Voltage Upgrade of an EQ Medium Voltage Motor Insulation System

EQTMM 2018
Clearwater Beach, FL
October 31, 2018
Form-Wound MV Insulation System
Design & Construction

Source: Courtesy of Schulz Electric
Form-Wound MV Insulation System Materials

- Slot Liner: Nomex 410 (4160 ONLY)
- Filler Strips: Nomex 410
- Slot Wedge: G-200
- 15% Silver Solder
- Felt Blocking
- Corona Tape (6.9 kV ONLY)
- Epoxy Resin
- Surge Rope
- Magnet Wire: Square or Rectangular with Enamel Coating, with or without Fiberglass Coating
- Mica Insulating Tape (Groundwall)
- Fiberglass Support Tape
- 7.5 KV EPDM Lead Wire
- Coated Fiberglass Sleeving
Form-Wound Insulation System
Coil Forming

Source: All Photos Courtesy of Schulz Electric
Form-Wound MV Insulation System
Coil Insertion
Form-Wound MV Insulation System
VPI Process

Source: Photo Courtesy of Schulz Electric
Form-Wound MV Insulation System
Post-VPI

Source: All Photos Courtesy of Schulz Electric
Form-Wound MV Insulation System

Typical End Use Applications

- Typically Large Motor (> 350 HP to 2000 HP)
  Medium Voltage (4.16 kV, 6.3 kV, 6.6 kV, 6.9 kV)
- RHR, SI, LPCS, HPCS
- HELB and MSLB Accidents Outside Containment

Source: All Photos Courtesy of Schulz Electric
MV Form Wound Insulation
System EQ Basis

- IEEE 323-1974/1983
- IEEE 344-1975/1987
- IEEE 334-1974
- IEEE 275-1992
- NUREG-0588, Cat I
- EPRI TR–104872
- Schulz Report N4446EQFWCD, Rev. 2
- HELB/MSLB Outside Containment

Source: All Photos Courtesy of Schulz Electric
# Form Wound MV EQ Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Schulz MV 4.16 kV System</th>
<th>Typical Plant Parameter</th>
<th>Method</th>
<th>Meets /Exceeds (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation - Gamma TID</td>
<td>5.73 x 10⁷</td>
<td>&lt;1.0 x 10⁶</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature Peak/Profile</td>
<td>355°F for 50 sec. and 395°F for 100 sec.</td>
<td>&lt;200°F</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Pressure Peak/Profile</td>
<td>70 PSIG</td>
<td>Atmospheric</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>100%</td>
<td>100%</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Parameter</td>
<td>Schulz 4.16 kV System</td>
<td>Typical Plant Parameter</td>
<td>Method</td>
<td>Meets /Exceeds (Y/N)</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>----------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Chemical Spray</td>
<td>N/A</td>
<td>N/A</td>
<td>Not Required</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermal Aging</td>
<td>2840 Hours @ 185 °C</td>
<td>N/A ¹</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Activation Energy</td>
<td>1.192 eV ² (r = 0.994053)</td>
<td>N/A ¹</td>
<td>Test</td>
<td>Yes</td>
</tr>
</tbody>
</table>

1. No specific plant requirement for thermal aging temperature/duration or activation energy, however resulting QL should be 40 – 60 years.


1. N/A indicates not applicable.

2. Derivation includes a regression analysis with a correlation coefficient of 0.994053.
## Form Wound MV EQ Parameters

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<thead>
<tr>
<th>Parameter</th>
<th>Schulz 4.16 kV System</th>
<th>Typical Plant Parameter</th>
<th>Method</th>
<th>Meets /Exceeds (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submergence</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Voltage Rating</td>
<td>4160 VAC</td>
<td>4160 VAC</td>
<td>Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Insulation System</td>
<td>Class F (^1)</td>
<td>Class F or Class B</td>
<td>Test</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^1\) Insulation system was thermally qualified via IEEE-275 as Class F.

\(^2\) Some U.S. plants have 6.6 kV or 6.9 kV MV EQ Insulation Systems. Most European plants MV electrical supply is 6.3 kV.
Form Wound MV EQ Profile

Source: Schulz Electric EQ Report N4446EQFWCD, Rev. 2
Form Wound MV EQ Profile

The temperature profile between 200 and 1400 seconds will be on a best effort basis.

- 355°F @ 200 seconds
- 355°F @ 50 seconds
- 255°F @ 500 seconds
- 255°F @ 1000 seconds
- 315°F @ 1100 seconds
- 175°F @ 2 hours & 47 minutes
- 125°F @ 5 hours & 34 minutes
- 395°F @ 1400 seconds maintain for a minimum of 100 seconds

POST-ACCIDENT THERMAL AGING
365°F Dry - Hold for 179 hours
The ramp to 365°F shall be at a rate not to exceed 5°C per hour

Remove to thermal aging chamber at 365°F following the 24-hour point of the test

203 hours total test time (End of test)

Source: Schulz Electric EQ Report N4446EQFWCD, Rev. 2
Insulation System Voltage
Upgrade Design Basis

- Original Insulation System Rated 4.16 kV
- Insulation System New Voltage Rating 6.9 kV
- Primary Aspect to Design Change is to Maintain Insulation System Groundwall <94 Volts/Mil
Thickness of Groundwall can be Increased
- Materials with Higher Dielectric Strength Can be Utilized
- Schulz Electric Elected to Increase Thickness of Groundwall to Avoid Introduction of New Material

\[ X = \left( \frac{V}{94 \frac{V}{mil} \times T} \right) \times 0.5 \]

- \( X \) = Number of half lap layers of ground wall insulation
- \( T \) = The thickness of a single layer of ground wall insulation, in mils
- \( V \) = Line voltage of the motor

Using 8-mil Groundwall, Minimum number of half-lap layers = 4.6; Rounded up to 5 half-lap layers (10 total layers)
- 6900 Volts/80 mils = 86.25 Volts/mil


IEEE 1776- 2008 "Recommended Practice for Thermal Evaluation of Unsealed or Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Pre-Insulated Stator Coils for Machines Rated 15 000 Volts and Below"
IEEE 323-1983, Sec. 6.5.3, Extrapolation and Interpolation, states, "Extrapolation and interpolation are analytical techniques which may be used to qualify equipment by extending the application of test data. Two types of extrapolation and interpolation are possible:

1. Extrapolation or interpolation of successful performance at a specific service condition to a different service condition.

2. Extrapolation or interpolation of successful performance of a specific piece of equipment to similar equipment."
Upgraded 6.9 kV Insulation System EQ Basis

IEEE 323-1983, Sec. 6.5.3, Extrapolation and Interpolation, states, “Extrapolation or interpolation to other equipment by similarity can be used when the following criteria are met:

- **6.5.3.1** Materials of construction shall either be the same or equivalent. Any identified differences shall be shown not to adversely affect performance of the safety function(s).
- **6.5.3.2** Size may vary if the basic configuration remains the same and dimensions are related by known scale factors. Consideration shall be taken of such factors as thermal effects of different surface areas and seismic effects of different masses and modes.
- **6.5.3.3** Shape. The shape shall be the same or similar (subject to restrictions of size) and any differences shown shall not adversely affect the performance of the safety function(s).
- **6.5.3.4** Stress. Operating and environmental stresses on the new equipment shall be equal to or less than those experienced on the qualified equipment under normal and abnormal conditions.
- **6.5.3.5** Aging Mechanisms. The aging mechanisms that apply to the tested equipment encompass those that apply to the similar equipment.
- **6.5.3.6** Function. The safety function(s) as evaluated shall be the same (for example, activate to operate or de-activate to operate).”
Corona Tape was Utilized in the 6.9 kV Insulation System to Alleviate Potential Damage from Partial Discharge

Partial Discharge - A form of electrical discharge occurring between conductors when the breakdown voltage of an intervening gas (usually air) is exceeded and the gas ionizes (EPRI TR-104872)

Partial discharge occurs when the electric field intensity is high enough to locally ionize the air adjacent to the solid insulation.

In motor insulating systems, partial discharge can occur at the following locations:
- Within insulation system voids
- On voids/defects at the surface of the ground wall insulation
- On the coil surface where it exits the core
- Between adjacent coils in the end turn winding area

Potential for Onset of Partial Discharge 5-7kV
Based Upon IEEE-323 1983, Sec. 6.5.3 Evaluation, Two Areas Need Further Evaluation

- Evaluation for Suitability of Application and Qualification of Corona Tape

- Is Partial Discharge a New Aging Mechanism for the 6.9 kV Insulation System Not Previously Required for the 4.16 kV Insulation System?
EPRI TR-104872, “Guidelines for the Qualification of Insulation Systems for Use in Rewinding Nuclear Safety-Related Harsh Environment Motors”

Comprehensive discussion on partial discharge and how it relates to the commercial nuclear power industry

Specifically addresses partial discharge as a potential aging mechanism in the context of insulation system qualification for nuclear harsh environment end use applications
TR-104782, Sec. 4.3.2.5, Voltage [Aging]

- At medium voltage levels below 7 kV, the use of quality VPI resin treatments produces essentially void free windings.

- Winding designs in the 5 - 7 kV range use conductive coatings in the slot and semi-conductive coatings on a portion of the coil extensions to further minimize the potential for corona.
When the insulating system is designed to effectively eliminate the potential for partial discharges, prolonged voltage exposure is not a significant aging mechanism.

For medium voltage machines < 7 kV, the effects of corona and partial discharge are minimized by designing the systems with vpm stresses substantially below 100 vpm, using micaceous insulations, and using VPI resin treatments that achieve essentially-void-free coil design.

Consequently, voltage is not a significant aging mechanism when these types of insulation systems are properly designed and fabricated.
Upgraded 6.9 kV Insulation
Partial Discharge – Aging Mechanism?

- Voltage Endurance Data of Various Materials (10 mil) based upon ASTM 2275 Testing, “Standard Test Method for Voltage Endurance of Solid Electrical Insulating Materials Subjected to Partial Discharges” (Ref. EPRI TR-104872, Figure 4.7)
- Data suggests that most materials and configurations exhibit a voltage endurance threshold
- Below this threshold, voltage aging either does not occur or is insignificant
Schulz Electric FW MV Insulation System Design Characteristics

- 4.16 kV and 6.9 kV Insulation Systems Utilize a Quality Epoxy Resin that has been subject to EQ and Thermal Endurance Testing
- 6.9 kV Insulation System Utilizes Corona Tape in the Motor Stator Core Slot to Reduce the Potential of Partial Discharge
- 4.16 KV and 6.9 kV Insulation Systems Groundwall Insulation Design <94 Volts/mil
- Schulz Electric Winding Design and VPI Process Produces Essentially-Void-Free Construction
Upgraded 6.9 kV Insulation
Partial Discharge – Aging Mechanism?
Upgraded 6.9 kV Insulation Partial Discharge – Aging Mechanism?

- **TR-104782, Sec. 4.3.2.5, Voltage [Aging]**
  - Test protocols of IEEE 275 [and by Extension IEEE-1776] requires a voltage test as part of the test sequence
  - The voltage test is used to define winding failures and is not considered an “aging mechanism”
  - No currently accepted methods for performing and extrapolating accelerated voltage endurance tests to simulate the degradation that may occur during normal operation over life of motor
  - The task group [SC 2.2] agreed that the voltage testing performed in IEEE 334-1994 is acceptable for qualification purposes
  - Schulz Electric Performed IEEE-275 Tests (4.16 kV) and IEEE-1776 tests (6.9 kV) on the Respective MV Insulation Systems
Conclusions on Partial Discharge

Motor Insulation Systems <7 kV Not Subject to Significant Partial Discharge Potential

Motor Insulation Systems that Incorporate Low Voltage Stress Designs (<100 VPM), Quality Materials and Controlled Processes (e.g. Coil Fab, VPI, Post-Fab Tests and Inspections) Further Reduce Potential for Partial Discharge

An “Essentially-Void-Free” Insulation System Significantly Reduces Potential For Partial Discharge
Conclusions on Partial Discharge


- Partial Discharge is NOT Considered a Significant Aging Mechanism (for EQ Purposes) of Motor Insulation Systems Rated <7 kV that Incorporate Quality Design, Materials and Manufacturing Practices
Upgraded 6.9 kV Insulation Thermal Endurance Test

- IEEE 334-1994, Sec. 6.3.4.1, Recommends use of IEEE 275-1992 to Establish Average Life Characteristics of Form Wound Insulation Systems
- Original 4.16 kV Insulation System Tested IAW IEEE 275-1992
- High Potential Portion of Test Conducted at 9000 VAC Commensurate With 4.16 kV Voltage Rating of Insulation System
Upgraded 6.9 kV Insulation Thermal Endurance Test

- Current Active Standard is IEEE 1776-2008 for Thermal Evaluation of MV Insulation Systems
- IEEE 1776-2008 was Utilized for Schulz Electric 6.9 kV Insulation System Testing
- Testing Methodology Practically Identical to IEEE 275-1992
- High Potential Portion of Test Conducted at 13,800 VAC Commensurate With 6.9 kV Voltage Rating of Insulation System
- Comparison of Data Obtained from IEEE 275-1992 for the 4.16 kV Insulation System can be Accurately Compared to Data Obtained from IEEE 1776-2008 Testing for the 6.9 kV Insulation System
**Upgraded 6.9 kV Insulation Thermal Endurance Test**

**Fabricate Formettes**

**Thermal Aging**
- (at T1)
- (1 hr, 60Hz, 1.5g)

**Voltage Test**
- (wet)

**Moisture Exposure**
- (48 hr, 95%-100% humidity)

**Failure Data for T1**
- m1 @ t1
- m2 @ t2
- m10 @ t10

**Test Sequence Shown for Failure Data at Test Temperature T1**

**Sequence Repeated with New Motorettes at T2 & T3**

**Failure Data Plotted and Life Line Calculated**

**Formette Fab (Pre-VPI)**

**Formette Fab (Post-VPI)**

**Thermal Aging**

**Vibration Aging**

**Humidity Exposure**
Upgraded 6.9 kV Insulation
Thermal Endurance Test

Hi-

Pot Test at 9000 VAC

Eminent Failure to Ground
> 200 mA Leakage Current
## Upgraded 6.9 kV Insulation Thermal Endurance Test

### Aging Temperature

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Initial Aging Cycle</th>
<th>Schulz Electric ID Number</th>
<th>Eltek ID Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>260°C</td>
<td>48 hours</td>
<td>N-8409-F1</td>
<td>1505-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-8409-F7</td>
<td>1505-1</td>
</tr>
<tr>
<td>240°C</td>
<td>168 hours</td>
<td>N-8409-F5</td>
<td>1506-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-8409-F6</td>
<td>1506-3</td>
</tr>
<tr>
<td>220°C</td>
<td>504 hours (^1)</td>
<td>N-8409-F2</td>
<td>1507-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-8409-F3</td>
<td>1507-6</td>
</tr>
</tbody>
</table>

\(^1\) Increased to 840 Hours After 2nd Cycle

### Specimen Data

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temp (ºC)</th>
<th>Life (hrs)</th>
<th>Temp (ºC)</th>
<th>Life (hrs)</th>
<th>Temp (ºC)</th>
<th>Life (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1507-1 Coils</td>
<td>220</td>
<td>3948</td>
<td>240</td>
<td>1260</td>
<td>260</td>
<td>456</td>
</tr>
<tr>
<td>1507-2 Coils</td>
<td>220</td>
<td>3948</td>
<td>240</td>
<td>1260</td>
<td>260</td>
<td>456</td>
</tr>
<tr>
<td>1507-3 Coils</td>
<td>220</td>
<td>3948</td>
<td>240</td>
<td>1764</td>
<td>260</td>
<td>504</td>
</tr>
<tr>
<td>1507-4 Coils</td>
<td>220</td>
<td>3948</td>
<td>240</td>
<td>1932</td>
<td>260</td>
<td>552</td>
</tr>
</tbody>
</table>

Note: Increased to 840 Hours After 2nd Cycle
Upgraded 6.9 kV Insulation Thermal Endurance Test

Time vs. Temperature – Average With Regression Trendline

Life in Hours

1/T (K)

100000.00
10000.00
1000.00
100.00
10.00
1.50E-03 1.60E-03 1.70E-03 1.80E-03 1.90E-03 2.00E-03 2.10E-03 2.20E-03
Thermal life line of 6.9 kV System is above 4.16 kV System Yielding a Higher Mean Life at Rated Temperature of 180°C

Resulting Activation Energy and High Correlation Efficient of the 6.9 kV Insulation System, Coupled with Favorable Comparison of the Data to the 4.16 kV Insulation System Shows the Data is Reliable and Accurate

Similar Trendline and Final Data Results Provides Supporting Evidence that No Additional Failure Modes Have Been Introduced with Addition of Corona Tape

<table>
<thead>
<tr>
<th>Insulation System</th>
<th>4.16 kV</th>
<th>6.9 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activation Energy (eV)</td>
<td>1.192</td>
<td>1.1265</td>
</tr>
<tr>
<td>Intercept (A)</td>
<td>-9.01</td>
<td>-7.88</td>
</tr>
<tr>
<td>Slope (B)</td>
<td>6002.97</td>
<td>5675.09</td>
</tr>
<tr>
<td>Correlation Coefficient (r)</td>
<td>+0.994053</td>
<td>+0.97789</td>
</tr>
</tbody>
</table>
Conclusions of Thermal Endurance Testing

- IEEE-275 and IEEE-1776 are Identical Thermal Endurance Tests for Motor Insulation Systems

- These Tests Incorporate the Significant Aging Mechanisms that Motors Experience During Normal Operation During Installed Life of the Motor
  - Thermal Aging Stressors
  - Mechanical/Vibration/Cyclic Aging Stressors
  - Voltage/Electrical Stressors
  - Moisture/Humidity Exposure

- Final Test Data Results of the 6.9 kV Insulation System are Favorable and Comparable to the 4.16 kV Insulation System

- Addition of Corona Tape to the MV FW Insulation System Design Did Not Introduce Any New Failure Modes, Adversely Affect the Thermal Rating or Safety Function of the Insulation System or Motor
Qualification of Corona Tape for Normal and Accident Radiation Conditions is by Analysis

Insulation System Currently Qualified to $5.73 \times 10^7$ Rad Gamma

Corona Tape is Polyester Fleece Impregnated with Conductive Varnish Containing Carbon Black

The Varnish is a Polyurethane or Polyester Based Resin
Most Comprehensive Test of Anti-Corona Varnish as Discrete Material is CERN Report 85-02, “Radiation Tests on Selected Electrical Insulating Materials for High-Power and High Voltage Application”

CERN Report 85-02 Lists Three Polyurethane Based Anti-Corona Resins with the following Radiation Damage Thresholds

- $5 \times 10^9$ Rad Gamma ($5 \times 10^6$ Gray)
- $1.1 \times 10^{10}$ Rad Gamma ($5 \times 10^7$ Gray)
- $3.1 \times 10^{10}$ Rad Gamma ($5 \times 10^7$ Gray)

This Data is also Consistent with the Following Other Radiation Threshold Damage References:

- CERN 82-10, Compilation of Radiation Damage Test Data Part III: Materials Used Around High-Energy Accelerators
### Table 12
Anticorona varnish

<table>
<thead>
<tr>
<th>No.</th>
<th>Material Type</th>
<th>Dose</th>
<th>Specific surface resistance at 5 kV/at 15 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>E 21</td>
<td>Polyurethane resin filled with SiC</td>
<td>0.0</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>LL5</td>
<td>$5 \times 10^6$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>BBC, Baden</td>
<td>$1.1 \times 10^7$</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Anticorona varnish in HV applications</td>
<td>$3.1 \times 10^7$</td>
<td>116</td>
</tr>
</tbody>
</table>
Upgraded 6.9 kV Insulation
Corona Tape – Radiation

EPRI TR-103585 (Excerpt)

CERN 82-10 (Excerpt)
Conclusion for Corona Tape Radiation Analysis

- Available Radiation TID per Original Insulation System Qualification = $5.73 \times 10^7$ Rad Gamma

- Lowest Gamma Radiation Damage Threshold for Similar Anti-Corona Base Material = $5 \times 10^9$ Rad Gamma

- Corona Tape Utilized for the 6.9 kV Insulation System is Qualified by Analysis with Sufficient Margin
Schulz Electric Qualified a FW 4.16 kV MV Motor Insulation IAW IEEE 323-1974/1983 by Test

Insulation System was Upgraded from 4.16 kV to 6.9 kV

IEEE 323-1983 Provides a Methodology to Extend the 4.16 kV Insulation System to the 6.9 kV Insulation System via Extrapolation and Interpolation

6.9 kV Insulation System Design Utilized a new Material (Corona Tape) to Address Potential of Partial Discharge
Summary

- Partial Discharge of 6.9 kV Insulation System was Determined NOT to be a Significant Aging Mechanism
- Additional Thermal Endurance Testing was Performed on 6.9 kV Insulation System to Address Normal Operational Aging Mechanisms with Corona Tape
- Analysis was Utilized to Address Radiation Aging of Corona Tape
- The 6.9 kV FW MV Insulation System is Environmentally Qualified based upon Test and Analysis
Thank You!

Questions?

James M. Dean
AES Nuclear, Inc.
Chairman IEEE-334 (SC 2.2)