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Technical Note

Expanding the Safe Operating Area of Polypropylene Dielectric IGBT Snubber Capacitors

ABSTRACT

Important developments of IGBT's (Insulated Gate Bipolar Transistors) in recent years have been focused on increasing power handling capability and increasing reliability including short circuit tolerance. Snubber capacitors have also undergone changes in construction enabling increased power handling and short circuit tolerance. This paper describes the maximum envelope for operation of the new generation polypropylene snubber capacitors in IGBT inverter applications.

INTRODUCTION

Power systems containing IGBTs must be designed so the transient voltage caused by the high di/dt that occurs at gate turn off is minimized. Left uncontrolled, this transient voltage can exceed the blocking voltage rating of the IGBT and cause it to fail. In order to minimize the transient voltage a wound construction polypropylene film capacitor mounted as close to the IGBT terminals as possible is usually recommended.

The acceptable amount of overshoot voltage is determined by the maximum DC voltage that an inverter power circuit is subject to and the IGBT voltage ratings [1]. The peak current to turn off under a fault condition can be as high as 6 - 10 times the device current rating [2]. This peak current under the fault condition will proportionally increase the overshoot voltage. It may also be shown that the reliability of the IGBT device is inversely proportionally to the junction temperature. The factors of peak overshoot voltage, dv/dt and junction temperature define a safe operating area (SOA) for the device where normal service life can be expected.

Analogous parameters to the IGBT module can be defined for Polypropylene dielectric snubber capacitors in relation to safe operating area. Depending upon the manufacturing technology a film dielectric snubber capacitor will be able to withstand multiple excursions in excess of the nominal voltage rating. The peak current will have a repetitive or continuous rating in addition to an abnormal or fault tolerant rating. Ripple current ratings may be demonstrated to be proportional to power loss of the capacitor minus the heat dissipated, whereas the packaging technique is critical to this heat dissipation.

Capacitors have been constructed by CD-Aero to be used in the snubber application for IGBT modules as depicted in Figure 1. These capacitors used two distinct packaging techniques, tabs that mount directly to the bus bar near the IGBT terminals and a multi-pin termination for printed circuit board mounting [3]. The multi-pin termination is similar in construction to the dual in-line package (DIP) found in integrated circuits. The use of a circuit card is sometimes required to incorporate additional components such as power resistors and diodes in a "Clamp" circuit [4].

Fig. 1 CDE IGBT Snubber Capacitors

Snubber capacitors may be constructed of many dielectric systems. These may include polymer film with dual metallized electrodes, polymer film with discrete foil electrodes, and dielectric polymer film with a metallization deposited on its surface or in some cases, ceramic. Snubber capacitors ideally have polypropylene dielectric due to its low equivalent series resistance, high dielectric strength and high corona inception voltage.

Advancements in dielectric film manufacturing technology and metallization deposition techniques have led to the ability to operate capacitors manufactured with polypropylene at increased voltage stresses. As the voltage stress increases, the stress on the end edge contact region from current handling also increases.

single voltage excursion over the dielectrics maximum capability causes a short circuit and often equipment failure. Therefore a compensating increase in dielectric thickness is required and a component may be too large for the intended electronic equipment. A polypropylene dielectric capacitor constructed with metallization deposited on the dielectric surface often does not have an adequately robust end edge contact area or termination from the metallized dielectric film to the metal spray used. One of the most frequent reasons for failure is the detaching of the 'sprayed ends' from the electrode edges.

The use of Polypropylene dielectric film with dual metallized discrete electrodes offers the self-healing property of metallized film (not failing in a short circuit mode) with the high peak current capability (dv/dt) required for IGBT snubber applications. The dual metallized discrete electrode effectively doubles the electrode edge contact area. This enhancement minimizes failure mechanisms related to the sprayed metal bond in this area.

2. LABORATORY TEST SPECIMENS

The test samples were of five different ratings. These ratings were 0.33 µF, 1.0 µF and 3.0 µF with a nominal voltage of 1000 Vdc, and 0.47 µF and 1.0 µF with a nominal voltage of 1600 Vdc. These parts were all manu-factured by CDE under the construction designation RBPS. The dielectric construc-tion was polypropylene with discrete dual metallized electrodes. The packages were plastic cases with epoxy backfill.

The capacitors were all terminated with wide low inductance plated copper sheets soldered directly to the capacitor elements. All the samples used either an oval slotted hole mounting configuration or as in the case of the 3 µF 1000 Vdc and 1 µF 1600 Vdc parts a multi-pin dual in line circuit mounting configuration was used. The oval slotted hole configuration is used to mount directly to an IGBT package or bus bars as shown in Figure 2.

Fig. 2 IGBT with MDirect Mount" Snubber Capacitors

3. DESCRIPTION AND AIM OF THE TESTS

Capacitor samples were selected for determining their performance under normal and abnormal or fault tolerant conditions. This was with respect to DC voltage, peak current and ripple current. A summary of these test groups and test performed is shown in Table 1.

Table 1 CDE TYPE RBPS CAPACITOR TEST GROUPS						
Test Type	Test Group	Sample Size	Capacitance	Rated Voltage	Condition	Duration
DC Voltage Steady-State	1	12	0.47µF	1600 Vdc	90°C, 2080 Vdc	2000 Hours
	2	10	1.0 µF	1000 Vdc	90°C, 1300 Vdc	2000 Hours
	3	12	1.0 µF	1600 Vdc	90°C, 2080 Vdc	2000 Hours
Transient Voltage	4	5	0.33 µF	1000 Vdc	1.2/50, 1600 Vp	1000 Cycles
					1.2/50, 2000 Vp	1000 Cycles
	5	5	10 µF	1600 Vdc	1.2/50, 2560 Vp	1000 Cycles
					1.2/50, 3200 Vp	1000 Cycles
	6	5	3.0 µF	1000 Vdc	1.2/50, 1600 Vp	1000 Cycles
					1.2/50, 2000 Vp	1000 Cycles
Peak Current	7	8	4.7µF	1600 Vdc	2180 Amps Peak	10,000 Cycles
	8	8	1.0 µF	1000 Vdc	1780 Amps Peak	10,000 Cycles
	9	6	3.0 µF	1000 VdC	3520 Amps Peak	10,000 Cycles
Ripple Current	10	6	4.7 µF	1600 Vdc	18 Arms, 85°C 70 kHz	500 Hours
	11	6	1.0 µF	1000 Vdc	26 Arms, 85C1C	1000 Hours
	12	6	3.0 µF	1000 Vdc	35 Arms, 85°C 55 KHz	700 Hours
					42 Arms, 85°C 55 KHz	100 Hours
					49 Arms, 85°C 55 KHz	100 Hours
					56 Arms. 85"C 55 KHz	100 Hours

A. DC Voltage-Steady State (Endurance)

This test was designed to show the capacitors ability to operate with a certain DC bus voltage that might be found in a power inverter. The standard test for a film capacitor described by many industry standards such as IEC 384 16, is 1.25 times rated voltage DC at maximum climatic temperature. In this case the RBPS voltage ratings were at 85°C. The failure criteria of the IEC standard is ΔC/C of 3% at 2000 hours for "Grade I" capacitors and ΔC/C of 5% at 1000 hours for "Grade 2" capacitors.

The test conditions chosen were 1.3 times the rated DC voltage at 90°C. This was done to demonstrate that the capacitors would consistently meet the 1.25 x rated voltage at 85°C criteria. Capacitance and dissipation factor (Tangent of Loss Angle) at 1 kHz were monitored at the intervals of 500, 1000 and 2000 hours.

There are capacitors specified for IGBT snubber applications that are only tested at rated voltage. Some of these products are even specified with failure criteria allowing a chosen number, one or more capacitors to become short or open during the test period. Products manufactured to this type of specification are designed to operate at a level substantially reduced from the voltage marked on the capacitor. Furthermore, a capacitor design that allows any permanent dielectric failures at the rated voltage may be inadequate for its intended use.

B. Transient Voltage (1.2/50 us Wave)

This test is designed to show the ability of a capacitor to withstand a voltage level for a brief duration greatly exceeding the rated voltage level. The test is referred to in IEEE C62.41 [8] and EN32400 [6]. The rise time to the peak voltage is 1.2 microseconds which provides little voltage stress on the capacitor yet induces a severe current pulse. The fall time of the waveform is 50 microseconds to the half voltage level. The fall region is the portion where dielectric failure might typically occur.

The transient voltage test was performed by measuring each capacitor value as shown in Table 1 for capacitance and dissipation factor at 1 KHz before and after testing. The 1000 Vdc parts were given 1000 cycles at 1600 volts peak followed by 1000 cycles at 2000 Volts peak. The 1600 Vdc parts were given 1000 cycles at 2560 Vdc followed by 1000 cycles at 3200 Vdc. The test voltages were chosen to be 160% and 200% of the respective rated voltages.

C. Peak: Current

A typical waveform for current seen by an IGBT snubber capacitor is shown in Figure 3. In this example, the peak current is 200 amps and decays to zero within about twenty microseconds. The peak current may be related to voltage slope (dv/dt) or conversely by equation (l).

$$I_p = C \frac{dv}{dt} \qquad (1)$$

Where Ip = Peak Current, Amps
C = Capacitance, Microfarads
dv/dt = VoltsIMicrosecond

It is known that snubber capacitors must be designed to withstand repetitive current pulses as shown in Figure 3 without loss of termination from capacitor element to leads. However, since the peak short circuit current usually reaches 6 to 10 times the nominal device current [2], this must be contemplated in snubber capacitor design.

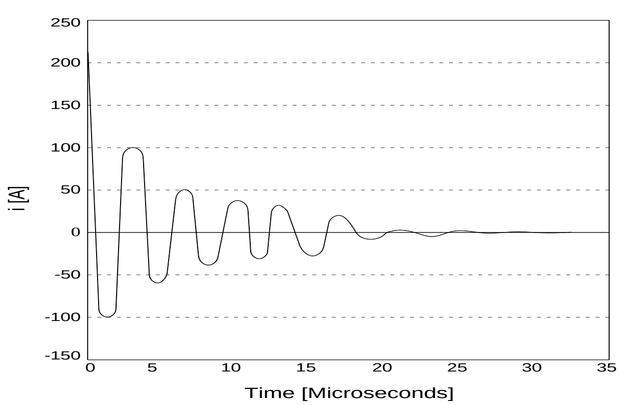

Fig. 3 Typical Repetitive Current on Capacitor

In the Figure 4 example, a 1 µF capacitor was charged to its rated voltage of 1000 Vdc and the ringing on discharge was at 400 KHz.

In this high current test case, CDE snub-ber capacitors were charged to their peak voltage and discharged using high voltage vacuum relays with no series impedance added. This was done in order to simulate the worst possible case for current stress on the capacitors. Just as in the IGBT switch off, a ringing is formed by the tank circuit of snubber capacitors and the stray inductance in the discharge loop. An example of this ringing discharge is shown in Figure 4. Each capacitor tested as shown in Table 1, was measured for capacitance at 1 KHz and ESR at 100 KHz initially and after 10,000 cycles.

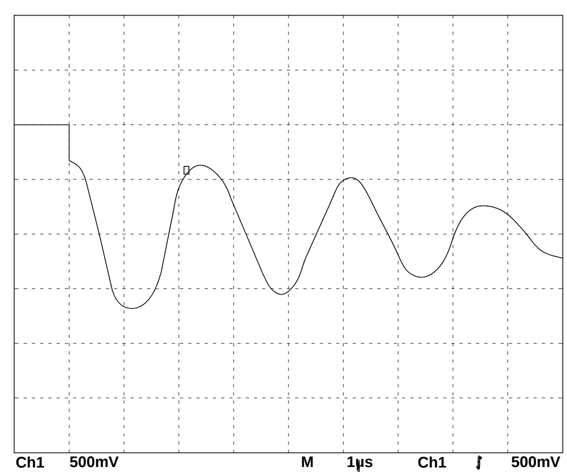

Fig. 4 High Frequency Ringing Discharge Waveform

The peak voltage slope (dV/dT) may be derived using equation 2.

$$\frac{dv}{dt} = \frac{2\pi V_o \cdot 0.71}{T} \qquad (2)$$

Where Vo = Peak Voltage

And T = 1/Ringing Frequency

Using the result of equation (2) and equation (1) the peak current may be derived.

D. Ripple Current

This test is designed to show that the snubber capacitor would not overheat when subjected to a continuous (rms) current value. The capacitor temperature due to internal heating plus the ambient temperature should not exceed the maximum allowable temperature for the dielectric system. The capacitor temperature due to internal heating equals the heat generated minus the heat convected out of the capacitor. The generated heat in watts is calculated by multiplying the rms current squared times the measured ESR in ohms. The heat convected out of the capacitor depends upon many factors including [9]:

Whether of not the capacitor is in still air or in forced air cooling ambient

How well the capacitor is heat sunk. and

The lead wire or other termination type used.

The heavy copper plates soldered directly to the capacitor elements acting as terminals may be demonstrated to be heat sinks for convecting out of the capacitor. Therefore these act to effect not only the terminal factor but the heat sinking factor as well. The goal of this analysis was not to compare the plated copper terminals to other connection methods such as lead wires but instead demonstrate the performance of this termination method.

Three capacitor groups were subjected to high frequency alternating ripple current as listed in Table 1. This was accomplished by using a power amplifier fed by an oscillator signal in series with and forming a resonant circuit with an inductor and the capacitors under test [3]. The capacitors were all wired in series giving them an equal current stress and a "J" type thermal-couple was imbedded in two specimens from each test group. A third similar thermal-couple was placed in the forced air oven during test to monitor the ambient temperature.

One of the test groups (l.0 µF 1000 Vdc) was done at an independent laboratory and the other two groups, (0.47 µF 1600 Vdc and 3.0 µF 1000 Vdc) were tested at CDE. The testing at an ambient temperature of 85°C was chosen to be at a current level exceeding published 55°C ratings for the capacitors. In addition to temperature monitoring the electrical parameters of capacitance and dis-sipation factor at 1 kHz and ESR at 100 KHz were periodically monitored.

After 700 hours of testing at 35 Arms on the 3 µF 1000 V dc capacitors it was determined that the two monitored parts had about an 8°C heat rise over the measured ambient temperature of 86°C, reading 94.1 and 93.8°C respectively. Furthermore, changes in all of the measured electrical parameters were negligible. Therefore, it was decided to increase the current step wise 20% or 7 Arms every 100 hours until a 30°C heat rise or hot spot temperature of 115°C was obtained. The hot spot of 115°C occurred at 56 Arms. The increase was accomplished by increasing the voltage amplitude while maintaining the resonant circuit at 55 kHz. The final voltage stress was about 60 Vrms per capacitor so any changes in the electrical parameters could be inferred to be thermal or current related and not a voltage related phenomena.

4. RESULTS AND COMMENTS

DC Voltage -Steady State (Endurance)

The results of this testing are depicted in Table 2. This shows that all of the capacitance changes were positive and less than 1.25% with one exception. This exception was a single capacitor in the 1.0 µF 1600 Vdc group that had a gain in capacitance of 0.85% at 1000 hours and a capacitance loss of 3.38% at 2000 Hours. No changes in dissipation factor occurred on any of the test samples in any group throughout the 2000 hour duration.

Table 2

DC VOLTAGE ENDURANCE
130% NOMINAL VOLTAGE, 90°C

	Initial		500 Hours			1000 Hours			2000 Hours		
	Cap (µF) 1 KHz	% DF 1 KHz	Cap (µF) 1 KHz	% DF 1 KHz	Delta Cap	Cap (µF) 1 KHz	% DF 1 KHz	DeRa 1 KHz .	Cap (µF) 1 KHz	% DF	Delta
0.47 µF (1600 Vdc), n = 12											
AVG	0.4910	0.02	0.4924	0.02	0.30%	0.4922	0.02	0.26%	0.4925	0.02	0.32%
MIN	0.4861	0.02	0.4876	0.02	0.20%	0.4867	0.02	0.12%	0.4868	0.02	0.14%
MAX	0.4955	0.02	0.4974	0.02	0.49%	0.4974	0.02	0.45%	0.4976	0.02	0.47%
1.0 µF (1000 Vdc), n = 10											
AVG	1.061	0.02	1.067	0.02	0.52%	1.067	0.02	0.60%	1.068	0.02	0.66%
MIN	1.049	0.02	1.054	0.02	0.09%	1.055	0.02	0.38%	1.056	0.02	0.47%
MAX	1.069	0.02	1.075	0.02	0.66%	1.067	0.02	0.75%	1.077	0.02	0.76%
1.0 µF (1600 Vdc), n = 12											
AVG	1.066	0.02	1.074	0.02	0.75%	1.073	0.02	0.70%	1.070	0.02	0.39%
MIN	1.057	0.02	1.069	0.02	0.46%	1.068	0.02	0.37%	1.028	0.02	0.46%
MAX	1.078	0.02	1.083	0.02	1.14%	1.082	0.02	1.14%	1.083	0.02	-3.38%

This capacitor evaluation demonstrated the ability of the capacitor design to operate reliably at a DC bus voltage up to the ratings of requirements for the ratings as outlined in the IEC 384-16 specification. The single occurrence outside the 3% change allowed 1000 Vdc and 1600 Vdc respectively at 85°C. The designs tested are also in conformance with "Grade 1"
was at an increased acceleration for both temperature (90 vs 85°C) and voltage (130 vs 125%).

A. Transient Voltage (1.2/50 µS Wave)

The results of this testing are depicted in Table 3. This shows that no capacitor exhibited a dielectric failure or any increase in equivalent series resistance (ESR). It may also be observed that all capacitance changes were less then 0.1% with the 1.0 µF 1600 Vdc test group showing a capacitance loss of between 0.1 and 0.3% at the 3200 Vdc or 200% voltage condition.

Table 3 TRANSIENT VOLTAGE TEST (1.2/50 µS WAVE)								
	Initial		1000 Pulses 1600 VDC			1000 Pulses 2000 VDC		
Sample	CAP (µF) 1KHz	ESR (ohms) 100	CAP (µF) 1 KHz	ESR (ohms) 100 KHz	DELTA Cap	CAP 1 KHz	ESR (ohms) 100 KHz	DELTA Cap
.33 µF (1000 VDC)								
1	0.3375	0.006	0.3375	0.006	0.00%	0.3375	0.006	0.00%
2	0.3233	0.006	0.3232	0.006	-0.03%	0.3233	0.006	0.00%
3	0.3435	0.006	0.3434	0.006	-0.03%	0.3434	0.006	-0.03%
4	0.3424	0.006	0.3423	0.006	-0.03%	0.3424	0.006	0.00%
5	0.3349	0.006	0.3348	0.006	-0.03%	0.3348	0.006	-0.03%
1.0 µF (1600 VDC)								
1	1.017	0.004	1.017	0.004	0.00%	1.016	0.004	-0.10%
2	1.003	0.004	1.002	0.004	-0.10%	1.000	0.004	-0.30%
3	1.011	0.004	1.011	0.004	0.00%	1.010	0.004	-0.10%
4	1.010	0.004	1.009	0.004	-0.10%	1.008	0.004	-0.20%
5	1.008	0.004	1.008	0.004	0.00%	1.007	0.004	-0.10%
3.0 µF (1000 VDC)								
1	3.032	0.002	3.032	0.002	0.00%	3.032	0.002	0.00%
2	3.099	0.002	3.099	0.002	0.00%	3.099	0.002	0.00%
3	3.056	0.002	3.054	0.002	-0.07%	3.055	0.002	-0.03%
4	3.029	0.002	3.028	0.002	-0.03%	3.028	0.002	-0.03%
5	3.095	0.002	3.095	0.002	0.00%	3.095	0.002	0.00%

B. Peak Current

This testing produced almost no noticeable changes in the electrical parameters monitored of 1 KHz capacitance and 100 KHz ESR.

Therefore it can be concluded that 10,000 cycles to the severe peak current levels on these test specimens produced no noticeable degradation to the terminations of the capacitors.

C. Ripple Current

The heat rise or "hot spot temperature" was monitored for two capacitors each from the three groups tested. The heat rise is depicted for the 1.0 µF 1000 Vdc and 3.0 µF 1000 Vdc parts in figures 5 and 6 respectively. The third group, 0.47 µF 1600 Vdc had a heat rise for both monitored pieces of less than 3°C from the ambient temperature of 85°C at its 18 Arms, 70 KHz condition.

During the testing for all of the three groups capacitance changes were positive and less than 0.5% except for in the special step-wise current testing of the 3 µF 1000 Vdc group.

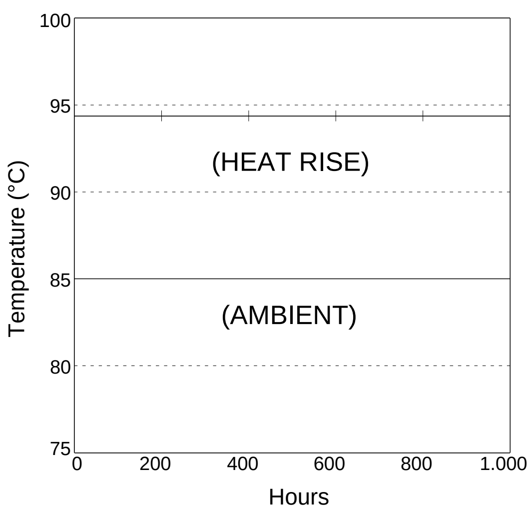

Fig. 5 Hot Spot Temperature vs Time 1 µF 1000 Vdc

At 700 hours where the step-wise increase commenced the capacitance change was less than 0.25% positive. The change was less than 0.5% after the 42 Arms condition, less than 2% after the 49 Arms and less than 3% after the 56 Arms condition. No significant changes (> 0.0005 Ohms) occurred to any of the 100 KHz ESR values during the testing for all sample groups including during the 3 µF step-wise current increase.

The heat rise for the stepwise current testing is plotted versus the applied ripple current in Figure 6. Using regression analysis for the stepwise increase, almost a perfect linear relationship is obtained with a slope of 1.08°C/Amp. This result shows substantial heat convection occurred from the 3 µF packages since power is proportional to the square of the current.

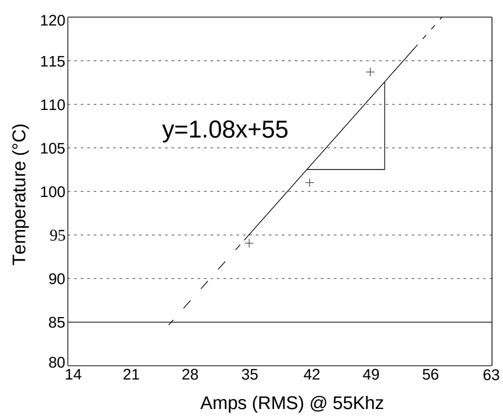

Fig. 6 Hot Spot Temperature vs Applied rms Current

5. CONCLUSION

An extensive battery of tests was performed on a new polypropylene dielectric snubber capacitor construction. These tests demonstrate the new construction has a level of performance allowing reliable operation at normal nameplate operating conditions in addition to abnormal or fault tolerant conditions.

The new construction uses dual metallized electrodes for increased end termination reliability and heavy copper sheets soldered directly to the end termination for lower inductance and increased heat dissipation from the package. These factors define a new safe operating area (SOA) for IGBT snubber capacitors.

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CDE Corp.
167 John Vertente Blvd.
New Bedford, MA 02745
Tel: 508-994-9661
Fax: 508-995-3000
www.CDE.com