CAPACITORS FOR RFI SUPPRESSION OF THE AC LINE: BASIC FACTS

Fourth Edition

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THE NEED FOR RFI SUPPRESSION

Various national agencies require that the level of RFI (Radio Frequency Interference) emitted by most electrical equipment be limited. Frequencies above 30MHz tend to radiate directly from the generating circuits, while those below 30MHz are usually conducted by the AC line and other connections. These are capable of radiating (or receiving) RFI.

Filtering The AC Line

To meet the conducted RFI limits an AC input filter is usually required. The type varies widely depending on the equipment. Where the interference is generated by a single source (such as a commutating motor) it is best to locate the filter as close to the source as possible. If the interference is widespread but contained in a metallic enclosure (such as in a switched-mode power supply) the filter is best located at the AC cord entry point. Filtering is usually accomplished with capacitors especially designed for AC use, often in conjunction with chokes or transformers of various designs.

RFI is conducted on the AC line either symmetrically or asymmetrically. Symmetric interference can be envisioned as a source connected between the main and neutral wires. A line-to-line capacitor (designated as type X) properly applied is effective for this type. Asymmetric interference is represented by a source between either main or neutral and chassis ground. A line-to-ground capacitor (type Y) provides filtering in this case.

While the X capacitor may be of any practical value, the Y capacitors generally must be kept to small values to limit the 50/60Hz leakage current to ground. 4700pF is a typical Y capacitor value. Common X capacitor values are 0.1 through 1.0µF. Sometimes even higher values are required depending on the interference frequencies. In general, improved P.C. layout practices result in smaller required capacitor values. Also, two X capacitors of smaller value are generally better, especially in the pi-configuration with a choke.

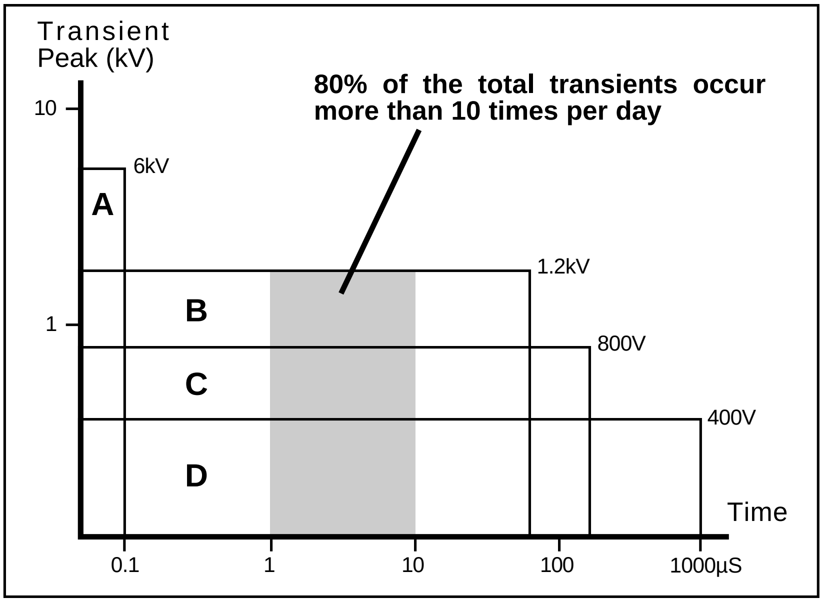
SAFETY CONSIDERATIONS

Due to their placement on the AC line a failed RFI suppression capacitor is capable of causing injury either by shock or fire. The problem is exacerbated by conditions on the line. On a daily basis the line conducts voltage surges and transients which often attain amplitudes of several kilovolts.

Because of the potential for injury the various safety agencies provide testing and recognition for X and Y capacitors. **It is interesting that while UL has standards for various line connected devices including capacitors, they require a consumer product manufacturer to recommend that the appliance be unplugged while away from home!** This is because TV and appliance fires continue to occur due to line transients despite the standards. **Specifying the dielectric and characteristics of an RFI capacitor is as important as the required agency approvals.**

Conditions On the AC Line

A European study by Unipede (a consortium of power producers) revealed the types of transients found on the line:



Types of Transients Found on the Line (see text for descriptions)

The four types are:

A = 0.1µS/6kV
Atmospheric interference such as lightning.

B = 60µS/1.2kV
Failure in the network or in nearby equipment, such as flashovers and fuse breakings.

C = 200µS/800V
On/off operation of equipment such as motors, air conditioning units, etc.

D = 1000µS/400V
Pulses from equipment such as welders, thyristors, triacs, etc.

80% of all transients have a duration between 1 and 10µS and amplitudes up to 1.2kV. These occur more than 10 times per day. Assuming a lifetime of 10 years the RFI capacitors must withstand over 30,000 such surges, as well as lesser numbers with amplitudes up to 6000 volts. The Unipede data agrees with IEEE Std. 587 which recommends equipment be tested with a 6kV damped sinusoid. IEEE 587 is discussed on page 7.

RFI CAPACITOR AGENCY APPROVALS

The various agency requirements for RFI capacitors have important differences, although the EC has converged on a common standard. One must be careful in specifying RFI capacitors to avoid being surprised when the final product is itself submitted for approval.

United States (UL)

The United States actually does not have a national safety agency. Underwriters Laboratories (UL) is a private corporation. Various federal and state laws require that electronic products be listed with any Nationally Recognized Testing Lab (NRTL) of which UL is the most widely known. NRTLs typically test end products to UL standards (plus those of other countries) and very few test primary components such as capacitors. Therefore it is sufficient to discuss only UL.

UL was established over 100 years ago by a group of insurance companies to promote product safety as a means of reducing insurance claims. Accordingly UL's focus has generally been on traditional consumer products. This is the case even today. For example, an RFI capacitor used in a television receiver has very strict safety requirements established by UL. An RFI capacitor in an electronic ballast has less stringent requirements. The same was true of RFI capacitors in switched mode power supplies until UL adopted the IEC950 standard.

At the present time there are two UL standards related to RFI capacitors: UL1414 and UL1283. UL1283 is actually a standard for potted RFI filters. The only meaningful reason to have UL1283 recognition for a capacitor is to demonstrate the capacitor's ability to survive the tests that the filter must undergo. *UL1283 recognition of a capacitor is not required by any UL equipment standard*. The requirements are not very stringent, consisting primarily of a dielectric withstand test.

UL1414 is specifically required for television and radio receivers and certain telecommunications equipment. The tests are quite stringent. A capacitor may be rated for either 125 or 250VAC (nominal) at 85ºC. The requirements of UL1414 at 250VAC are summarized:

- A 1500VAC dielectric withstand test for 1 minute.
- Be subjected to 50 discharges from a cap charged to 10kV through a 1000Ω resistor, then pass a 1kV dielectric withstand test.
- A 1008H endurance test at +85ºC with an applied voltage of 440VAC 60Hz. Once per hour, for 0.1S, the voltage is raised to 880VAC.
- A passive flammability test.
- An active flammability/expulsion test.

The UL requirements for RFI capacitors can be broken into four general categories:

<u>Summary of UL Requirements for RFI Capacitors by Application</u>

TV, radio and certain telecom equipment: UL1414 is required.

Capacitors employed in potted RFI filters: UL1283 is required.

Capacitors employed in power supplies for IEC950 applications (including those in potted RFI filters): No UL standard applies. Capacitors must comply with the appropriate IEC standard.

RFI capacitors in other equipment: No UL standard applies. Capacitors are expected to survive the equipment tests which may include overvoltage, dielectric withstand and abnormal temperature testing.

Canada (CSA)

CSA requirements closely parallel that of UL, with CSA C22.2 No. 1 being equivalent to UL1414 and CSA C22.2 No. 8 being equivalent to UL1283. Although some details differ, the CSA standards are applied in an equivalent manner to their UL counterparts.

UL and CSA Cross-Licensing

UL and CSA have entered into cross-licensing agreements on a wide variety of standards. This means that UL can test and certify compliance to CSA standards and vice-versa. For example one may have UL evaluate an RFI capacitor to the requirements of UL1414 and CSA C22.2 No. 1. UL would then make tests which conform to both standards including any differences which exist. Such a capacitor would bear the standard UL mark and a new “cUL” mark. The latter is fully accepted by CSA.

UL Mark

cUL Mark

IEC (International)

The IEC is an international body which can pass recommendations but does not in itself have approval power in any country. The USA, Canada, Russia, Japan, most of Europe and many other countries participate. While the North American RFI capacitor standards have traditionally been unlike IEC recommendations this may change in the future. The impetus for change is the business equipment standard IEC950 which has been adopted virtually worldwide. IEC950 has specific requirements for RFI capacitors which are not met by any UL or CSA standard, even though UL and CSA have themselves adopted IEC950 (as UL1950 and CSA C22.2 No. 950). UL and CSA will allow an RFI capacitor that meets the *European* capacitor requirements.

The original IEC standard IEC384-14 defined three RFI capacitor classes. These were: **Type Y** for line-to-ground use, **type X2** for line-to-line in normal applications, and **type X1** for stringent line-to-line applications. In the pre-European unification days VDE and others adopted the standard verbatim while the Nordic countries and Switzerland adopted a version with significant variations. Since IEC384-14 was created a market need developed for increased safety of RFI capacitors. This resulted in an updated version which was adopted by the European Community.

European Community

In an effort to reduce the costs of doing business across the borders of EC member nations the European Community has unified the safety standards which were formerly different in every country. One may now, for example, have a computer tested in only one member country and sell it in all member countries. These unified, or “harmonized” standards are identified with an “EN” designation. The European standard for business equipment (IEC950) is EN60950. Similarly the standard for RFI capacitors (IEC384-14) is EN132400.

The EC has a different approach to RFI capacitor standards compared to UL and CSA. The EN standard is quite different in its requirements and it is applied to all types of AC operated equipment, not just a few select categories. Since most equipment is designed for worldwide use the EN standard is important to North American designers as well as to Europeans.

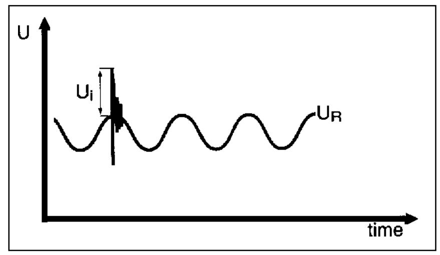
EN132400 (IEC384-14)

EN132400 defines a total of seven classes of RFI capacitor, three X classes and four Y classes. The required class is determined by the equipment standards for the final product. For typical business equipment and computers covered under EN60950 (IEC950) the applicable classes are X2 and Y2.

Major Tests of EN132400

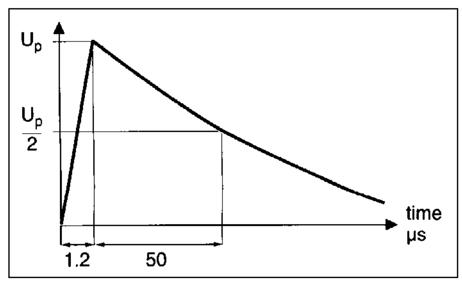
Active Flammability

The capacitor under test is connected to rated voltage through a transformer and filter. 20 transients are then introduced across the capacitor at random intervals while rated voltage remains applied. The amplitude of the transient is dependent on the class of capacitor. The capacitor may not flame during this test.



Impulse Test

Up to 24 impulses are applied to the capacitors under test. The amplitude of the impulse is dependent on the class of capacitor. The impulse waveform is monitored. If the waveform of any three successive impulses show that no self healing has occurred the capacitor is considered to have passed the test and no further transients are applied. If self healings occur so that no three successive impulses are free of self healings, a total of 24 impulses are applied. If more than three transients total were free of self healings the capacitor is considered acceptable.



Endurance Test

The same capacitors which passed the impulse test are then placed in an oven at the maximum rated temperature. The applied voltage is 1.7 times rated voltage for Y capacitors and 1.25 times rated voltage for X capacitors. In addition, once every hour the voltage is increased to 1000VAC for 0.1 second. The endurance test continues for 1000 hours. Afterward the capacitors undergo a dielectric withstand test and are then measured. If the changes in critical parameters are within limits the capacitor is considered to be acceptable.

X Capacitor Applications

The class of X capacitor is determined by the equipment standard applicable to the device and the "installation category," meaning the type of connection to the AC line. These installation categories are defined by IEC664. In general one encounters installation category II (connection to ordinary wall outlets) and installation category III (connection to main power trunk lines within a building). The X capacitor classes are covered in order of popularity.

Class X2

The most common class of X capacitor as it covers applications using line voltages from 150 to 250VAC (nominal) which are plugged into ordinary wall outlets. In Europe this covers a lot of ground: Computers, hair dryers, fax machines, hand power tools and so on. These capacitors are impulse tested with 2.5kV if their value is 1.0μF or less. For larger values the impulse voltage is 2.5kV/√C (in μF).

Class X1

This class will be called for in installation category III applications such as for an industrial printer or minicomputer which is connected to a 3-phase line. Industrial lighting ballasts can also fall into this category. These capacitors are impulse tested with 4.0kV if their value is 1.0μF or less. For larger values the impulse voltage is 4.0kV/√C (in μF).

Class X3

A general purpose category with no impulse test. To date no known equipment standard allows the use of class X3 capacitors. It might be allowed in the future in devices which are never used except under the supervision of an operator, for example in a hand power tool.

Y Capacitor Applications

IEC950 and other equipment standards define several grades of insulation which protect the end user from electric shock. These are **basic insulation, supplementary insulation, reinforced insulation** and **double insulation**. These categories are used for all types of insulating materials which separate exposed conductive elements from dangerous voltages. This includes Y capacitors which are allowed to bridge the insulation. Most commonly basic or supplementary insulation is bridged by Y capacitors but in some applications the designer may desire to bridge reinforced or double insulation.

EN132400 has four classes of Y capacitor which conform to the insulation grade being bridged and line voltage used. In ordinary data processing equipment class Y2 is generally required when bridging the AC primary to ground. Some applications such as bridging the DC side of the primary to ground may require a Y1 type. All four classes are described in order of their popularity.

Class Y2

The most popular type. Such a capacitor is allowed to bridge basic and supplementary insulation with line voltages up to 250VAC (nominal). This is the normal case for power supplies used in data processing equipment. These capacitors are impulse tested with 5kV. (Those with previous RFI experience will recognize this class as being similar to the old “class Y” with SEV approval.)

Class Y1

For bridging reinforced or double insulation. This is a new category. In Europe in the past one was required to use two separate capacitors in series to bridge double insulation requirements. Now one class Y1 capacitor is allowed. These capacitors are impulse tested with 8kV and are suitable for line voltages of up to 250VAC (nominal).

Class Y3

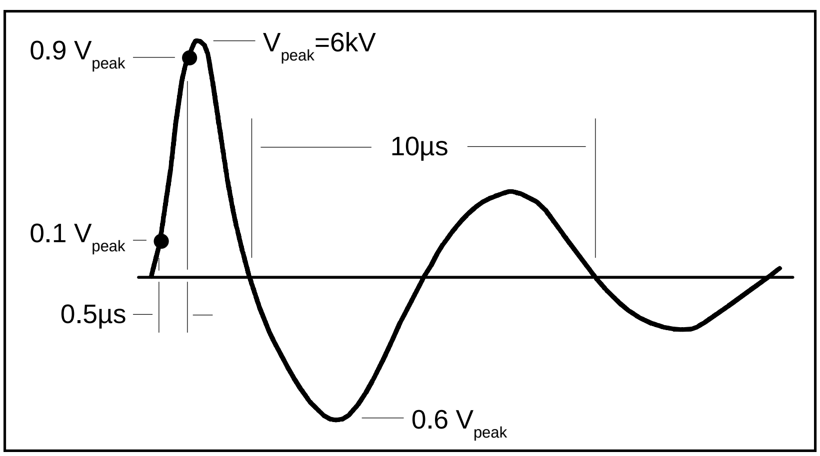
For bridging basic and supplementary insulation with line voltages up to 250VAC (nominal) but without an impulse test. To date no known equipment standard allows the use of class Y3 capacitors, although it is presently being considered for use on the secondary side of a transformer. As with the X3 it might also be allowed in the future in devices which are never used except under the supervision of an operator.

Class Y4

For applications with line voltages up to 150VAC (nominal) with an impulse test of 2.5kV and bridging basic and supplementary insulation. No known equipment standard yet allows the use of Y4 capacitors.

PERFORMANCE STANDARDS - IEEE587 (ANSI / IEEE C62.41)

Safety agency approvals do not insure product performance. Simply stated, equipment may fail after a line transient provided it fails "safely." The Institute of Electrical and Electronics Engineers (IEEE) has answered the call for a performance specification. Passing the IEEE587 standard gives reasonable assurance that equipment will **survive** a severe line transient. IEEE587 is of particular interest to manufacturers of uninterruptable power supplies, surge protectors, lighting, computers and terminals, business equipment and any others who wish to assure their customers of the reliability of their product.



Surge Test Waveform Recommended by IEEE 587 for Class A Devices

IEEE 587 is broken down into three categories. Class A is for equipment connected to long branch circuits (such as a standard wall outlet). Class B is for short feeders and Class C is for devices connected to the main panel or outside.

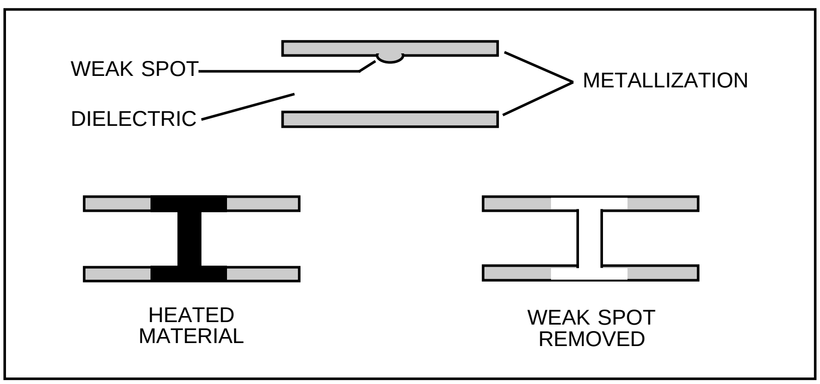
Class A devices are by far the most common. The major component of the testing is the application of a 6kV damped sinusoid to the AC input. This waveform is meant to simulate the ringing found on long branches when lightning strikes the power line. Many manufacturers meet the standard by incorporating up to three surge suppressors in the primary circuit. **In some cases the surge suppressors have been eliminated by specifying RFI capacitors made with impregnated paper because they have been demonstrated to survive the 6kV transient.**

EVALUATING RFI CAPACITORS

As with any component, the designer wishes an RFI capacitor to perform reliably throughout the product's lifetime. However even the strongest part may fail under a surge of sufficient energy. An RFI capacitor must then fail in a safe manner. The potential for liability in event of shock or fire requires that all devices connected to the AC line be carefully evaluated.

Withstanding Surges-Self Healing

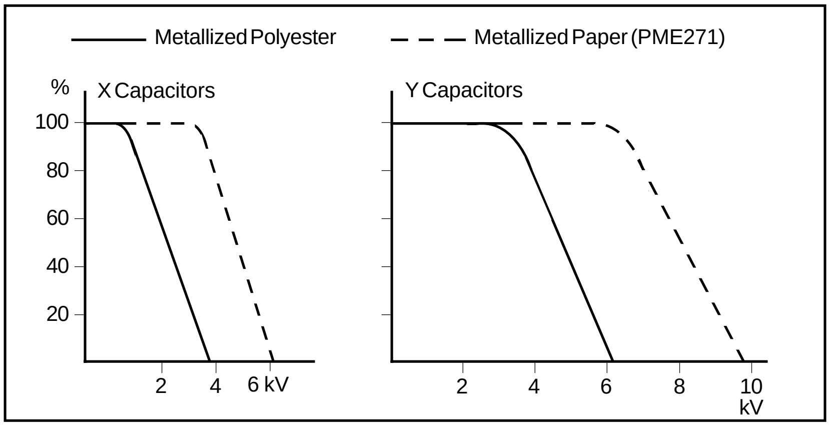
There are three types of RFI capacitors commonly in use on the AC line. These are impregnated metallized paper, metallized film and ceramic. The first two are categorized as "self healing" or "clearing" while ceramic is not. The property of self healing, properly designed into a capacitor, can extend its life while maintaining a small size and safe operation.



Self Healing in a Metallized Capacitor

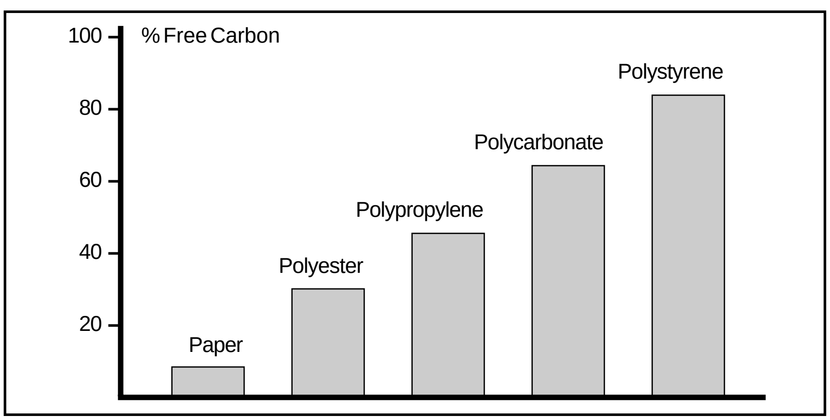
A self healing capacitor is designed to withstand a certain surge voltage. Beyond that the weakest point in the dielectric may break down, resulting in an internal short. Because the current is momentarily very high at the failure site the metallization melts away from the hole in the dielectric. That area becomes isolated and will not cause a short again. As a successful self healing is very small and of short duration the capacitor remains functional.

Self healing can either lengthen or shorten a capacitor's life. If the capacitor begins to self heal at too low a voltage the routine surges encountered on the line will eventually melt away a sizable portion of the metallization. More importantly, conductive residue may be left behind. The combination of many self healings and conductive residue can lead to a resistive short in the capacitor. Such a condition may cause excessive leakage current to the chassis or overheating which can lead to destruction or even fire. This coincides with studies on TV fires which show that the majority occur after the unit has been operated for some time.



Percentage of Capacitors Without Detectable Self Healings vs. Applied Voltage

It is therefore important to know when a capacitor begins to self heal. In general an impregnated metallized paper capacitor will self heal at much higher voltages than a metallized film type. This is because the entire winding is impregnated with epoxy, filling in any weaknesses and voids. A film capacitor cannot be impregnated and therefore may be left with weak spots in the dielectric. Multilayer windings and quality control will reduce the problem, but some weak spots may remain. Therefore for a given value and physical size an impregnated paper capacitor will self heal at higher voltages.



Free Carbon Remaining After Self Healing For Various Dielectrics

The chance of a self healing causing a resistive short circuit is a function of the conductive residue, specifically carbon, left behind. A low carbon content promotes successful self healing. A higher content will gradually reduce the insulation resistance of the capacitor with each self healing. Impregnated paper leaves the lowest percentage of carbon, followed by polyester. For this reason RFI capacitors are constructed primarily of those two dielectrics. Note that all of these are metallized as opposed to film-foil capacitors. The self healing properties of metallized capacitors makes them preferable over film-foil types in applications where high transients (such as those on the AC line) are found.

Ceramic capacitors do not self heal. Therefore they must be constructed to survive surges as tested by the various safety agencies. Should a transient on the line exceed the strength of the dielectric it can fail in an unsafe manner (short circuit). Because of their construction ceramic RFI capacitors can be larger than those made with impregnated paper.

Stability

The temperature and voltage stability of a capacitor is important, especially in a Y application. All equipment subject to agency approvals has limits on the allowed leakage current to the chassis ground. The permitted leakage generally ranges from 50µA in medical applications to 0.5mA in business equipment. Higher leakages are usually not allowed so that in case of a ground interruption operators are not exposed to excessive currents. Because of the normal conduction of 60Hz in a Y capacitor its value is generally limited to 470pF in medical devices and 4700pF in other applications. (Filters permanently installed with a rigid ground are allowed higher leakages.)

The leakage current should be evaluated throughout the temperature range and with all tolerance errors identified. The factors which must be considered are:

Ceramic	**Paper & Film**
Tolerance in value	Tolerance in value
Temperature stability	Temperature stability
AC voltage dependence	
Aging	

Sourcing Considerations

While the temperature characteristics of impregnated paper and film capacitors from different manufacturers are nearly identical, this is not true of ceramic capacitors. This is due to the origin of the raw materials. The ceramic used in Y capacitors is “blended” from various compounds and metals. Each manufacturer has its own processing technique so the temperature characteristics vary even when the same ceramic type is listed in the catalogs.

Metallized Paper vs. Ceramic Y Capacitors

Because of their instability over time and with voltage, ceramic Y capacitors must be carefully evaluated if the desired capacitance value results in leakage currents approaching the maximum allowed value. The following analysis demonstrates one such case. In this example the maximum value of ceramic Y capacitor that can be used is 3300pF. However the increased stability of the impregnated metallized paper Y capacitor allows the use of 4700pF. **Not only does the metallized paper technology provide excellent self healing (instead of a possible short circuit) but it can also allow the use of higher capacitance values.**

Evaluating an Impregnated Paper Y Capacitor

The important characteristics of a paper capacitor are the tolerance and temperature variation. Take as an example the Rifa PME271Y. The tolerance is 20% and the temperature variation is –5% at –25ºC, +6% at +85ºC. (The actual temperature range is –40 to +100ºC but these values were chosen to conform to the range of typical ceramic capacitors.)

As an example a power supply designed to operate at either 125VAC 60Hz or 250VAC 50Hz will be considered. The maximum allowable leakage current is 0.5mA. The Rifa capacitor maximum value will be:

$$C_{max} = C_{rated} \times 1.2_{(tol)} \times 1.06_{(temp)}$$

The leakage current (at the upper voltage limit) is:

$$I = 0.5mA = 250_{(vac)} \times 2\pi \times 50_{(Hz)} \times C_{rated} \times 1.2 \times 1.06$$

Solving for C_{rated}:

$$C_{rated} = \frac{5 \times 10^{-4}(amps)}{250 \times 2\pi \times 50 \times 1.2 \times 1.06}$$

$$= 5000pF$$

So any value under 5000pF can be considered acceptable. Assume therefore that a 4700pF PME271Y is selected. Now the minimum expected value is calculated. The lower capacitance limit will not have an effect on safety but does determine how effective the capacitor is at reducing conducted RFI.

$$C_{min} = C_{rated} \times 0.8 \times 0.95$$

$$= 3572pF$$

Evaluating A Ceramic Y Capacitor

The important characteristics of a ceramic capacitor are the tolerance, temperature variation, AC voltage dependence and aging. Some assumptions must be made because complete data is not readily available from the manufacturers. However tests were performed on ceramic capacitors to establish realistic numbers. It would be wise to obtain the maximum temperature and AC voltage dependence data **from each approved manufacturer.** A typical part has the following characteristics:

Tolerance: 20%

Temperature variation +/-10%
Should be verified by measurement.

AC voltage dependence: +33%

Many ceramic Y caps are specified at +5 VAC 1kHz even though the part will be exposed to 250VAC 50Hz. The AC voltage dependence will vary by manufacturer and should be considered for each. Of the two types measured, +33% is the lower value.

Aging: -7%

Using the established aging rate of –2% per decade in hours and ignoring the aging effect in the first 10 hours after soldering. A lifetime of 6 years is assumed.

The maximum expected capacitance will be:

$$C_{max} = C_{rated} \times 1.2_{(tol)} \times 1.1_{(temp)} \times 1.33_{(ac\ dep)}$$

The leakage current is:

$$I = 0.5mA = 250 \times 2\pi \times 50 \times C_{rated} \times 1.2 \times 1.1 \times 1.33$$

Solving for C_{rated}:

$$C_{rated} = \frac{5 \times 10^{-4}}{250 \times 2\pi \times 50 \times 1.2 \times 1.1 \times 1.33}$$

$$= 3626pF$$

One may therefore choose a standard value not greater than 3300pF. **Using a 4700pF ceramic capacitor (as is possible with impregnated paper) could cause some units to exceed the leakage current limitation because of the temperature and voltage instability of ceramic capacitors.** The situation becomes far more critical in medical applications with a 50µA limit. The stability of impregnated paper capacitors makes them ideal for Y applications.

To complete the analysis the minimum expected value is calculated:

$$C_{min} = 3300pF \times 0.8 \times 0.9 \times 1.33 \times 0.93$$

$$= 2939pF$$

The results of the comparison are summarized:

	Impregnated Paper	**Ceramic**
Max. standard value	4700pF	3300pF
Expected min. value	3572pF	2939pF

The impregnated paper capacitor will provide greater RFI protection for a given leakage current specification.

APPLICATION OF RIFA RFI CAPACITORS

Rifa RFI capacitors are available in several varieties according to their application, value and agency approvals. Complete data may be found in the Evox-Rifa catalog.

RFI capacitors for IEC950 and other power supply applications:

Metallized paper (PME) types provide excellent self healing and flame retardancy for critical applications. Metallized polyester (PHE) types meet safety agency requirements in an economical self healing design. X1 capacitors are also available but not listed here.

Type X2		Type Y2		Type Y1	
PME285*	0.001 to 0.1µF	PME289*	0.001 to 0.022µF	PME294*	470 to 4700pF
PME271M*	0.001 to 0.6µF	PME271Y	0.001 to 0.1µF		
PHE830	0.01 to 2.2µF				
PHE820*	0.01 to 2.2µF				

* Items also recognized according to UL1414 and C22.2 No.1, required in TV, radio and certain telecom equipment in North America. These may be used as either X or Y capacitors in UL1414 applications if the end product is sold only in North America.

Delta capacitors for IEC950 and other power supply applications:

Delta capacitors contain one X2 cap and two Y2 caps in a single package. Has worldwide approvals to meet IEC950 requirements.

PZB300	X2 cap values:	0.1 and 0.15µF
	Y2 cap values:	2200 and 4700pF

Metallized paper X2 capacitors for 440VAC applications:

Fully approved in Europe. (UL and CSA standards do not apply. This capacitor will satisfy most equipment standards for North America.)

PME278 0.001 to 0.15µF

Metallized paper RFI and snubber capacitors without agency approvals:

Suitable for use in North America where agency approvals are not required on the capacitors, including snubbing and other applications not on the AC line input.

PME260	125VAC	PME261J*	500VAC
PME261K	220VAC	PME264*	660VAC
PME261E*	300VAC		

* Suitable for North American industrial applications (including on the AC line input) with voltages greater than 250VAC. No requirement for UL and CSA approvals on the capacitors at these voltages. Satisfies most equipment standards.

RC networks for snubbing and contact protection:

Series PMR in 125 and 250VAC models. A variety of R and C values, some with agency approvals for various applications.

Evox-Rifa, Inc. also manufactures a complete line of radial lead film capacitors for snubbing, pulse and DC applications, and offers small DC brushless fans from Shicoh Engineering.