

SUPPLEMENT 3 MINIMIZING CAPACITOR CASE RUPTURE — AN OVERVIEW

John E. Harder
Advisory Engineer

R.D. McClain, Manager
Capacitor Equipment Engineering

George E. Mercier, Manager
Capacitor Unit Engineering

Westinghouse Electric Corporation
Bloomington, Indiana

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Abstract

This paper discusses those factors of design, manufacture, and application which most affect the reliable performance and minimization of case rupture of capacitor units on electric transmission and distribution systems. It is the objective of the paper to help the casual capacitor user identify items which are most important in the selection and application of capacitors - to assure reliable performance.

Background

During the past several years there have been numerous discussions relating to capacitor reliability and case rupture performance. This high level of attention probably stems both from increasing emphasis on safety and environmental protection, and from several incidents of high capacitor failure rates.

Most of these discussions have been related to capacitor case rupture curves, capacitor fusing, and testing of capacitor units to improve reliability.

While the reliability of Westinghouse power capacitor units has probably been the best in the industry over the past several years, we nevertheless have had incidents of higher than desirable failure rates and have been involved in discussions of capacitor reliability and protection with many users.

Several observations emerge from this experience:

1. There appear to be some misconceptions regarding tests to predict the reliability of capacitor units.
2. Some of the field problems which have been experienced may have been aggravated by application oversights.
3. In a number of cases the bank protection has been defective or inappropriately adjusted.
4. In some cases, a more thorough examination of the equipment during installation and/or more thorough or regular maintenance examinations might have helped avoid problems.

As a result of these observations, we have come to the conviction that users seriously interested in reducing case rupture probability need to review all aspects of capacitor selection, application, installation, protection, and maintenance for their equipment installations.

As an aid in this regard, we would like to share a number of observations and experiences which we feel may be helpful to some users in improving the reliability of their capacitor installations. These comments are primarily directed at shunt capacitors for power factor correction in utility systems at 2400 volts or higher, in equipments of pole top installation, in metal enclosed equipment, and open stacks.

Case Rupture

Capacitor case rupture, if it occurs, may pose several problems:

1. Potential hazards to people and property from force expelled parts and possible fire.
2. Dielectric fluids leaking onto painted surfaces may finishes.
3. Potential environmental hazard (particularly in the case of older apparatus containing polychlorinated biphenyls (PCB)) and the necessity for special cleanup, disposal, and reporting.

This vulnerability exists in addition to the cost of system vars and the costs of repair, maintenance replacement.

The severity of a specific occurrence may depend on many factors. Rupture size may vary from a small fracture (with "weeping" fluid loss) to disintegration of the capacitor and broadcast of parts and material.

Factors affecting the severity include at least:

1. The cause and location of the initial dielectric failure.
2. Capacitor unit design and rating.
3. Fault protection employed for the unit and equipment.
4. Equipment arrangement (series and parallel operation, grounding, etc.).
5. System characteristics.

For example, a fault at the top edge of a winding caused by transient overvoltage might give a more violent release of energy than a puncture brought about by overvoltage in the central portion of the winding. Or, a capacitor container with large, flexible sides might accommodate slow development of gas pressure from a low level arc better than a capacitor with a smaller more rigid container. Available system fault current, or the proximity of a nearby, parallel connected capacitor, and the power input and rupture violence.

Case rupture is not one uniform phenomenon with one ultimate consequence. It is, rather, the result of many varied sets of circumstances, with many possible outcomes. About the only two things that are uniform about capacitor case ruptures are:

1. The case is fractured at least to the point where fluid may leak out.
2. It is undesirable.

Rather than analyzing the details of all of the possible case rupture phenomena, in this paper we focus on those factors which experience indicates will tend to minimize the numbers and violence of case ruptures.

THE CAPACITOR UNIT

The single most important factor in minimizing capacitor case rupture is the reliability of the capacitor units themselves. The reliability is determined by both the capacitor design and by the manufacturing quality control processes.

Design and Testing

Basically, capacitor designs are determined by matching the field performance requirements with sufficient design performance capabilities to insure adequate margins between the two throughout the anticipated period of use. The capacitor design must take into account a complex set of physical, chemical, electrical and mechanical properties involving the materials used in the capacitor as well as the manner in which they are combined to make up the capacitor. Potential capacitor materials and designs are evaluated by utilizing test methods that have previously been found to be particularly useful and by continually devising new tests to make more accurate assessments of the materials or capacitor designs.

When film-type capacitors were introduced more than 10 years ago, the problems associated with capacitor operation at high ambient temperatures were essentially eliminated due to the low temperature rise of this type of capacitors. The limiting design factor was shifted from a thermal to a partial-discharge-inception-voltage problem. Therefore, more and more attention has been paid to overvoltage endurance testing and partial discharge testing of modern capacitors.

Partial discharge testing is used in many types of capacitor evaluation tests. One of the traditional methods is to measure the partial discharge inception and extinction voltages of capacitors using either electronic or ultrasonic type detection equipment. The partial discharge performance is related to both the impregnating fluid used and to the design of the winding. (Table 1)

Because of the improvement in partial discharge inception and extinction due to the use of rolled foil construction, Westinghouse high voltage capacitors utilize this design improvement to provide an increased design margin.

The partial discharge inception voltage (PDIV) and partial discharge extinction voltage (PDEV) are also measured as a function of dielectric temperature (Figure 1)

TABLE 1

Type	Design	Fluid	Partial Discharge Voltages at 25°C (Percent Rated V)	
			PDIV	PDEV
1	AFPFA	Polychlorinated biphenyl	158	117
2	AFPFA	Polychlorinated biphenyl	200	133
3	AFPFA	Isopropylbiphenyl	250	187
4	AFPFA	Phthalate ester & trichlorobenzene	236	139
5	AFPFA	Butylated mono-chlorodiphenyl ether	208	167
6	AFPFA	Mineral Oil	170	65

A = conventional foil
 PPF = 75 ga. film, 45 ga. paper, 75 ga. film
 ar = narrow foil with rolled edges
 PDIV = Partial discharge inception voltage
 PDEV = Partial discharge extinction voltage

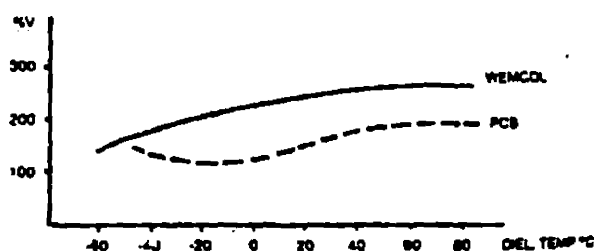


Figure 1 Partial Discharge Inception Voltage
 Typical curve: Variations occur with dielectric designs

Another useful test that has been used is an overvoltage cycling test. This is used with several variations. Type I is shown in Figure 2.



Figure 2 Overvoltage Cycling Test: Type I

In this test, the capacitor is tested for 24 hours (48 cycles) at each V_1 level (raised in 0.1 V_1 steps each 24 hours), until failure occurs. During this test the partial discharge intensity is monitored and is a measure of the dielectric degradation that is occurring during the test (Table 2)

TABLE 2

Design	Fluid	V_1 Failure Levels % Rated V
AFPFA	PCB	230
AFPFA	PCB	280
AFPFA	Wemcol	280

A = conventional foil
 FP = 160 ga. film, 45 ga. paper
 a = narrow straight edge foil
 ar = narrow foil with rolled edge
 PCB = polychlorinated biphenyl
 Wemcol = isopropyl biphenyl

This test is also performed to determine the effect of low temperature in a Type II test (Figure 3). In this test the capacitor is cooled to a low temperature before the test and re-cooled after 15 cycles to maintain the dielectric within a narrow range of low temperature. Results are shown in Table 3

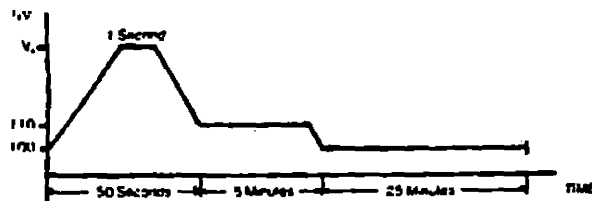


Figure 3 Low Temperature Overvoltage Cycling Test: Type II

TABLE 3

Design	Fluid	Temp °C	V _i Failure Level % Rated V
AFPFA	PCB	-25	215
AFPFAr	Wemcol	-40	250

A = conventional foil
FPF = 75 ga. film, 45 ga. paper, 75 ga. film
ar = narrow rolled edge foil

In another variation, Type III, the V_i value is maintained at a constant value and the test capacitors are cycled for a pre-determined number of times (Figure 4). After the overvoltage cycling, the power factor is measured at 100°C as a means of detecting effects of dielectric degradation (Table 4).

TABLE 4

Design	Fluid	Temp	Initial P.F. 100°C	Final P.F. 100°C After 1000 Cycles
AFPFA	PCB	25°C	.050	.099
AFPFAr	PCB	25°C	.040	.044
AFPFAr	Wemcol	25°C	.047	.049

A = conventional foil
FPF = 75 ga. film, 45 ga. paper, 75 ga. film
ar = narrow rolled edge foil

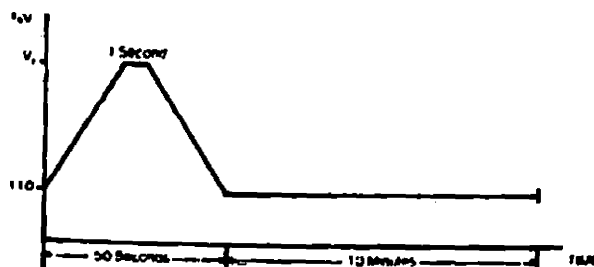


Figure 4 Overvoltage Cycling Test: Type III

Still another overvoltage cycling test, Type IV, is made as shown in Figure 5. In this test, the samples are tested to failure (Table 5). In addition, the partial discharge intensity is monitored during the test (Figure 6) and the length of time that the partial discharges persist after an overvoltage is measured (Table 6)

TABLE 5

Design	Fluid	Cycles to Failure
AFPFA	PCB	47
AFPFAr	PCB	187
AFPFA	DEHP + 25% TCB	130
AFPFA	Wemcol	> 1340
AFPFAr	Wemcol	> 1340
AFPFA	DINP	10
AFPFA	MCS 1238	560

A = conventional foil
FPF = 75 ga. film, 45 ga. paper, 75 ga. film
ar = narrow rolled edge foil
DEHP = diethylhexylphthalate
TCB = trichlorobenzene
DINP = diisononylphthalate
MCS 1238 = isopropylbiphenyl + sulfone

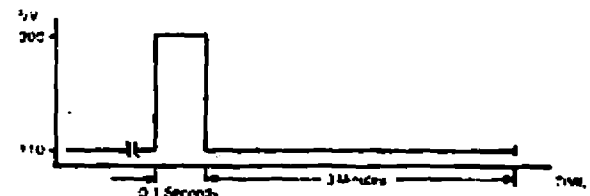


Figure 5 Overvoltage Cycling Test: Type IV

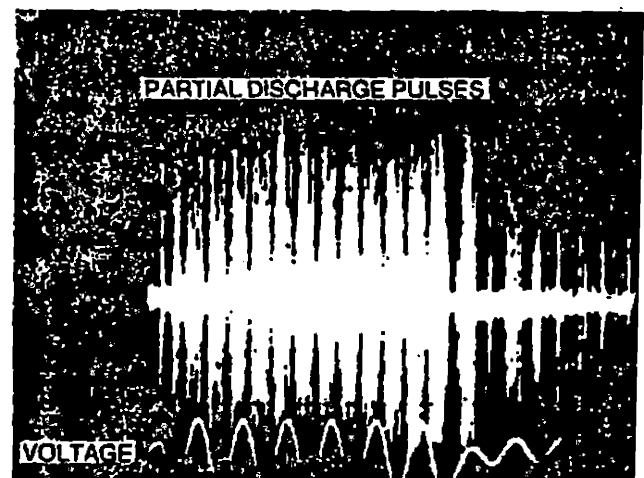


Figure 6 Oscillogram from Overvoltage Cycling Test: Type IV

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TABLE 6
Partial Discharge Intensity - Picocoulombs

Design	Fluid	During OV	2 Cycles After OV	8 Sec After OV
AFPPA	PCB	4000	200	< 2
AFPPAr	PCB	600	80	< 2
AFPPA	Wemcol	400	150	< 2
AFPPAr	Wemcol	200	< 2	< 2
AFPPA	DEMP + 25% TCB	1500	200	50

A = conventional foil
 FPF = 75 ga. film, 45 ga. paper, 75 ga. film
 ar = narrow rolled edge foil
 DEMF = diethyleneglycolterephthalate
 TCB = trichlorobenzene

Voltage capability is also measured by step-stress tests (Figure 7). In this test the voltage is maintained at a fixed value for a specified period and then is increased to the next higher voltage step until failure occurs. Partial discharges or power factor may be monitored either during or after each step (Table 7). When this test is used at low temperatures, the capacitors are re-cooled after each voltage step.

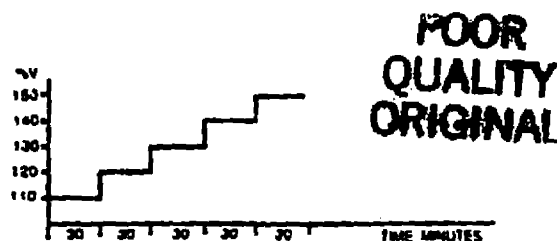


Figure 7 Step-Stress Test

TABLE 7

Design	Fluid	Temp °C	Voltage Step at Failure, % Rated
AFPPA	PCB	-40	140
AFPPAr	Wemcol	-40	150
AFPPAr	Wemcol	-55	140

A = conventional foil
 FPF = 75 ga. film, 45 ga. paper, 75 ga. film
 ar = narrow rolled edge foil

Low temperature switching tests are also used to check the effect of transient overvoltages. Capacitors are switched for a specified number of times at increasing voltage levels until failure occurs. The switching transient is typically a per unit voltage of 1.75 times the test voltage level. The continuous test voltages are maintained for approximately two minutes, then turned off for a few seconds and switched on again with the associated transient. This switching test is usually made at various temperatures to establish a relationship between switching voltage and temperature (Figure 8).

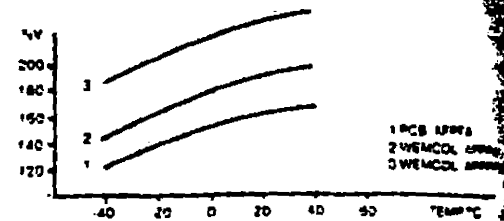


Figure 8 Low Temperature Switching Tests

A similar test to simulate effects of transients oscillatory discharge stress test (Figure 9).

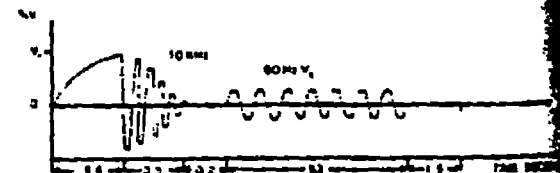


Figure 9 Oscillatory Discharge Test

The capacitor is charged with a dc power supply to a voltage V_1 and discharged at a pre-selected frequency and reversal. Then an ac power source is switched at a voltage V_2 for a specified time. The number of cycles required to cause failure is measured (Table 8).

TABLE 8

Design	Fluid	Peak V, % Rated	60 Hz. RMS V, % Rated	No. Cy to Fail
AFPPA	PCB	300	100	30
AFPPAr	Wemcol	300	100	> 10.0
AFPPAr	Wemcol	400	100	1.4
AFPPAr	Wemcol	400	100	4.1

These are but a few of the overvoltage tests used to assess the voltage capability of capacitors, but they are among the newer tests devised for this purpose. In general, these tests all predict that most non-PCB fluids perform much better than PCB fluids using the same film-dielectric system. They also indicate that, of the PCB fluids compared, the Wemcol (isopropyl alcohol) impregnated systems perform with the best results, with exception.

Manufacturing and Quality Control

Design tests such as those discussed above are essential in establishing the capability of a system to meet performance requirements. However, when large quantities of a particular product design are actually manufactured, only strict adherence to the use of proper manufacturing techniques and materials will insure that the quality of the product is produced. The verification that the proper test methods and materials have been used comes from product

spection and tests For a product such as capacitor units, a heavy emphasis should be placed on production (routine) testing of every capacitor produced. Although this adds some initial cost to the product, it gives the maximum assurance of a reliable, trouble-free capacitor with lower long-term costs. This is a desirable goal from both the user's and the manufacturer's viewpoint. Capacitors are a static device which should require little or no maintenance and also should have a long, useful life with a low field failure rate.

There are many manufacturing techniques and tests used to make high quality capacitors. Some of the more critical of these are:

1. Winding in a clean room with temperature, humidity and particle control.
2. Dry overpotential tests on windings and assemblies.
3. Dry capacitance and discharge resistor test.
4. Dry leak test of container and bushings.
5. Batch-type drying and liquid filling process.
6. Thorough heat treatment to insure complete impregnation.
7. Power factor measurement at maximum internal temperature limit at rated voltage - all capacitors (routine test).
8. Ultrasonic partial discharge measurement to assure complete impregnation has been achieved - all capacitors (routine test).
9. Overpotential test on all capacitors (routine test) at a dc voltage of 4.3 or 6.25 times rated voltage for 10 seconds (test level selected by the customer with regard to application requirements).
10. Final leak test by heating units to maximum dielectric temperature limit for a minimum of six hours.

These production tests on all capacitors will assure a customer that each capacitor received has been checked against potential problems in each of the following basic areas of concern:

Potential Problem Area	Production Assurance Test
Thermal	P.F. at rated voltage at maximum dielectric hot spot temperature
Dielectric strength	dc overpotential test
Partial discharges	Ultrasonic partial discharge measurement
Fluid leakage	High temperature leak test

When these production techniques and tests are employed and are backed up by proper design tests, the capacitor user will have assurance that he will actually receive capacitors that will perform reliably on his system.

CAPACITOR UNIT APPLICATION

The rather large number of field problems which have been aggravated by inappropriate unit selection has been somewhat surprising to us. While we are not naive enough to believe that the basic application documents (AI IEEE Standard 18-1969 or NEMA CP1) are thoroughly understood by all individuals involved in selecting capacitors, we are somewhat surprised at the apparent lack of awareness of factors which need to be considered in selection of capacitor units.

In selection of units, basically four items need to be considered: voltage, current, kVAC, and temperature.

Voltage

The recommended overvoltage application limit for capacitor units is illustrated in Figure 10. This figure applies to the voltage across the active element of the capacitor (Note: for units not connected to the case, the voltage applies to the insulation between the active element and the case. The "BIL" for units connected to the case applies only to the strength of the bushing(s).)

Some of the circumstances which have resulted in exceeding the recommended limits include:

1. Restriking of capacitor breakers or switches produced voltages in excess of the recommended impulse limits.
2. Voltage rise across short-circuit-limiting reactors in series with the capacitor has resulted in higher than recommended continuous voltage.
3. Group fusing of three phase ungrounded capacitor banks has, at the time of unit short circuit, resulted in overvoltages for units in the unfaulted phase exceeding the recommended limit.
4. If the substation bus voltage continuously runs above nominal, on banks with several series groups, an increase in voltage due to the loss of one unit in one series group may result in a voltage in excess of the recommended voltage balance of the units in that group. A conservative application would consider the maximum applied voltage (including any addition to crest voltage from harmonics) plus the maximum allowable unbalance.
5. High harmonics, in addition to leading to current and thermal overloading, can also add sufficiently to peak-to-peak voltages across the capacitor to bring about internal partial discharges and degradation of the dielectric. Such applications occur when standard shunt capacitors are used for power filters on the basis of fundamental frequency requirements and without consideration of short time, and continuous harmonic currents.

In determining the coordination between surge arresters and capacitors, the protective level of the arrester for 1.2 microseconds and longer can be compared (without margin) with the 4 times per year recurrence impulse voltage application limit of the capacitor. The capacitor tends to act as a filter, eliminating the

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consider front-of-wave sparkover for the arrester. The "margin" is inherent in the selection of the 4 times per year limit along with the fact that arrester values are maximum. Also, the presence of the capacitors at the arrester location eliminates the need for considering the short time reflections which need to be considered in transformer and switchgear protection. In addition, the very presence of the capacitor on the system tends to act as short circuit to high frequency transients on the system, and will often reduce otherwise excessive voltages to below arrester sparkover levels.

Applied voltages in excess of the recommended limits make the unit vulnerable to damage. To ensure that the reliability of the installation is important, application in excess of the recommended application limits should be avoided, to minimize the risks associated with possible increase in failure probability.

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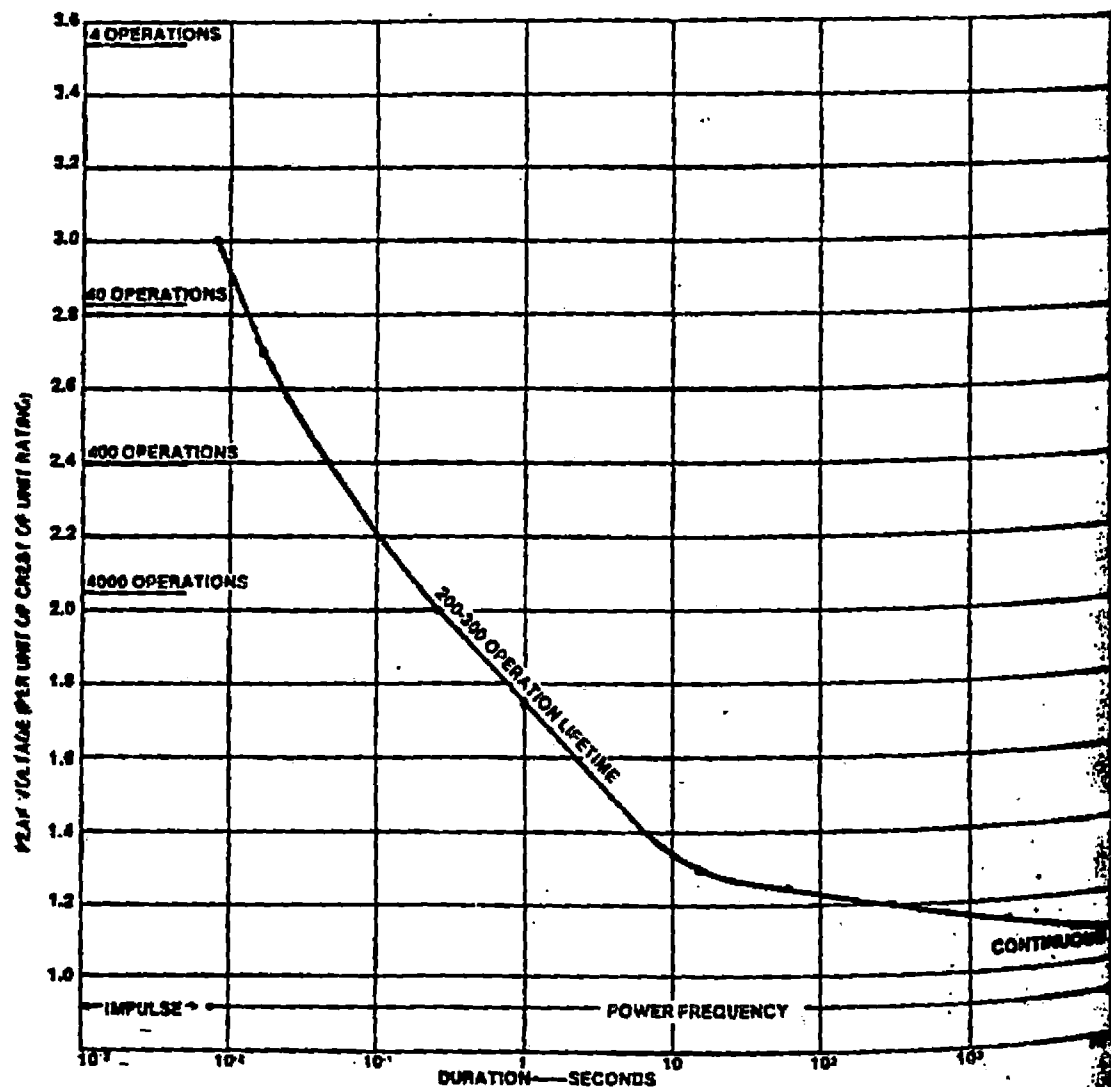


FIGURE 10 - CAPACITOR OVERVOLTAGE APPLICATION GUIDE

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Current

The recommended overcurrent application limit for capacitor units is shown in Figure 11. The subject of overcurrent application has been under consideration in both NEMA and IEEE standardizing committees, the recommendations may change in the near future. Also, the overcurrent capability of fuses, circuit breakers, bus work, CT's, etc. used in capacitor equipments may not always be the same as the capacitor units. For these reasons, applications falling in the shaded area of Figure 11 should be checked with the proposed manufacturer of the equipment. The situations for which overcurrents most often need to be considered are:

1. Large rectifier installations
2. Large arc furnaces or welders
3. Large SCR controlled equipment
4. Tuned filters
5. Resonant system conditions
6. Small capacitor banks frequently switched in with large banks

Experience indicates very little problem to capacitor from current alone. The most common "current" problems have been baked-out fuses and burned-out current transformers due to harmonic overcurrents. Capacitors are more commonly limited by total kVAC than by current alone.

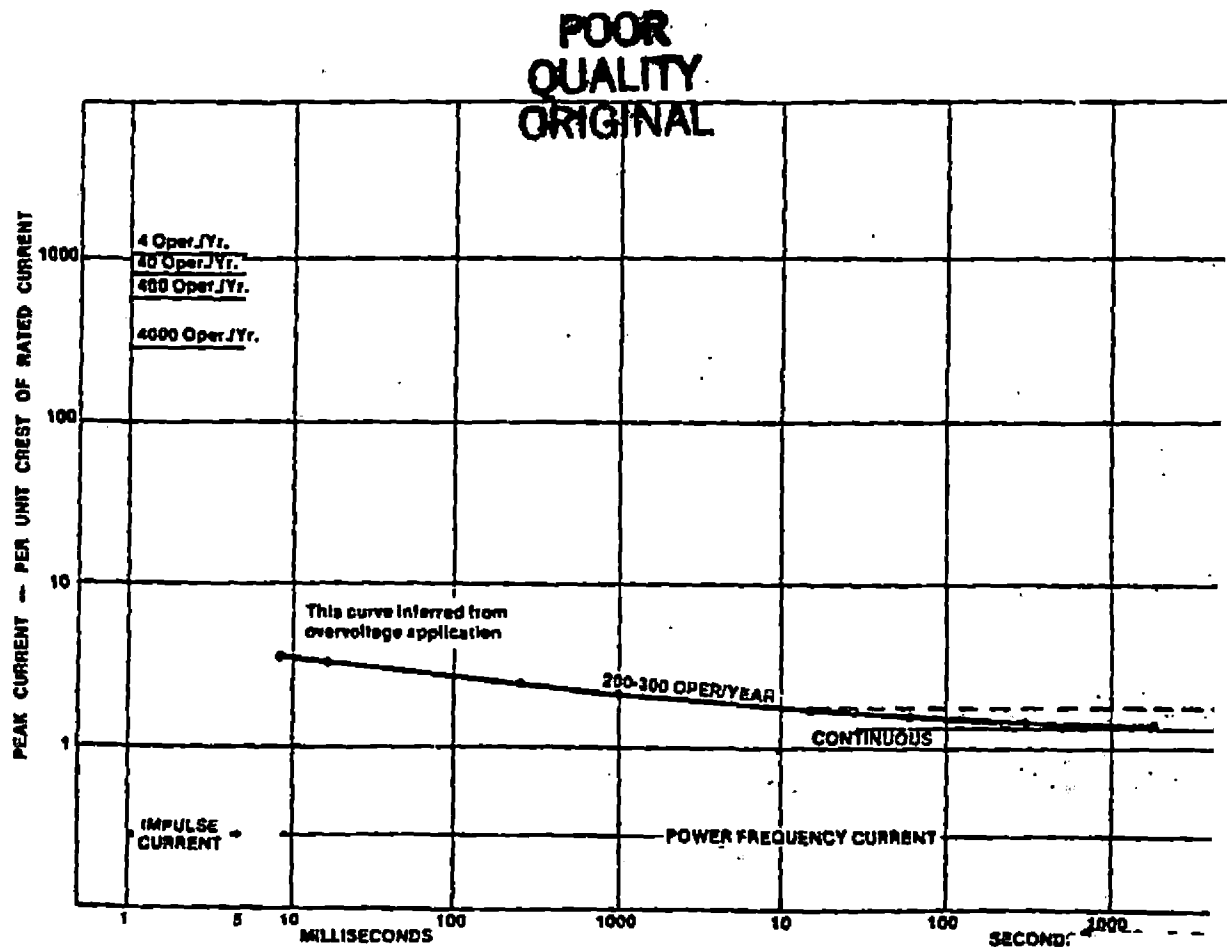


FIGURE 11 CAPACITOR OVERCURRENT APPLICATION GUIDE

kVAC

The total continuous kVAC in a capacitor unit should be limited to 1.35 times nominal. In determining the total kVAC, factors to be considered include system voltage as a per cent on nominal, capacitor unit capacitance as a per cent of nominal (standard limits -0, +15%), and harmonic current content.

The system conditions which may lead to excess are essentially the same as those listed under (above), with the exception of switching. These will usually result in the selection of higher the voltage capacitor units to meet both the voltage requirements of the installation. A failure to the units appropriately has resulted in units being in excess of their recommended kVAC limit with excessive temperatures.

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Ambient Temperature

Standard individual capacitor units are intended to be thermally stable at 46°C and are intended for a normal annual average ambient temperature of no higher than 35°C. More realistic limits for equipments are 35-40°C for the hottest day expected at the location and an annual average of 20-25°C.

Large capacitor installations inside of buildings in hot climates (and especially those close to large furnaces) need careful consideration of ambient temperature. The heat dissipated by the units themselves can add to the ambient temperature in an enclosed area. For such high temperature applications, an ambient temperature alarm and trip relay is appropriate.

Capacitor unit voltage, current, kVAC and ambient temperature are important considerations in avoiding vulnerability to capacitor units and equipment failure. Avoiding unit failure is the first and most important step in minimizing the probability of capacitor case rupture.

PROTECTION

Sophistication of protection is related to the size of the capacitor installation and the effect on the system in the event of unit or equipment failure.

Individual unit or group fusing serves as the first line of protection for larger installations. Unbalance relaying quickly removes the bank from the system in the event of excessive numbers of unit fuse operations or other failure within the bank. Major fault protection is provided by system overcurrent relaying or overcurrent relaying in the capacitor switching circuit breaker.

A number of observations have been made concerning each of these areas of protection, which will be discussed.

Fusing

The optimum fuse is the smallest, fastest fuse which will not result in nuisance operations and which will meet the voltage, fault current, and energy requirements of the location.

Fuse-case rupture coordination has been the subject of much discussion and confusion. Fuse total clearing curves are, relatively speaking, the result of a rather well standardized test procedure, and result from a rather uniform melting phenomenon from fuse link to fuse link at a given current level. Over the years rather consistent procedures have been developed for fuse-fuse and fuse-relay coordination. Even in this rather mature area of coordination, there are occasional reports of mis-coordination.

Capacitor case rupture is not one rather uniform sequence of events as in fuse link melting and clearing. There are many modes of failure resulting in different probabilities of case rupture. Even in one kVAC rating, the physical volume of the can, internal connections, operating temperature, as well as many other variables probably have some influence on the case rupture characteristics.

Note that the normal current in a 24 kV unit is more than eight times the current of a 20 kV unit of the same kVAC rating. The normal current through a 24 kV capacitor is the same magnitude as the current in a severely faulted 20 kV capacitor. This distinction is not normally made at the low current end of the case rupture curves.

The great majority of case rupture tests reported have been started with essentially completely failed units. In the field, there is at least a possibility that the unit fault will develop gradually, pack by pack. Perhaps the presence or absence of parallel capacitors will have an effect on the internal gas generation during this partially faulted condition. Capacitively limited fault currents in high voltage shunt capacitor banks may have different arcing and gas generation characteristics than inductively limited fault currents on a distribution feeder or in the laboratory.

There may be a great many differences between the conditions surrounding a faulted capacitor in service than the conditions surrounding a pre-faulted capacitor under going case rupture tests in the laboratory.

We understand that some users occasionally re-fuse capacitors that are not noticeably bulged, without testing them (a practice which we would discourage). This may result in energizing faulted units a second time, increasing the probability of case rupture. Depending on the nature of the fault, the fuse may clear before the unit shows any visible signs of bulging.

Several users have commented that their observed case rupture probability is higher than the expected 10% based on coordinating a fuse with the capacitor case rupture curves (which are plotted at the 10% probability case rupture level). Considering all of the possible differences between field conditions and laboratory test conditions, this is not entirely surprising. We regard the case rupture curves as giving an indication of capacitor case rupture performance under a stated set of conditions. The process of case rupture testing has led to many improvements in case rupture performance. The case rupture curves, however, are probably not an adequate basis for predicting case rupture probability of field capacitors under a wide variety of field conditions. Field experience with given fusing practices is the ultimate measure of case rupture probability. Certainly we would not suggest using fuses rated higher than suggested by the case rupture curves, but lower rated fuses may be desirable for some types of installations.

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Current Limiting Fusing

On distribution banks where system available fault current exceeds about 5000 amperes, some form of current limiting fusing is desirable to avoid excessive internal fault energy. Also, on large substation banks with many units in parallel, current limiting fuses are recommended to limit the energy discharged into a fault from parallel units.

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Relaying

Inappropriate relay settings, defective relay systems, and absence of relay protection altogether have and can result in extensive capacitor bank damage in the event of arcing within the bank.

Smaller group-fused banks (up to about 1200kVAC at 12 kV) usually involve no special relaying protection. Backup protection is provided by system relaying. Relaying should at least be considered for larger banks using individually fused capacitors.

In considering relaying, at least three kinds of protection need to be considered:

1. Unbalance protection. Fuse operations on some units may cause the voltage to increase on other units in the same group. Unbalance protection may give an alarm for a small amount of voltage rise and trip the bank off to avoid damage from excessive voltage rise.
2. Group arc-over protection. For some bank configurations, an arc in one capacitor group will have limited fault current because of other groups in series. Transients associated with such an arc can damage capacitors, blow fuses, cause violent case ruptures from high voltages, etc. The bank should be disconnected quickly (certainly within one-half second) for a group arc-over.
3. Phase-to-phase and phase-to-ground faults. These faults should be removed quickly, and without reclosing to avoid high transient voltages and currents. Sometimes this protection is provided by bus fault or feeder protection.

There has been some mention in the industry of the use of pressure switches in individual capacitor units to detect low current faults. While there is little doubt that pressure switches can reduce the probability of case rupture from certain types of low current faults in switched capacitor equipment, there is some question as to the economic viability of wide scale application of pressure switches. Pressure switches are probably not a viable alternative on individually fused capacitors in large assemblies, particularly at transmission voltages.

SHIPPING AND INSTALLATION

In many cases transportation from the manufacturing plant to the installation site is the most severe duty required of a capacitor equipment.

New capacitor equipment should be thoroughly inspected on installation. Look especially for: (1) leaks, (2) loose hardware, terminals, or fuses, (3) broken porcelain, (4) dented containers, (5) broken frames or busses. Any damage revealed requires restoring the parts to original condition or replacement of parts.

Lifting instructions should be followed and proper lift points used in unloading or moving.

It is further suggested that a check of the material received be made against the erection drawing requirements

and that nameplate ratings be verified. Some failures have occurred because the wrong rating of fuse or capacitor was applied.

During installation, follow the manufacturers recommendations in ensuring connection with adequate bus or lead conductors with capability of at least 135% of rated nominal capacitor current. Normally the capacitor circuit breaker overload trip is set to trip between 135% and 200% of rated nominal capacitor current. All bus joints and connections to terminals must be properly prepared and tightened as a loosened, overheated, melted bus joint can induce a restriking bus fault with disastrous consequences to the capacitors.

Depending on the method of protection against an internal bank fault, it may be necessary to establish very close balance between the capacitances of the phases. When individual capacitor rack capacitance values are provided arrange the racks in accordance with the manufacturer's recommendation. Check the capacitance value for each phase, independently, to ascertain that values are matched within tolerance. For banks connected wye-wye, compare the impedances of sections 1 and 2 of the same phase as well as the impedances of the three phases of the same section. Use these impedance checks to calculate the effectiveness of the relay protection scheme. D withstand dielectric strength tests might be made on bus and spacing insulators to detect any cracks resulting from shipment, handling, or installing. Upon initial energization of a large capacitor bank, the signal to any relays used for detecting unbalance should be checked to reestablish proper initial balance.

MAINTENANCE

Regular maintenance and inspection can help reduce probability of trouble and limit the possible consequences. As a minimum, visual inspection for blown fuses, damaged insulators, bushings, or containers (for leakage or swell) is recommended. Polluted atmospheres or environments may require periodic cleaning of porcelain insulators, bushings. Weathered surfaces should be refinished as required.

Blown fuses can result from improperly installed or excessive harmonic or inrush current, external arc fault in the capacitor. Before replacing the fuse restoring service, inspect the capacitor for visible signs of external damage and after shorting the capacitor, rec the capacitance. A small, hand held capacitance meter (such as the Doric Model 130 C-Meter) is convenient and useful for this. Do not re-fuse or re-energize a fully or partly faulted capacitor as the damage suffered at the initial fuse operation may be such as to cause a high probability of case rupture during the second operation. In event that no damage to the capacitor is detected, re-fuse with the correct fuse element. In all cases when energizing a capacitor after re-observe safety precautions against potential failure case rupture.

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At least several capacitor failures have resulted in damage to capacitor installation because of apparent lack of maintenance of the protective system. Regular checks should be made that the correct current through a CT (or voltage on a PT) will cause proper relay, alarm, and breaker operation. Protective gaps on CT's should be checked for proper clearance and breakers should be hi-potted on a reasonably regular basis.

If there has been a major failure resulting in external arcing in a capacitor installation, the entire installation should be thoroughly inspected before trying to re-energize it:

1. All capacitors should be checked for proper capacitance; installations with several series groups should have the capacitance balanced so the voltage divides equally among the series groups.
2. All capacitor units should be checked for excessive corrosion or bushing contamination and any indication of leaks. Units should be painted and bushings cleaned as required. Leaking units should be eliminated.
3. All fuses should be checked for continuity, expulsion fuses checked for tightness.
4. All insulators should be inspected and any badly chipped ones replaced.
5. In addition, the relaying check suggested earlier should be done before re-energizing the bank.

Based on past experience, a thorough examination of the bank will likely reveal some unexpected items.

OTHER CONSIDERATIONS

Switching

Inappropriate selection of switches or breakers for capacitor switching has and can cause problems for both the capacitor bank and the system. Switches used for capacitor switching should be rated for capacitor switching; the contacts should not bounce on closing or restrike on opening. It is also desirable to test the breaker or switch in place after installation but before energizing the capacitor bank. Interrupters should be hi-potted in place. It is also desirable to check the timing of interrupters where there are several interrupters in series per phase. Shipping damage, which may not be obvious by visual examination of the breaker, has caused breaker malfunction and resulting capacitor bank damage.

Bank Configuration

Grounded vs. Ungrounded. Grounded banks result in lower transient voltages on the capacitor switch and may result in less unit overvoltage for individual fuse operation. Ungrounded banks have no ground path for certain harmonic currents, minimize ground currents during switching, and may limit fault current for some fault conditions. For transmission voltage banks, the base insulation is reduced or eliminated by a grounded wye connection; most banks 230 kV and higher are connected grounded wye.

Series and parallel groups. Generally a bank with the fewest number of series groups and the maximum number of parallel units is easiest to protect. In this case a certain per cent change in capacitance for one group is easiest

to detect and represents the loss of a large number of units.

Filter Banks

While overvoltage and overcurrent guidelines were given in an earlier part of this presentation, the design of filter banks should almost always be done in cooperation with the manufacturer. Mounting of reactors, connection and protection of capacitors, selection of ratings, etc. can almost always be aided by the manufacturer's experience with previous banks.

SUMMARY

Capacitor case rupture is the result of many, varied phenomena. Most important in minimizing the probability of case rupture is the correct application of reliable capacitor units. In addition, proper protection can help minimize the probability of rupture in the event of failure.

Many of the factors involved in capacitor reliability application, and protection have been discussed. Satisfactory performance is not a matter of fusing alone, or of capacitor construction alone, or of protective relaying alone, or of application criteria alone....but requires balanced attention to all of the factors as outlined in the paper.

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