Capacitor element technology: Improving system reliability and performance

Introduction

Eaton's ongoing research and development program has produced many manufacturing and design innovations. Several of these innovations have been incorporated within Eaton's Cooper Power series power capacitor offerings including Standard-duty (SD type), Heavy-duty (HD type), Extreme-duty (XD type) and Internally fused units. These improvements have resulted in numerous performance, packaging and safety advantages beyond those found in other designs.

Connection overview

High voltage power capacitors are constructed internally out of smaller capacitors commonly referred to as "elements", "windings" or "packs." These elements have discrete voltage and kvar ratings associated with them. They are interconnected through a combination of series and parallel connections to obtain the desired capacitance and deliver proper kvar, when operated at rated voltage and frequency.

The design, construction and assembly of these connections have direct correlation on the unit ratings, performance and life. Eaton utilizes a laser cut edge, extended foil design, with a mechanical crimp assembly to join neighboring elements. This design has several benefits over other foil treatments (mechanically cut, folded mechanically cut) and connection techniques (solder, ultrasonic weld).

Discharge Inception Voltage (DIV)

A prime example of benefits yielded from Eaton's research and development capacitor projects has been partial discharge phenomenon and its role in capacitor design. The electrical breakdown of a capacitor most commonly begins with the initiation of corona or partial discharge. When the voltage across the plates of a capacitor dielectric system is raised, a level is reached where a multitude of partial discharges begin to occur at a consistent voltage level. This is referred to as the Partial Discharge Inception Voltage (DIV) of the dielectric system.

There are a variety of factors that influence capacitor DIV:

- Material properties (film and fluid)
- Impurities
- Dielectric thickness
- Temperature
- Fluid processing quality
- Foil edge treatment
- Element geometry
- Dielectric design dtress

Space or stacking factor of solid dielectric

Partial discharges are very short-duration, minute current pulses that have been observed to occur in dielectric systems under high electrical stresses. Partial discharges are normally detected using current-sensing instrumentation connected to the dielectric system which responds with a resonant output to the short-duration current pulses within the dielectric device.

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Present scientific data associates partial discharges with the electrical breakdown of gas bubbles in regions of high electrical stress. The gas bubbles could be present naturally in the dielectric medium or could be created in the liquids due to the electric field. The bubbles permit gaseous phase discharges which can be measured with the test equipment. When the voltage on the dielectric system is slowly raised, partial discharges should first occur in the region where the electrical stress is the highest – most commonly the edge of the foil.

Figure 1 illustrates a field plot of a parallel plate dielectric system representative of a power factor correction capacitor. The equipotentials are a measure of the electrical stress in that region. As the equipotentials come closer together, the stress increases. The equipotential lines group together near the conducting plate edge. This means that the electrical stress is the highest in this region and decrease further from the edge.

In a well-impregnated capacitor dielectric system, the inception of partial discharge activity will be associated with the foil edge since this is where the electrical stress is the highest.

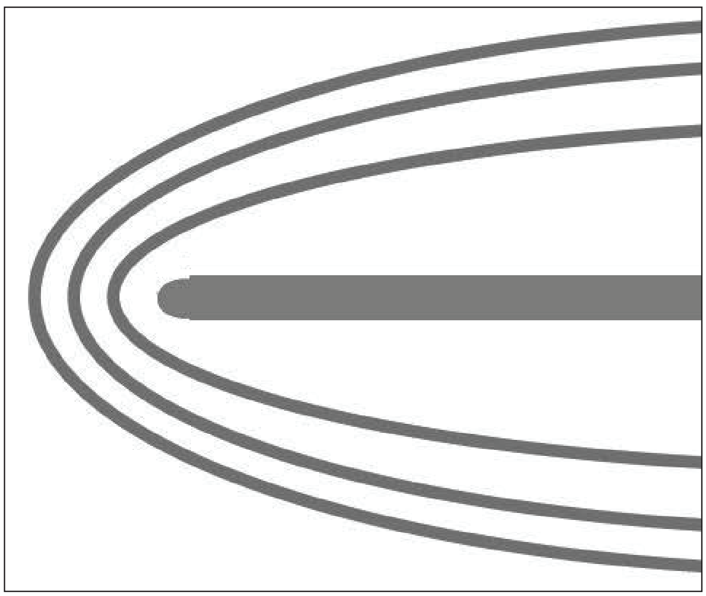


Figure 1. Field plot of a parallel-plate dielectric system.

Experience and testing must establish a design which assures adequate life of the materials. An additional safety factor should be applied to keep the dielectric from going into corona as the capacitor is operated within the duty cycles specified in industry standards. Operation in corona can rapidly cause permanent damage and failures. However, proper design parameters utilizing an adequate safety factor will allow long operational life of the dielectric system.

Foil edge treatments

Foil edge treatment and technology has been an area of regular advancement as this is commonly the region of highest electrical stress. The condition of the edge of the conducting plate has a large effect on the performance and operating capability of the capacitor, including the capacitor's DIV performance. There are several foil edge treatment techniques that are used in the industry today.

Mechanical slitting of the foil edge is the basic method of edge slitting for large mill rolls of aluminum foils. Historically this was the most common edge profile used in capacitor elements. This edge profile has widely been abandoned in modern capacitor construction, primarily because the mechanically slit edge has many tears and protrusions that significantly reduces the DIV as illustrated in Figure 2.

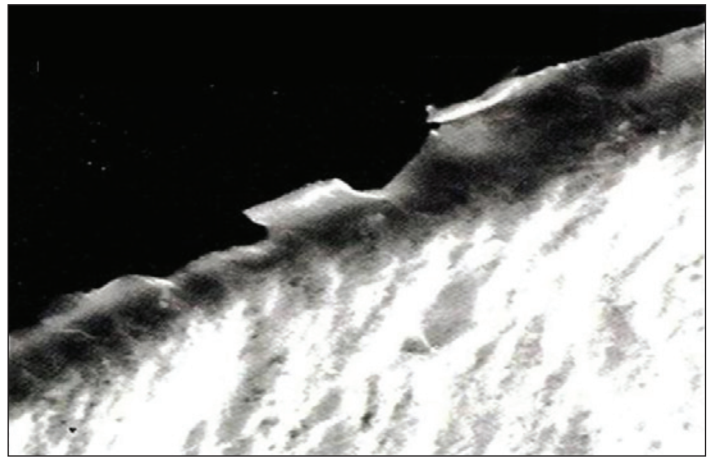


Figure 2. Mechanical slitting method.

In most modern-day capacitors, this edge has further treatments performed before it is wound into capacitor elements. Some manufacturers will utilize the mechanical slitting method and then fold the foil edge over itself to form a more uniform material edge. The foil, with a mechanically slit edge, is loaded onto the element winding machine and the winding machine has a device which forces the edge to "fold over" as it passes across winding rollers before the edge is wound into the element. The primary negative with a folded mechanical slit method is the excess material at the fold. This double foil thickness will consume additional space, resulting in the need for more dielectric fluid to fill the additional space between foils caused by excess edge material. Extra material and fluid means larger, heavier and more costly capacitor units.

Laser cutting of the foil edge provides an edge profile as shown in Figure 3. The foil mill roll is passed through a laser cutting device in the final slitting operation. This laser cut edge is then positioned on the winding machine so that the laser cut edge is internal to the element winding. Laser cut edge treatments provide a foil edge profile that is consistent with a smooth radius that results in improved DIV while maintaining a compact unit profile.

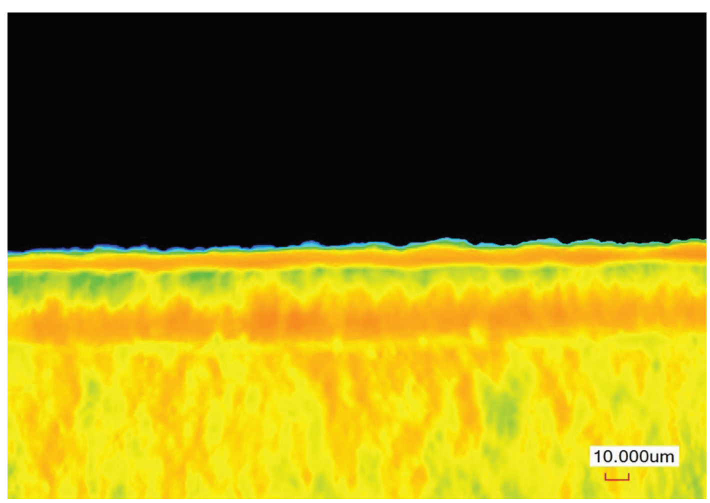


Figure 3. Laser cut method.

Elements connections

Individual capacitor elements must be electrically connected in a combination of series and parallel connections to provide rated unit capacitance and kvar. This construction arrangement is critical to ensure that the proper design voltage is applied to elements and that the elements operate at the designed electrical stress.

Eaton's capacitor designs employ an extended foil mechanical crimped connection. As shown in figure 4, extended foil mechanical crimping utilizes a specially designed flag connector (crimp) to mechanically connect the foils of neighboring elements. One side of each conducting aluminum foil is extended out of the edge of the element to allow for connection. The opposite edge of the foil that remains inside the element would be the laser cut edge. The extended foil edges are then crimped together with the extended edges of neighboring elements. This technique results in a repeatable connection with very low resistance. This connection lends itself to 100% quality assurance verification by a simple measurement of each compressed crimp.

Figure 4. Mechanical crimp method.

Alternative construction methods include extended foil soldered edge and ultrasonic weld techniques. In these designs the extended foils are either soldered or ultrasonically welded together with the extended edges of a neighboring element.

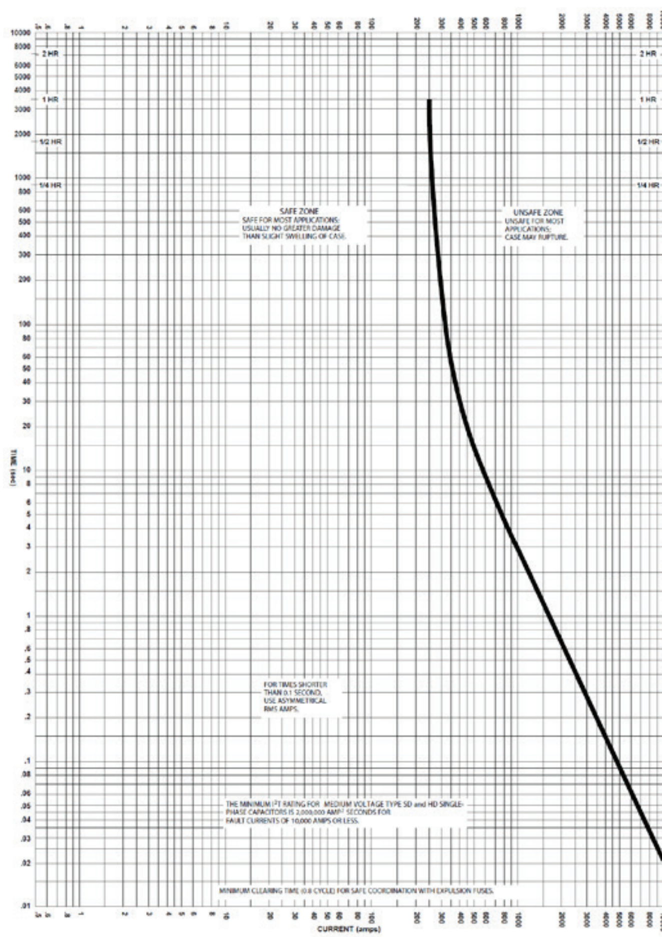
The benefits of the mechanical crimp method over other these techniques are primarily related to removal of failure modes and performance improvement. In the mechanical crimp technique, the series and parallel contacts are made utilizing only the extended foil, as opposed to a binding or filler material that will have different electrical and mechanical properties than the parent foil. The mechanical crimp method successfully eliminates localized heating, and cold solder joint failure modes, ensuring exceptional uniform current distribution resulting in outstanding transient performance and energy handling capability.

Tank rupture

Extended foil mechanical crimp connectors have many advantages that when combined, produce significant advances in safety and performance. These design features result in a mechanically stronger connection that is less prone to mechanically separate under high thermal energy discharge conditions. An additional benefit is a much lower resistance and more consistent connection than can be achieved through the other techniques previously described. The significance of this can be seen from examining the following formula which relates the I^2t withstand of a capacitor to its thermal energy (E) handling capabilities.

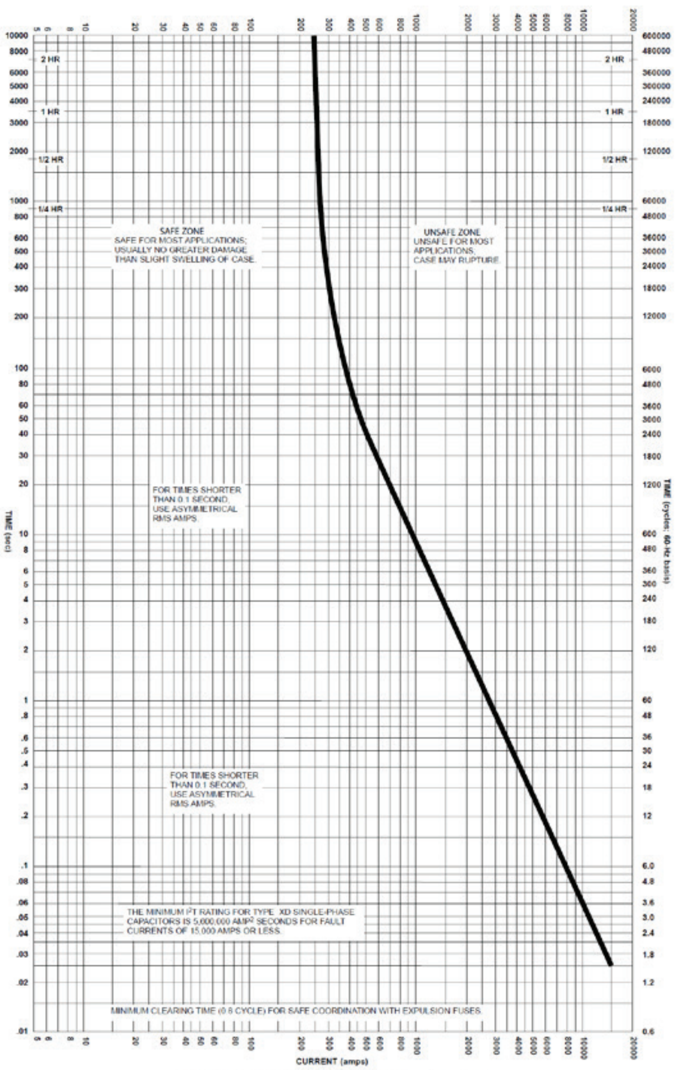
$$E = R \int I^2 \, dt \quad \text{therefore,} \quad E = R(I^2 t)$$

Note that as the resistance goes down, the value of I^2t goes up for the same thermal energy level. The I^2t withstand is what determines the tank rupture characteristics of a capacitor. Therefore, a lower resistance capacitor will exhibit a superior tank rupture characteristic. This is further illustrated in figures 5 and 6 below for 10 kA and 15 kA tank rupture curves based on unit classification (SD, HD, XD).



Tank-Rupture TCC for Medium Voltage Type SD and HD Single-Phase Capacitors

Figure 5. 10 kA Tank Rupture Curve



Tank-Rupture TCC for Type XD Single-Phase Capacitors

Figure 6. 15 kA Tank Rupture Curve

The tank rupture curve is far more definitive and reliable as opposed to previous designs. The predictability results in the same improved tank rupture performance regardless of the unit's voltage rating or kvar size. This is a significant departure from past designs, where a family of curves were necessary to describe the tank rupture characteristics of all available capacitor ratings. Thus, resulting in simplified coordination and control opportunities. In the end, these units are far less prone to rupture, resulting in safer operation and reduced cleanup concerns.

Conclusion

Eaton's research and development efforts have produced several design improvements which have been incorporated into capacitor unit products. Specifically, element construction featuring extended foil, laser cut active edge with a mechanical crimp assembly. These innovations result in units with the following:

- Higher reliability
- Increased safety
- Reduced risk of tank rupture
- High stacking factor optimizing active material and reducing package size
- Significantly increased discharge inception voltage (DIV) with highest design margin in the industry
- Improved fusing coordination margins
- Eliminated localized heating and cold solder joint failure modes, ensuring uniform current distribution resulting in outstanding transient performance
- Precisely controlled uniform rounded foil edge reducing the electric field stress.

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