.