DESIGNING TO MEET ISO7637 PULSE 5 (LOAD DUMP)

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Abstract: *ISO7637 Pulse 5 is a long high-energy transient. It's high energy means that unprotected Electronic Sub-Assemblies (ESAs) are usually damaged when exposed to it. This paper shows that a single large shunt transient suppressor (as often used by ESA designers) is often not sufficient to guarantee protection against pulse 5. This is especially true of ESAs designed for both 12V and 24V applications. The author derives a model for the energy absorption limit of the commonly used 5KP-series (5000 watt) for long-pulses because product datasheets specify limits only for short pulses. The author then examines alternatives circuits employing Darlington transistors and P-FETs. The advantages and disadvantages of each example circuit are explained.*

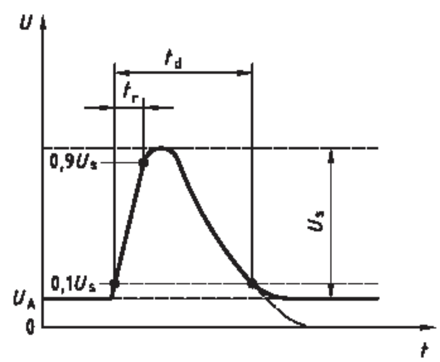
Introduction

ISO7637-2:2004[1] pulse 5 (load dump pulse) is designed to simulate the voltage surge produced by spinning alternators when the battery or some other significant load is accidentally disconnected. The energy produced by the resultant voltage surge is very high and can easily damage unprotected Electronic Sub-Assemblies (ESAs). The basic method of protecting an ESA is to shunt the supply voltage at the ESA input with a semiconductor transient suppressor. In many cases however the device has to absorb more energy than it can safely handle. Therefore alternative and more sophisticated circuits have been developed to address the problem.

In this paper basic transient suppression is first analysed in detail. Thereafter more sophisticated techniques described with their advantages and disadvantages explained.

Analysis of Pulse 5 with Basic Transient Suppression

The unsuppressed ISO7637-2:2004[1] pulse 5 (load dump pulse) is shown in figure 1.



Parameter	12 V system	24 V system
U_s	65 V to 87 V	123 V to 174 V
R_i	0,5 Ω to 4 Ω	1 Ω to 8 Ω
t_d	40 ms to 400 ms	100 ms to 350 ms
t_r	$\left(10\ ^{0}_{-5}\right)$ ms	

Figure 1 – ISO7637 Unsuppressed Load Dump Pulse*

* Courtesy of the International Standards Organisation.

These pulses carry very high energies that can easily damage unprotected Electronic Sub-Assemblies (ESAs). Table 1 shows the maximum energy in Joules for a 12V unsuppressed Cat IV pulse*.

Pulse Duration (td)	Source Resistance (Ri) 1 Ω	2 Ω	3 Ω	4 Ω	5 Ω	6 Ω	7 Ω	8 Ω
100 mS	164.54	82.27	54.85	41.14	32.91	27.42	23.51	20.57
150 mS	246.82	123.41	82.27	61.70	49.36	41.14	35.26	30.85
200 mS	329.09	164.54	109.70	82.27	65.82	54.85	47.01	41.14
250 mS	411.36	205.68	137.12	102.84	82.27	68.56	58.77	51.42
300 mS	493.63	246.82	164.54	123.41	98.73	82.27	70.52	61.70
350 mS	575.90	287.95	191.97	143.98	115.18	95.98	82.27	71.99

Table 2 – Maximum Pulse Energy (J) for Pulse 5a, 24V, Cat IV

* Calculated using the method given in Annex E.1.1.(e)[1] where $R_i=R_L$ (for maximum power transfer).

In a basic suppression circuit, excess energy is absorbed by a transient suppressor fitted in shunt with the supply into an ESA (figure 2).

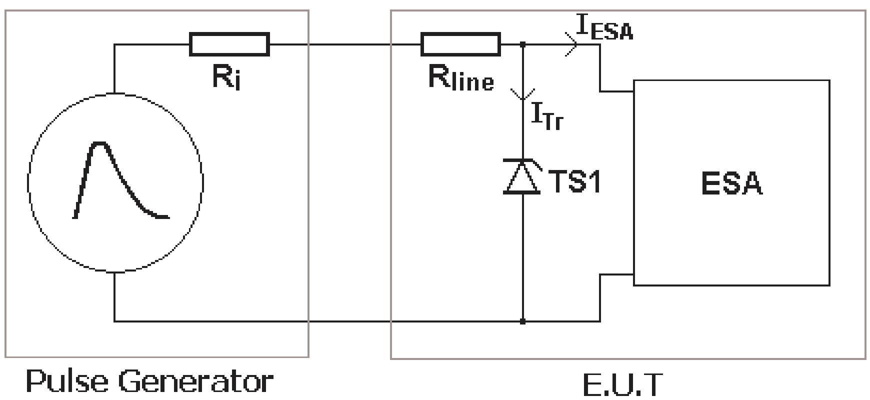


Figure 2 – Basic Suppression Example Circuit

The suppressor starts to draw current when its voltage threshold is reached and will then continue to limit the pulse to a safe clamping voltage by drawing the bulk of the surge current (I_{Tr}) into itself. The energy it absorbs by doing this (equ 1) is converted to heat and then dissipated.

Equ 1 $E_{Tr} = I_{Tr} \cdot V_{clamp} \cdot t_{clamp}$ (Joules)

Note that the suppressor doesn't have to dissipate all of the pulse energy, only the excess energy when the pulse amplitude exceeds the clamping voltage (shaded pink in figure 3). Also the energy used by the ESA itself must be subtracted. Taking again the example of a 12V unsuppressed Cat IV pulse. Table 2 shows the energy absorbed by a transient suppressor with a 45 volt clamping voltage. In this example t_{clamp} is approximately 20% of t_d and E_{Tr} is between 35% and 45% of the maximum available pulse energy.

The question then is "can a single transient suppressor safely absorb energies up to 149 Joules in 400mS?" To answer it we need to analyse how semiconductor transient suppressors work because the question can't simply be answered by inspection of a device's datasheet.

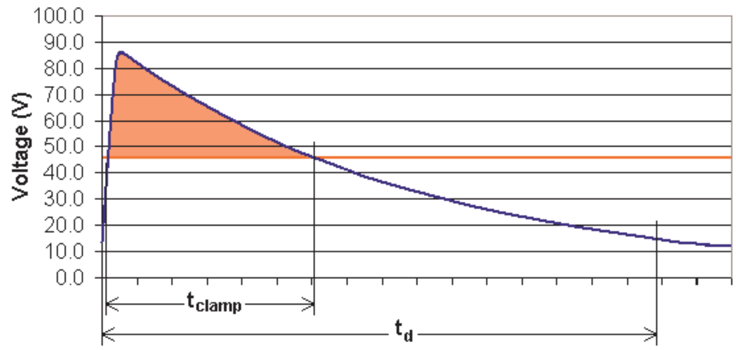


Figure 3 – Basic Suppression Example Waveform

Pulse Duration (td)	Source Resistance (Ri) 0.5 Ω	1 Ω	1.5 Ω	2 Ω	2.5 Ω	3 Ω	3.5 Ω	4 Ω
50 mS	18.57	9.62	6.26	4.50	3.41	2.68	2.17	1.80
100 mS	37.15	19.23	12.51	8.99	6.83	5.36	4.34	3.59
150 mS	55.72	28.85	18.77	13.49	10.24	8.04	6.51	5.39
200 mS	74.30	38.46	25.02	17.98	13.65	10.72	8.68	7.18
250 mS	92.87	48.08	31.28	22.48	17.07	13.40	10.85	8.98
300 mS	111.44	57.69	37.53	26.98	20.48	16.08	13.02	10.77
350 mS	130.02	67.31	43.79	31.47	23.89	18.76	15.19	12.57
400 mS	148.59	76.92	50.05	35.97	27.31	21.44	17.37	14.36

Table 2 – Energy (J) absorbed by TS1 for Pulse 5a, 12V, Cat IV (V_{clamp}=45V, R_{line}=0.1Ω)

Analysis of 5KP-Series Semiconductor Transient Suppressors

Many semiconductor manufacturers make 5KP-series transient suppressors. All produce datasheets with very similar specifications. These devices are one of the most commonly available high-energy suppressors and are frequently used in load dump pulse suppression circuits.

By convention the maximum energy rating of these devices is specified as a power (5000 W) for a 1mS pulse. This corresponds to a maximum energy rating of just 5 Joules @ t_d=1mS. What, however, is the limit for a 400mS pulse? To answer this question we need to consider how the device works.

These devices start to conduct current when the terminal voltage exceeds a threshold and take increasing current until the pulse is held down to a maximum clamping voltage. For example the 5KP28A has a threshold voltage of 31.1 volts and a maximum clamping voltage of 45.4 volts. This makes it ideal for use in dual 12V & 24V ESAs.

All the energy absorbed in the semiconductor junction of these devices is converted to heat. From the junction the heat spreads through the body of the component until it reaches the device extremities. As the outside surface of the device begins to warm up heat is lost to the environment. There are therefore three time-dependent modes of operation for these simple devices:

(i) For short pulses – heat spreads from the junction through the device body at a constant rate. Assuming this spreading is spherical we would expect the maximum dissipation energy for short pulses to follow an inverse square law.

(ii) For long pulses – heat is able to spread to the device extremities during the pulse. The device warms up at a rate dependent on its specific heat capacity. We would expect the maximum dissipation energy for long pulses to be constant because a the volume of material being heated is constant.

(iii) For very long pulses – heat is lost from the warm device to the environment at a given maximum continuous power. Therefore we expect the maximum dissipation energy for very long pulses to be directly proportional to the pulse duration.

The pulse width derating curve for the Diotec 5KP-series is given in figure 4. The derived equation for this curve being given in equ 2.

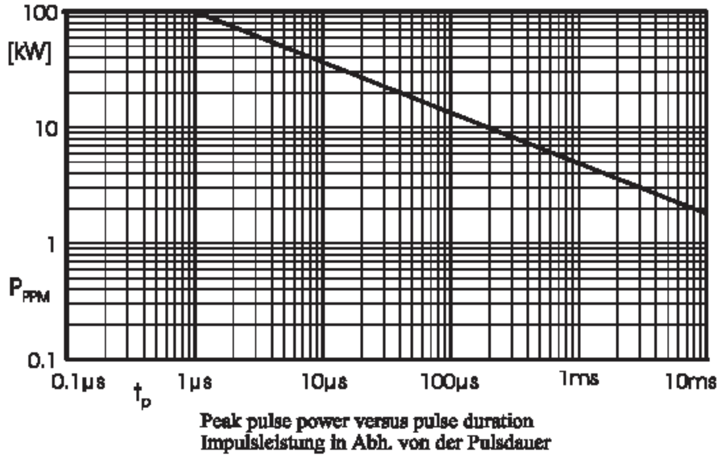


Figure 4 – Diotec 5KP-Series Pulse Width Derating Curve[2]

Equ 2 $P_{ppm} = 5000 \cdot t_p^{-0.435}$ (watts)

(where t_p is in mS)

Conversion to a maximum energy in Joules is simply a matter of multiplying through by t_p (equ 3).

Equ 2 $E_{max} = 5000 \cdot t_p^{(1-0.435)}$ (watts)

The result is a square-root law rather than the expected inverse-square law. Nevertheless the author is convinced there's an inverse-square law in the physics somewhere waiting to be discovered.

The Diotec datasheet shows only the short pulse model for derating P_{ppm}. Other manufacturers such as WTE are more honest. Figure 4 shows the pulse width derating curve for the WTE 5KP-series.

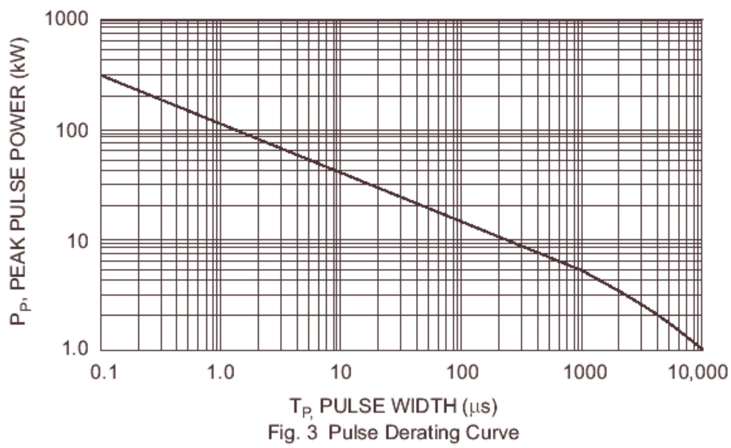


Figure 5 – WTE 5KP-Series Pulse Width Derating Curve[3]

It can be seen that at 10mS the curve is starting to droop, hinting that another model is coming into play. Unfortunately none of the datasheets available to this author give any parameters for this model so it was necessary to derive it from first principles.

For this derivation it is assumed that the body of the device is over-moulded in Thermally Conductive Epoxy with a volumetric specific heat of 1.9×10^6 $Jm^{-3}K^{-1}$[4]. Calculations of the long pulse energy limit are for both Diotec and WTE devices (table 3) have been derived from the device cylindrical dimensions by neglecting the effects of the copper connecting wires.

	WTE	**Diotec**	
Epoxy Specific Heat =	1.90×10^6	1.90×10^6	$Jm^{-3}K^{-1}$
Cylinder dia =	8.60×10^{-3}	8.00×10^{-3}	m
Cylinder end area =	5.81×10^{-5}	5.03×10^{-5}	m^2
Cylinder length =	8.60×10^{-3}	7.50×10^{-3}	m
Cylinder volume =	5.00×10^{-7}	3.77×10^{-7}	m^3
Cylinder sp heat =	9.49×10^{-1}	7.16×10^{-1}	JK^{-1}
Ambient temp =	25	25	ºC
Max case temp =	175	175	ºC
Max energy =	**142.4**	**107.4**	**J**

Table 3 – Calculation of Long-Pulse Energy Limit for 5KP-Series

The Diotec body is slightly smaller than WTE and therefore has a lower long-pulse energy limit.

This analysis is rather simplistic and neglects the internal temperature gradient from the generating junction to the dissipating case exterior. The author wasn't able to perform complex thermal modelling of these devices and so instead simply derated the energy limit to 50 Joules (long-pulse) to derive an overall model for the 5KP-series (figure 6, red line).

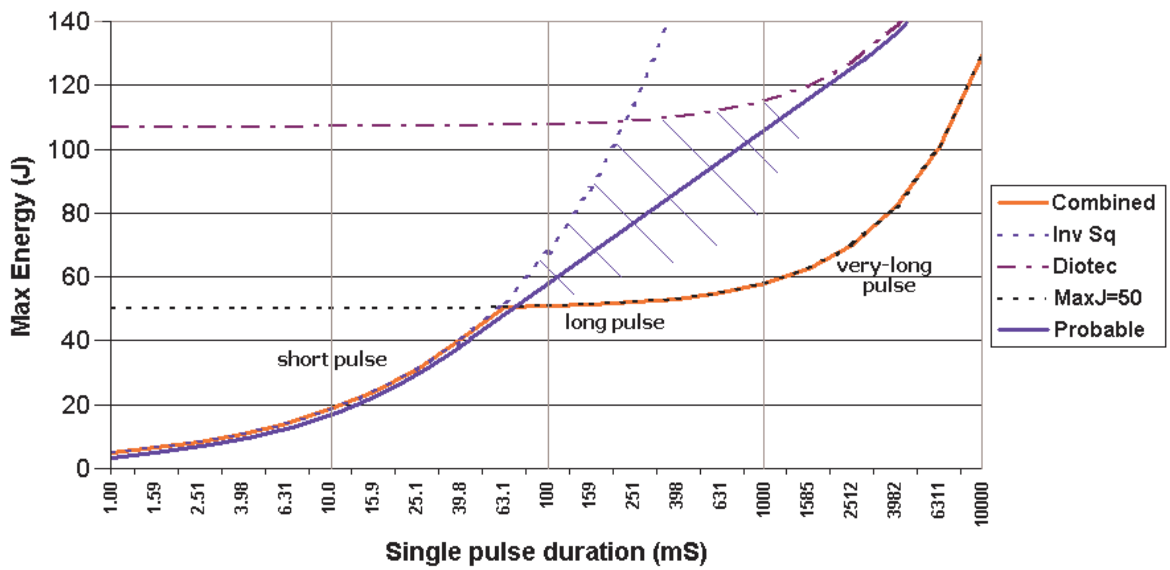


Figure 6 – 5KP-Series Calculated Energy Limit -v- Pulse Duration

The dotted blue line is the short pulse model derived from the datasheets[2][3]. The dotted black line is the 50 Joules long pulse limit. This rises for very long pulses (>1S) toward the continuous power limit (from the datasheets) of 8 JS^{-1}. The solid blue line shows the probable connection between short and very long pulse models for the Diotec 5KP-series. The shaded area hints at the uncertainty as to how long pulses really affect the overall curve. The red line is the curve used in all following calculations.

From figure 6 single device limits are derived for the same pulse durations as table 2 (see table 4).

Pulse Duration (td)	Max 5KP Energy (J)
50 mS	18.44
100 mS	27.33
150 mS	34.40
200 mS	40.51
250 mS	45.99
300 mS	50.48
350 mS	50.56
400 mS	50.64

Table 4 – Maximum energy (J) that can be absorbed by TS1 for Pulse 5a, 12V, Cat IV (V_{clamp}=45V)

Comparing tables 2 and 4 it can be seen that a single 5KP28A is not rated to absorb a 12V Cat IV pulse under all conditions. Table 5 gives the minimum number of devices that would be needed to absorb such a pulse.

Pulse	Source Resistance (Ri)							
Duration (td)	0.5 Ω	1 Ω	1.5 Ω	2 Ω	2.5 Ω	3 Ω	3.5 Ω	4 Ω
50 mS	2	1	1	1	1	1	1	1
100 mS	2	1	1	1	1	1	1	1
150 mS	2	1	1	1	1	1	1	1
200 mS	2	1	1	1	1	1	1	1
250 mS	3	2	1	1	1	1	1	1
300 mS	3	2	1	1	1	1	1	1
350 mS	3	2	1	1	1	1	1	1
400 mS	3	2	1	1	1	1	1	1

Table 5 – Number of 5KP28A Devices needed for 12V, Cat IV (V_{clamp}=45V, R_{line}=0.1Ω)

A 12V Cat III pulse can be absorbed by a 5KP28A under all conditions, but this is not the case for a dual-voltage EUT when absorbing a 24V Cat III pulse (Table 6) or Cat IV (Table 7).

Pulse	Source Resistance (Ri)							
Duration (td)	1 Ω	2 Ω	3 Ω	4 Ω	5 Ω	6 Ω	7 Ω	8 Ω
100 mS	2	1	1	1	1	1	1	1
150 mS	2	1	1	1	1	1	1	1
200 mS	3	2	1	1	1	1	1	1
250 mS	3	2	1	1	1	1	1	1
300 mS	4	2	1	1	1	1	1	1
350 mS	4	2	2	1	1	1	1	1

Table 6 – Number of 5KP28A Devices needed for 24V, Cat III (V_{clamp}=45V, R_{line}=0.1Ω)

Pulse	Source Resistance (Ri)							
Duration (td)	1 Ω	2 Ω	3 Ω	4 Ω	5 Ω	6 Ω	7 Ω	8 Ω
100 mS	3	2	1	1	1	1	1	1
150 mS	4	2	2	1	1	1	1	1
200 mS	5	3	2	2	1	1	1	1
250 mS	6	3	2	2	2	1	1	1
300 mS	7	4	3	2	2	2	1	1
350 mS	8	4	3	2	2	2	1	1

Table 7 – Number of 5KP28A Devices needed for 24V, Cat IV (V_{clamp}=45V, R_{line}=0.1Ω)

Advanced Pulse 5 Suppression Circuits

There is no guarantee, when multiple transient suppressors are shunted together, that individual devices will absorb energy equally. Therefore more advanced circuits are recommended where a single transient suppressor is unable to absorb the energy alone.

Darlington Suppression

A simple circuit employing a power Darlington transistor is shown in figure 7.

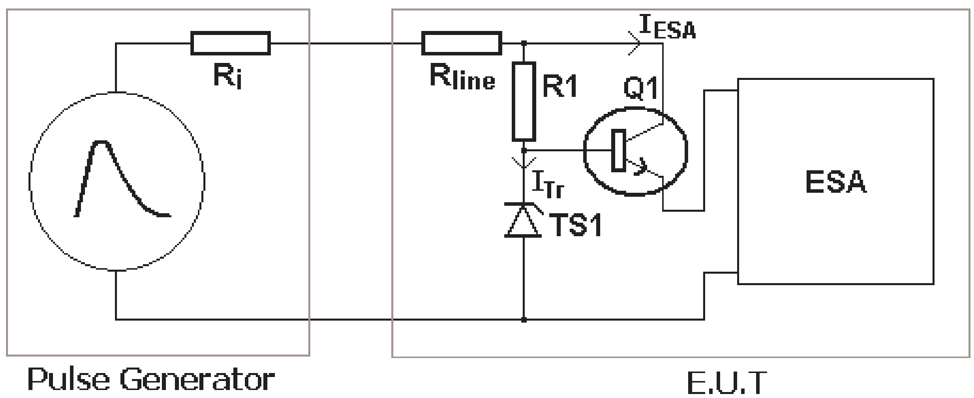


Figure 7 – Darlington Suppression Example Circuit

Advantage – R1 limits the surge current through TS1 and thereby the amount of energy it has to absorb.

Disadvantage – Q1 wastes energy in normal operation. Typically the voltage drop over Q1 will be between 1 and 2 Volts. For high-current ESAs the power wastage is usually unacceptable (up to 20 watts for I_{ESA}=10 A).

This circuit is only suitable for low-current ESAs where the voltage drop across Q1 can be tolerated.

P-FET Suppression

By replacing the Darlington with a low on resistance P-FET the voltage drop across Q1 can be reduced to 10s or 100s of milliamps (figure 8).

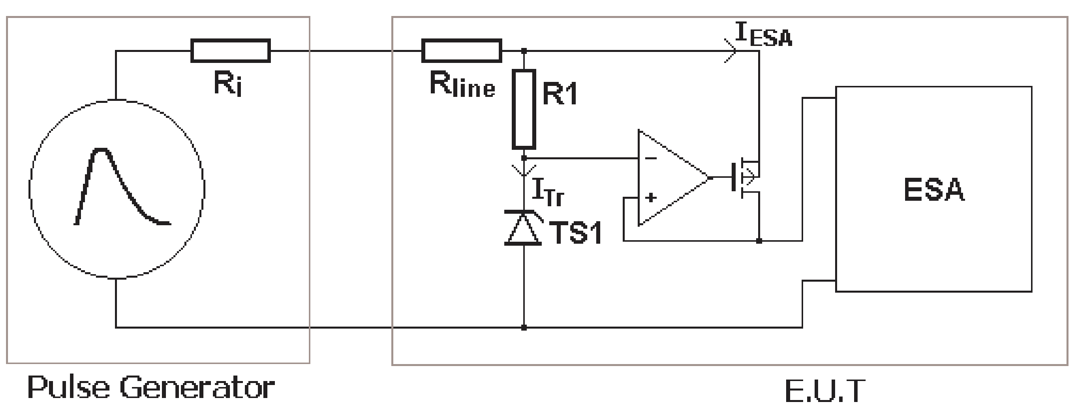


Figure 8 – P-FET Suppression Example Circuit

Advantage – R1 limits the surge current through TS1 and the saturated P-FET Rds-ON reduces power wastage in normal operation.

Disadvantage – It's very difficult to stabilise this circuit when pulse 5 is applied. To cope with the rising edge a fast response is required which tends to make the voltage fed to the ESA ring badly with dangerously high voltage peaks. This is especially a problem when I_{ESA} is not constant because this affects the loading and therefore damping of the protection circuit.

P-FET Isolation Switch

By changing the feedback loop to positive rather than negative the P-FET suppressor is converted to a pulse isolation switch (figure 9). This circuit protects the ESA by powering it down for the duration of the load dump pulse. Provided that the ESA can recover from the brown-out automatically the test can still be passed albeit class-C.

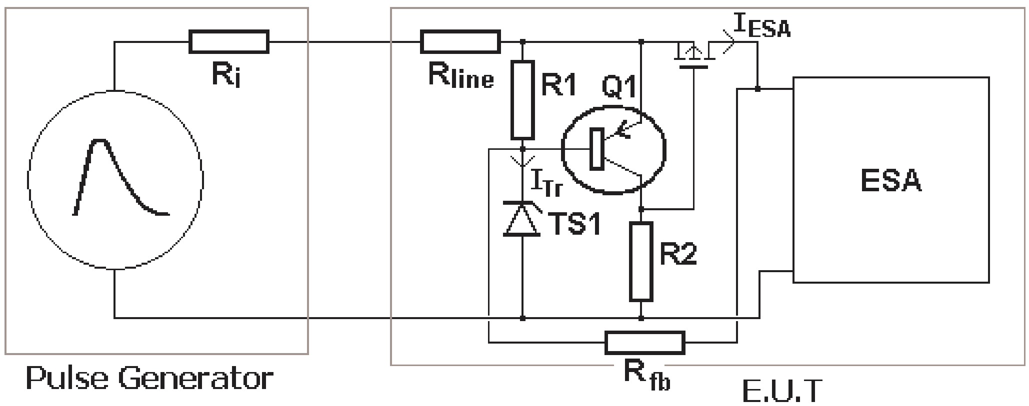


Figure 9 – P-FET Isolation Switch Example Circuit

Advantage – R1 limits the surge current through TS1 and the saturated P-FET Rds-ON reduces power wastage in normal operation. Rfb controls the on-off hysteresis points. The author has found it easy to design this circuit to be very stable under all ESA load conditions.

Disadvantage – The ESA experiences a power brown-out during pulse 5.

P-FET Suppression/Isolation Switches During Pulse 4 (Cranking)

Both the P-FET isolation switch and the P-FET suppressor can have problems when exposed to ISO7637-2 pulse 4 (cranking pulse) especially on 12V systems. When a car engine is cranked the battery voltage drops typically to about 6V. Often there is insufficient voltage available to keep the P-FET saturated. As a result Rds rises and the devices starts to dissipate energy. In one circuit the author designed the P-FET was liable to burn-out if the car didn't start quickly when cranked.

To overcome this problem it is important either to ensure the P-FET is kept in saturation often by using an ESA generated negative power rail, or to completely switch off the P-FET during cranking and then allow the ESA to recover automatically afterwards.

Conclusion

The energy requirements of arresting ISO7637 pulse 5a have been investigated. Deficiencies in simple single transient arrestor circuits shown by deriving the maximum energy that these devices can absorb from long pulses such as pulse 5. Of the alternatives to these simple circuits, the PFET isolation switch holds the most promise for both energy conservation and power stability.

References

[1] ISO 7637-2:2004 *Road vehicles — Electrical disturbances from conduction and coupling — Part 2: Electrical transient conduction along supply lines only.*

[2] Diotec Semiconductors *5 KP Series Datasheet — 07.01.2003.*

[3] WTE Power Semiconductors *5 KP Series Datasheet — 5000W Transient Voltage Suppressors — 2002 Won-Top Electronics*

[4] MG Chemicals — *Thermally Conductive Epoxy Encapsulating & Potting Compound 832-TC* http://www.mgchemicals.com/products/832tc.html#specs

Biographical Notes

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