Three-quadrant triacs for white goods

Much better immunity to spurious conduction

When a 3Q triac is specified for an application it is necessary to choose the best compromise between the triac's sensitivity and its immunity to loss of control. For the best commutation performance the least sensitive 3Q triac with the highest I_{GT} should be specified.

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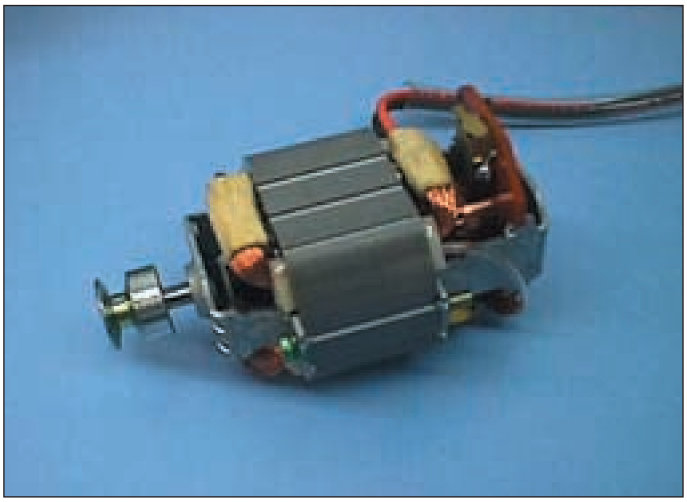

Figure 1: *A small appliance universal motor.*

Many "white goods" appliances contain a motor whose speed must be varied, either in discrete steps or continuously. Most of them use a series AC motor (often called a universal motor). These motors have field and armature windings that are connected in series. Although a "universal" motor can operate equally well on an AC or DC supply, a "series AC" motor is optimised for operation on an AC supply. Carbon brushes carry the current to the commutator, which in turn provides the connection means to the armature windings.

Series AC motors run at high speed when unloaded, typically 20,000 RPM or more, but their speed reduces markedly when a mechanical load is applied. Their speed can be varied easily by varying the mean input voltage. The electrical appliance market, white goods included, is usually very price sensitive. Their motors will have been cost reduced to a point that just gives sufficient power and lifetime. Effective motor control regime in a cost-minimised system can be achieved by use of a "phase control" circuit that uses a triac.

A well-designed phase control circuit, combined with the correct choice of triac, offers the most reliable, compact and cost-effective method of varying the power to an AC mains load. In its simplest form, only six components are required to implement it: a triac, two resistors, a capacitor and diac for triggering the triac, and a variable resistor to set the trigger delay. *Figure 2* shows the schematic. Filter components to meet EMC requirements have not been included.

The 100n capacitor charges up via the fixed and variable resistors to the breakover voltage of the diac (typically 32 V). The current pulse into the triac gate triggers the triac into conduction for the remainder of the

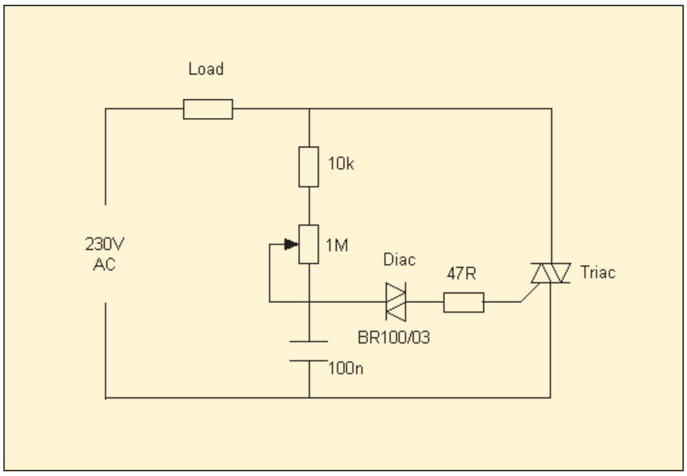

Figure 2: *All-purpose phase control circuit*

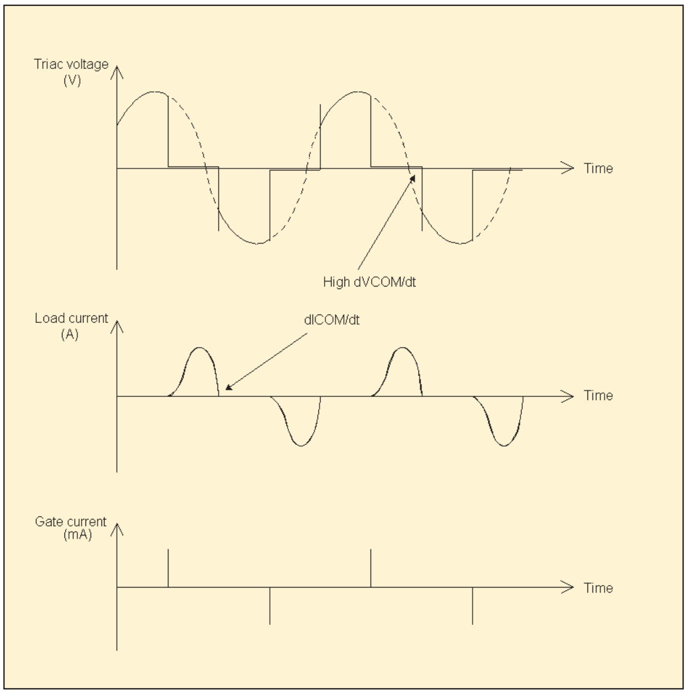

Figure 3:
Phase control waveform representations for inductive load

mains half cycle. The process repeats with opposite polarity every half cycle. The 10 k resistor is necessary to prevent excessively high and damaging charging currents flowing into the 100n capacitor. The 1M resistance is varied to control how fast the capacitor charges. This varies the phase angle of the trigger pulses, hence the mean power into the load.

A gate pulse duration of at least 10µs at the I_{GT} max level is desirable for assured triggering. This is achieved by the 47 Ω resistor, which limits the amplitude and increases the duration of the gate pulses. The gate pulse amplitude should be at least as high as the triac's specified I_{GT} max for assured triggering.

Representations of the phase control waveforms for inductive loads are shown in *Figure 3*.

The inductive load current waveform does not follow the shape of the input voltage waveform. Inductance tries to resist any change in current, causing it to rise slowly to a time-delayed peak, then fall increasingly rapidly to zero. The high $dI_{com/dt}$ results in an increased concentration of mobile charge carriers in the triac junction at the time when it is trying to return to the blocking state. In sufficient concentration these charge carriers can flow into the triac junction and act as unwanted gate trigger current, in the presence of the rising blocking voltage, to cause spontaneous triac turn-on. There is phase shift between the voltage and current waveforms; current lags voltage. When the load current passes through zero and the triac commutates, its blocking voltage must rise rapidly to the supply voltage at a rate limited only by circuit capacitance and triac junction capacitance. The high $dV_{com/dt}$ makes it more likely for any remaining mobile charge carriers to be collected into the triac junction to act as unwanted trigger current.

To control the inductive load using a standard triac, additional protective / limiting components will be essential: a series resistor-capacitor "snubber" across the main terminals of the triac to limit the $dV_{com/dt}$; a non-saturable inductor of a few mH in series with the load to limit the $dI_{com/dt}$ in cases where this is a particular problem for the triac.

In many instances they can even stress the triac and reduce the long term reliability of the circuit. For example, a badly specified snubber whose resistance is too low (lower than 100 Ω) can result in excessively high peak triac current and dI/dt every time the triac is triggered from blocking high voltage. This repetitive stress can cause progressive degradation around the gate due to multiple overcurrent hotspots in the region where conduction commences. The result is a triac gate that becomes less sensitive over time until it cannot be triggered any more. The answer would be to reduce the size of the protection components, or even remove them altogether. This ideal can only be realised if a latest generation three-quadrant triac is used.

The limitations of the 3+ triggering quadrant (T2-, G+) are explained in the following.

Triggering of a four-quadrant triac in the 3+ quadrant is made possible by an overlapping feature within the gate region, which causes Main Terminal 1 to supply electrons to trigger a thyristor element in the G-MT1 boundary. Main conduction then spreads to the main thyristor element from this intermediate state. Unfortunately the distribution of charge carriers during this triggering mode is very similar to that existing during 1-to-3 commutation (conducting with MT2 positive to blocking with MT2 negative). Therefore 1-to-3 commutation of a demanding load can easily be mistaken

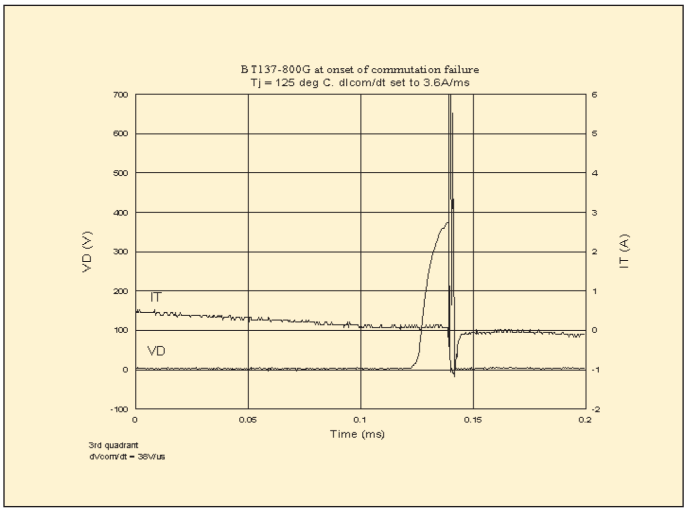

Figure 4:
4Q commutation failure, $dV_{COM/dt}$ = 36 V/µs, dIcom/dt set to 3.6 A/ms, Tj = 125ºC

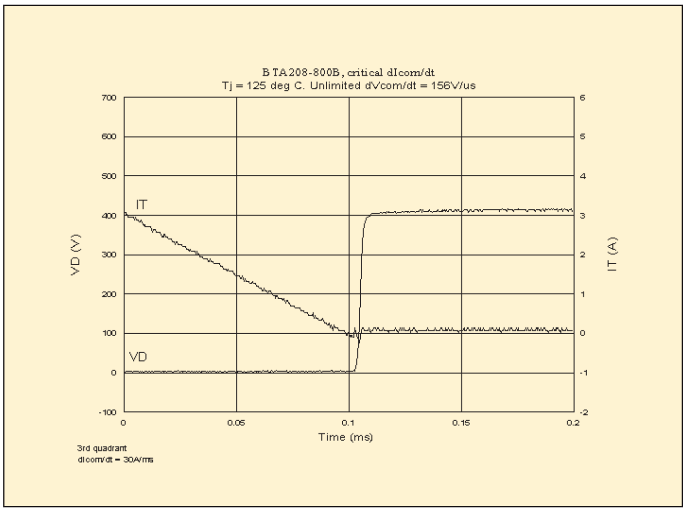

Figure 5:
3Q critical commutation (just prior to commutation failure), $dI_{COM/dt}$ = 30A/ms, unlimited $dV_{com/dt}$ of 156V/µs, Tj = 125ºC

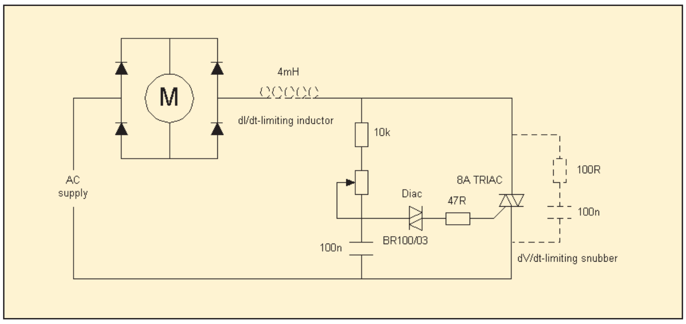

Figure 6a:
Phase-controlled rectifier-fed DC motor load imposes high $dI_{COM/dt}$ on triac.

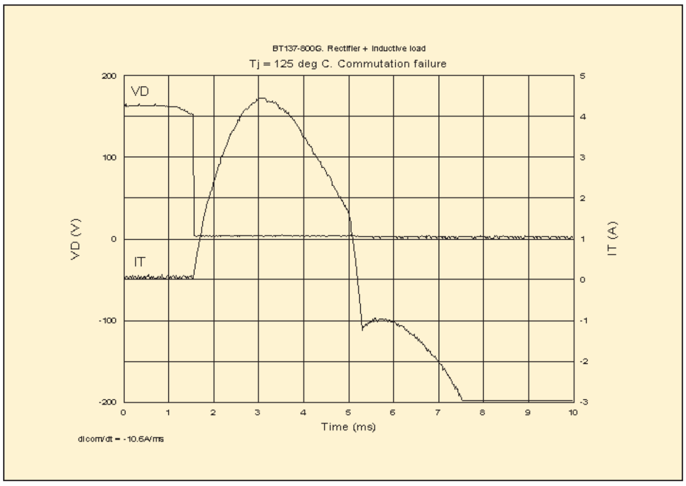

Figure 6b:
4Q triac commutation failure. $dI_{COM/dt}$ = 10.6A/ms, Tj = 125ºC.

by the triac as a legitimate 3+ trigger signal. In other words, the ability of a triac to trigger in the 3+ quadrant severely compromises its commutation performance, hence its immunity to spurious conduction and loss of control.

The four-quadrant to three-Quadrant triac advancement is explained in the following.

The overlapping gate feature has been removed from the three-quadrant triac construction to enable it to commutate under much more severe conditions of high $dI_{com/dt}$ and $dV_{com/dt}$. The only slight "disadvantage", if it can be called that, is the complete absence of any 3+ triggering capability. This is irrelevant in most applications since operation in the 3+ quadrant is usually avoided because of the triac's lower sensitivity, its poorer turn-on performance and the lower permitted rate of rise of its load current (dI_T/dt).

The 3+ quadrant (quadrant 4) is the least used of all the four quadrants. For example, self-triggered circuits like the discrete phase control circuit in *figure 2* operate automatically in the 1+ and 3- quadrants. Furthermore, control circuits that provide single polarity trigger pulses from a logic IC or a microcontroller are usually configured to sink gate current because they can sink current more easily than they can source current. Therefore triac operation is in the 1- and 3- quadrants. Everything works in the designer's favour and makes it easy to avoid 3+ operation.

Additional optimisation of three-quadrant triacs to maximise their commutation capability includes:

Geometric separation of the two antiparallel thyristors to lessen the chance of the conduction in one half affecting the other half at commutation.

Optimisation of the layout and resistance of the emitter short paths to limit transistor gains and to conduct away the mobile charge carriers safely and quickly to prevent them acting as unwanted gate trigger current at commutation.

Apart from the $dV_{COM/dt}$ and $dI_{COM/dt}$ benefits attached to three-quadrant triacs, additional benefits include vastly improved immunity to high rates of change of blocking voltage (dV_D/dt) and a better ability to maintain control at high temperature when they are at their most sensitive.

Temperature and triac sensitivity.

It is an unavoidable fact that any triac will become more sensitive the hotter it is. It becomes easier to turn on, either intentionally by an externally applied gate current, or unintentionally by an internally generated leakage current or capacitively coupled current. If the junction temperature of a triac is increased beyond Tj max, a temperature will be reached where internal leakage current will become sufficient to turn the triac on. This spontaneous conduction signifies complete loss of control. A three-quadrant triac is able to maintain better control than an equivalent four-quadrant triac at high temperature, as demonstrated later.

It is true to say that loss of control does not lead to automatic destruction of a triac, since reducing its temperature can restore control.

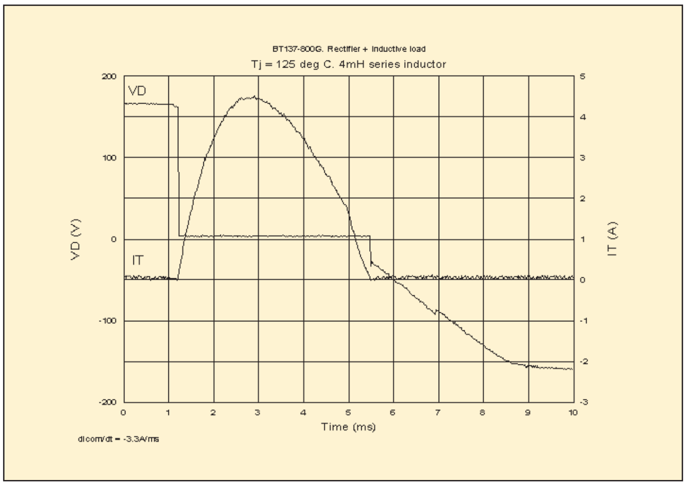

Figure 6c:
$dI_{COM/dt}$ limited by series inductor to 3.3A/ms. Tj = 125ºC. No commutation failure of 4Q triac.

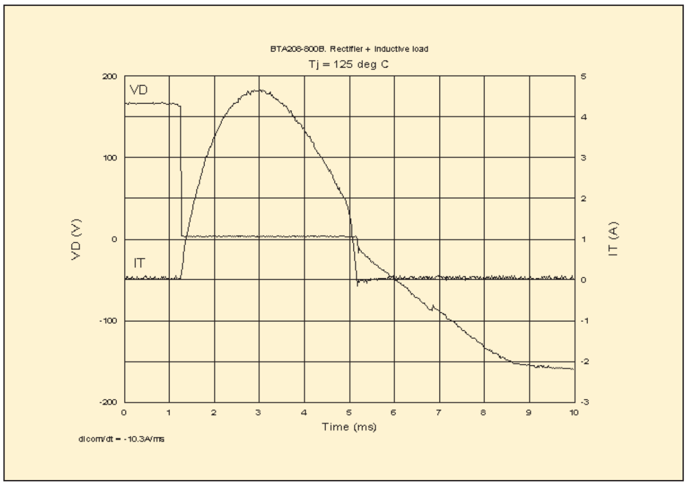

Figure 6d:
3Q triac. No series inductor, no snubber, no commutation failure. $dI_{COM/dt}$ = 10.3A/ms, Tj = 125ºC.

A sensitive triac that is easier to turn on intentionally is also easier to turn on unintentionally. This means that, for a given technology, the most sensitive triac with the lowest I_{GT} will have the lowest immunity to false triggering, therefore the lowest commutation performance. The following statement sums this up: commutation performance is proportional to I_{GT}.

For a given sensitivity, three-quadrant triacs will always offer a better commutation performance than four-quadrant triacs can offer.

When selecting a 3Q triac for a given application, the designer must choose the best compromise between sensitivity and immunity to loss of control. Whenever possible, and certainly in self-triggered discrete circuits that use a diac trigger, the least sensitive triac with the highest I_{GT} and the best commutation performance should be specified. When there is a limitation to the gate current that the drive circuit can sink, the triac with the highest I_{GT} should be specified that the drive circuit can drive comfortably. It is not a good policy to automatically specify the most sensitive triac available when the drive circuit can sink more gate current without too much difficulty.

Three-quadrant and four-quadrant triacs have been tested on commutation test equipment to assess and compare their maximum $dI_{COM/dt}$ and $dV_{COM/dt}$ capabilities at Tj = 125ºC. *Figures 4 and 5* show the results. The devices tested were:

Type no.	Technology	$I_{T(RMS)}$	I_{GT} max	V_{DRM}
BT137-800G	4Q	8A	50mA	800V
BTA208-800B	3Q	8A	50mA	800V

A rectifier-fed inductive load imposes one of the most demanding commutation conditions on any triac controlling it. As the supply voltage approaches zero, a point will be reached when it is lower than the voltage generated by the inductive load. The current on the AC side of the bridge rectifier will collapse rapidly to zero as the load current continues to freewheel around the bridge rectifier diodes. The high $dI_{COM/dt}$ that the triac experiences is limited only by the parasitic inductance on the AC side of the bridge. This can prevent most four-quadrant triacs, and some of the more sensitive gate three-quadrant triacs, from commutating reliably. The more sensitive four-quadrant triacs will be unable to commutate even the 0.1 V/µs of a 230 V 50 Hz sinewave rising from zero volts. In this case, a snubber would be of no use whatsoever, since dV/dt is already very low.

One answer to the problem would be to add a series non-saturable inductor to limit the $dI_{COM/dt}$ to a level that the triac can commutate. An RC snubber would also be required to slew any excessive $dV_{COM/d}t$ that might arise and assist the triac in withstanding the $dI_{COM/dt}$.

A far more elegant solution is to use a three-quadrant triac with the highest I_{GT} and the best commutation performance. It is then possible to eliminate all such protection components and guarantee correct operation up to Tj max. A three-quadrant triac is the only realistic choice.

A practical example – rectifier-fed small appliance motor.

The example in *figure 6a* shows a phase-controlled rectifier-fed DC permanent magnet motor as used in a small hand-held kitchen appliance. The same triacs as used in the earlier commutation tests were tested in this real commutation-testing application at a Tj of 125ºC.

Commutation failure of a 4Q triac is shown in *Figure 6b*. The high dI/dt at commutation can be seen to continue through the zero crossing with no attempt by the triac to block voltage.

The addition of a 4millihenry inductor in series with the load slowed the dI/dt sufficiently for the 4Q triac to commutate. *Figure 6c* shows the result. *Figure 6d* shows the 3Q triac commutating successfully without the

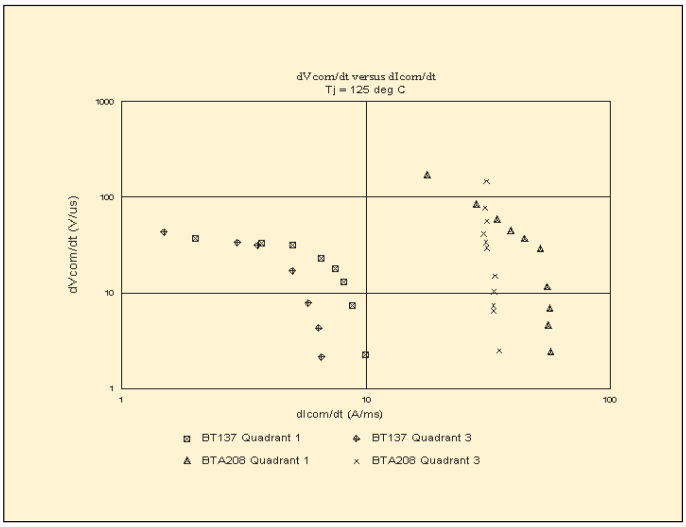

Figure 7:
$dV_{COM/dt}$ versus $dI_{COM/dt}$ for 3Q and 4Q triacs with same voltage, current and I_{GT} specifications.

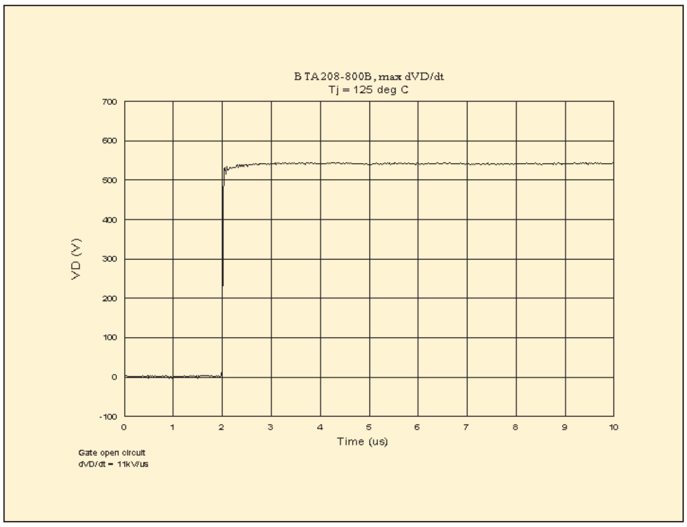

Figure 8b:
3Q triac. No dV_D/dt failure at limit of test equipment. dV/dt = 11 kV/µs, Tj = 125°C.

assistance of any protection components. *Figure 7* shows $dV_{COM/dt}$ plotted against $dI_{COM/dt}$ for both triac types.

The triacs tested in the rectifier-fed DC PM motor circuit were clamped to a hot block whose temperature was increased until the triac lost control – i.e. until the onset of commutation failure. The higher the failure temperature, the better the triac's commutation performance.

All triacs tested were rated at 8A RMS, 600V to allow meaningful comparisons. The commutation failure temperatures are shown in *table 1.* More sensitive examples of the 3Q triac have been included to illustrate the variation of commutation performance with temperature and I_{GT}. The commutation conditions imposed by the circuit during this test were $dI_{COM/dt}$ = 8.52 A/ms and $dV_{COM/dt}$ = 20V/µs.

Part number	Technology	$I_{GT\ max}$	Temp. at commutation failure
BTA208-600D	3Q	5mA	84°C
BTA208-600E	3Q	10mA	112°C
BTA208-600B	3Q	50mA	Still in control at 200°C
BT137-600G	4Q	50mA	65°C

Table 1: *Triac temperatures at commutation failure in the rectifier-fed DC PM motor circuit*

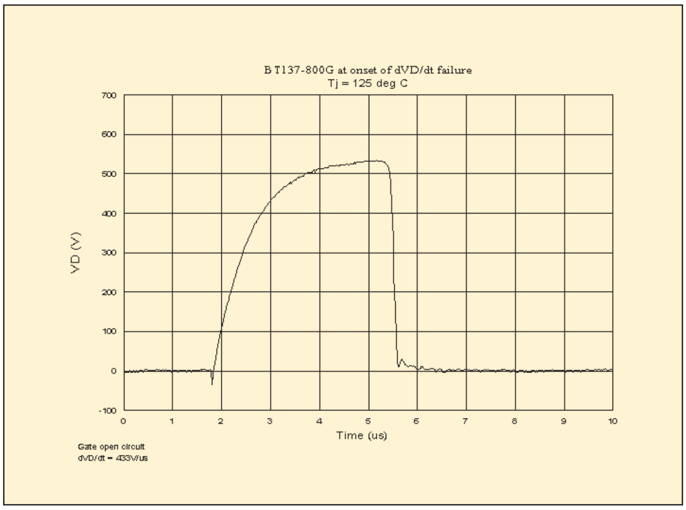

Figure 8a:
4Q triac at onset of dV_D/dt failure. dV/dt = 433 V/µs, Tj = 125°C.

The results are self-explanatory. They show very clearly the advantage of three-quadrant triacs over traditional four-quadrant technology. The least sensitive 3Q triacs can exhibit a quite phenomenal immunity to loss of control as proven by the 200°C test. The static dV/dt test results in the next section reinforce this message still further.

200°C was the hottest the hot block could achieve before its safety thermal fuse failed open circuit. It was not therefore possible to reach the commutation failure temperature of this triac.

200°C is well above the recommended 125°C Tj max for a triac. The successful 200°C test does not imply that a 3Q triac can routinely be used above 125°C. Longterm reliability and lifetime will inevitably reduce the higher the operating Tj above Tj max.

3Q and 4Q triac static dV/dt comparison.

The same triacs as used in the commutation comparison were also compared on dV_D/dt test equipment at Tj = 125°C. The results appear in *figure 8.*

Figures 8a and *b* show 4Q versus 3Q triac static dV/dt.

When compared to traditional four-quadrant triacs, more recently-developed three-quadrant triacs possess a much better immunity to spurious conduction and loss of control when operating under demanding conditions. These demanding conditions include:

Non-linear and/or reactive loads that impose high $dV_{COM/dt}$ and $dI_{COM/dt}$ on the triac,

High temperature operation close to Tj max when triacs become more sensitive and more prone to loss of control,

Noisy circuits that impose high dV_D/dt across the triac when in the blocking state.

Benefits for the appliance manufacturer.

The enhanced performance of three-quadrant triacs yields the following benefits to the OEM:

The reduction or elimination of protective snubbers and inductors that are essential for trouble-free operation of traditional four-quadrant triacs, simpler and smaller circuits, greater immunity to loss of control, and better long-term reliability due to the elimination of the protection components that can be a potential source of stress for the triac. ■

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