Power MOSFET in UIS/Avalance Applications

By Kandarp Pandya

Inductive loads require adequate attention in electronic control circuits, since otherwise they can lead to unclamped inductive switching (UIS) or avalanche conditions, which may occur when the device is turning off or it is already turned off. In fact, inductive loads may cause catastrophic failure of a MOSFET that appears otherwise to be operating within its specified current and power ratings. Failure analysis (FA) has shown that such conditions can result in electrical over stress (EOS), where the total energy dissipation exceeds the thermal capabilities of the MOSFET on the printed circuit board (PCB) assembly. The failure signature further points to localized dissipation of energy through a very small, randomly located die area. Insofar as the effects of UIS or avalanche are heterogeneous with respect to the die, failure can occur at current and power levels below the maximums specified by the datasheet. Avalanche in a MOSFET, like the natural phenomenon for which it is named, is an uncontrolled behavior, and one that cannot be characterized due to the non-homogeneity of die utilization during the event.

Solenoid actuators for two-position on/off control, automotive engine control units (ECU) with high frequency inductive switching control for fuel injection, and anti-lock braking systems (ABS) are among the applications that involve inductive loads. In the case of solenoid actuators, designers need to understand the significance of single pulse avalanche current ratings for different inductor values and corresponding permissible energy values, as shown on product datasheets. In the case of ECU and ABS applications, designers need to interpret the datasheet information to derive a repetitive avalanche current rating.

The thermal capability of the MOSFET in the system is the key factor that determines its survivability in the UIS/Avalanche mode operation. Therefore the key specifications we need to use from the datasheet are the following:

- Maximum operating temperature, T_J (max.)
- Drain-source breakdown voltage, V_{DS}
- $R_{th(j-a)}$ (max.) steady-state value
- Normalized thermal transient impedance, junction-to-ambient characteristics

The datasheet specification for single pulse avalanche current, I_{AS} is normally derived from a test that involves the MOSFET's destruction, so the measured value must be derated before turning it into a specification. Typically a 50 % guard band is applied to the test result value of the drain current at the failure point. The corresponding single pulse energy ratings E_{AS} are also derived by applying the same derating factor. Note that the I_{AS} and E_{AS} ratings are limited to specific test conditions, i.e. to a certain inductor value, test current pulse, and thermal capability for the PCB setup.

The datasheet value for junction-to-ambient maximum thermal resistance, $R_{th(j-a)}$ (max.), and transient thermal characteristics are derived from empirical measurements. These are also limited by boundary conditions. The MOSFET is soldered on a double-sided FR4 PCB with dimensions of 1" by 1" by 0.062" (25.4 mm by 25.4 mm by 1.5 mm) with 2 oz. (0.076 mm) of 100 % copper on both sides - ignoring the slit isolation to insulate the MOSFET drain, source, and gate terminals. The thermal characteristics of MOSFET in an actual system can be different, of course, so there is no easy way to relate datasheet information with the actual repetition rate, duty cycle, and board thermal capabilities the MOSFET will encounter in an end product. However, the good news is that most real-world PCB assemblies have better thermal performance characteristics than those used for datasheet characterization. This provides an inherent design margin when using the datasheet information as outlined below.

There are five parameters related to MOSFET stress:

- Avalanche current, single pulse, I_{AS} or repetitive, I_{AR}
- Time in avalanche, T_{AV}
- Circuit inductance, L
- Avalanche energy, single pulse, E_{AS} or repetitive, E_{AR}
- Starting junction temperature, $T_{J(Start)}$ - mostly T_{amb}

The following reference characteristics can be developed using datasheet values and mathematical formulas which relate the above parameters and extrapolations:

- I_{AV} vs. T_{AV} - single pulse avalanche current vs. time in avalanche
- I_{AS} vs. L - single pulse avalanche current vs. inductance
- E_{AS} vs. $T_{J(Start)}$ - single pulse avalanche energy vs. starting junction temperature
- I_{AR} vs. T_{AV} at 25 °C ambient - 2 % to 50 % duty cycle - repetitive pulse avalanche current vs. time in avalanche at 25 °C ambient
- I_{AR} vs. T_{AV} at 150 °C ambient - 2 % to 50 % duty cycle - repetitive pulse avalanche current vs. time in avalanche at 150 °C ambient

Power MOSFET in UIS/Avalance Applications

The above characteristics can help designers to minimize the stress to the MOSFET under UIS/avalanche operation. We should note that the above characteristics are only for reference because they are applicable only to the part mounted on the specific PC board used for datasheet characterization. Designs following these guidelines will safeguard MOSFET operation under UIS conditions for most applications. In fact many real life automotive PC board assemblies are far superior in thermal performance, but our approach provides an extra margin of safety to minimize the MOSFET failure.

In the following example we shall develop the above characteristics for Vishay Siliconix MOSFET SQM110N04-03[1].

Datasheet information:

- Maximum operating temperature, T_J (max.) = 175 °C
- Thermal resistance junction-to-ambient, $R_{th(j-a)}$ = 40 °C/W
- Drain-source breakdown voltage, V_{DS} = 40 V_{DC}
- Normalized thermal transient impedance, junction-to-ambient characteristics, figure 1

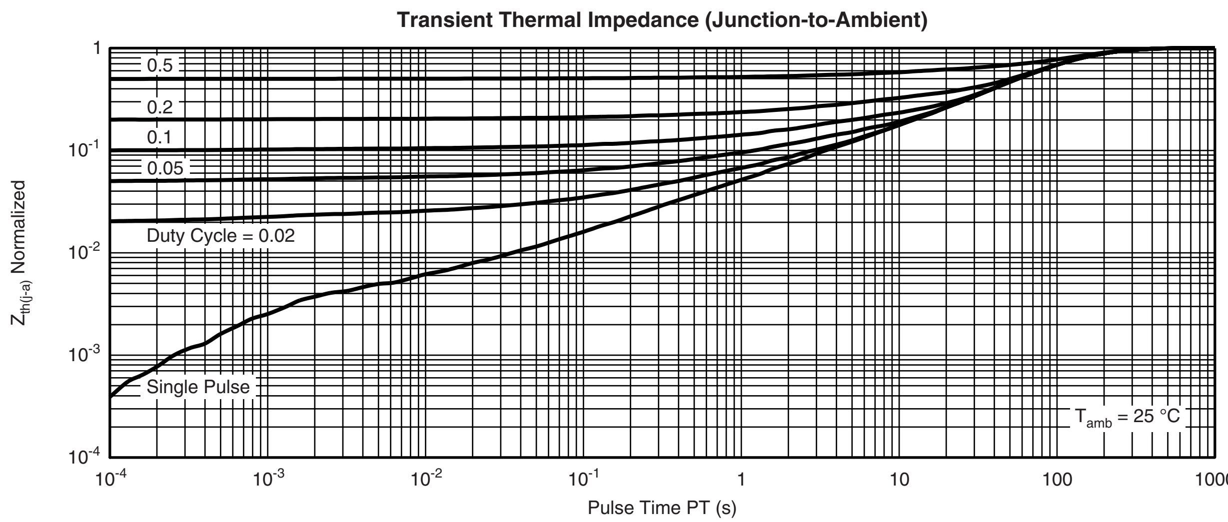

Fig. 1 - Normalized Thermal Transient Impedance, Junction-To-Ambient Characteristics

I_{AV} VS. T_{AV} - SINGLE PULSE AVALANCHE CURRENT VS. TIME IN AVALANCHE

The pulse time in figure 1 can be used as Time in Avalanche, T_{AV} for the square wave pulse. Thus figure 1 represents $Z_{th(j-a)}$, normalized thermal transient impedance, junction to ambient vs. time in avalanche T_{AV} characteristics for a single pulse:

$Z_{th(j-a)}$ (°C/W) vs. T_{AV} (s)

The corresponding thermal resistance $R_{th(j-a)}$ values can be derived by using the following equation:

$R_{th(j-a)}$ (°C/W) = $Z_{th(j-a)}$ normalized (number) x $R_{th(j-a)}$ (°C/W) Equation (1)

Where $R_{th(j-a)}$ max. = 40 °C/W

Now extract the value for single pulse avalanche current, I_{AV} (A) corresponding to T_{AV} (s)

Maximum permissible junction temperature, T_J (max.) = 175 °C

Ambient, T_{amb} = 25 °C

Hence, the junction temperature rise, ΔT can be derived by using the following equation:

ΔT (°C) = T_J (max.) (°C) - T_{amb} (°C) Equation (2)

ΔT (°C) = 175 °C - 25 °C = 150 °C

While maintaining the temperature rise, ΔT = 150 °C

ΔT (°C) = $R_{th(j-a)}$ (°C /W) x P_D (W) Equation (3)

Where P_D = Pulse power dissipation in watts

Power MOSFET in UIS/Avalance Applications

Rearranging equation (3)

P_D (W) = ΔT (°C)/$R_{th(j-a)}$ (°C/W) Equation (4)

Also

P_D (W) = ½ x V_{BR} (V) x I_{AV} (A) Equation (5)

Where

V_{BR} = Breakdown voltage in volts
V_{BR} = 1.3 x V_{DS} Maximum Drain-Source Voltage
V_{BR} = 1.3 x 40 V (from datasheet)

Rearranging Equations (4) and (5)

I_{AV} (A) = 2 x (ΔT (°C)/$R_{th(j-a)}$ (°C/W))/V_{BR} (V)

Extract I_{AV} (A) corresponding to T_{AV} (s) for ΔT = 150 °C

I_{AV} (A) = 2 x (150 (°C)/Rth(j-a) (°C /W))/1.3 x 40 (V) for $T_{J\ (Start)}$ 25 °C Equation (6)

Similarly, extract I_{AV} (A) corresponding to T_{AV} (s) for ΔT = 25 °C

T_J (max.) = 175 °C
T_{amb} or $T_{J\ (Start)}$ = 150 °C

While maintaining the temperature rise, ΔT = 25 °C

I_{AV} (A) = 2 x (25 (°C)/$R_{th(j-a)}$ (°C /W))/1.3 x 40 (V) for $T_{J\ (Start)}$ 150 °C Equation (6a)

I_{AV} vs. T_{AV} - Single Pulse Avalanche Current vs. Time in Avalanche characteristics with T_{amb} = 25 °C and T_{amb} = 150 °C are shown in figure 2.

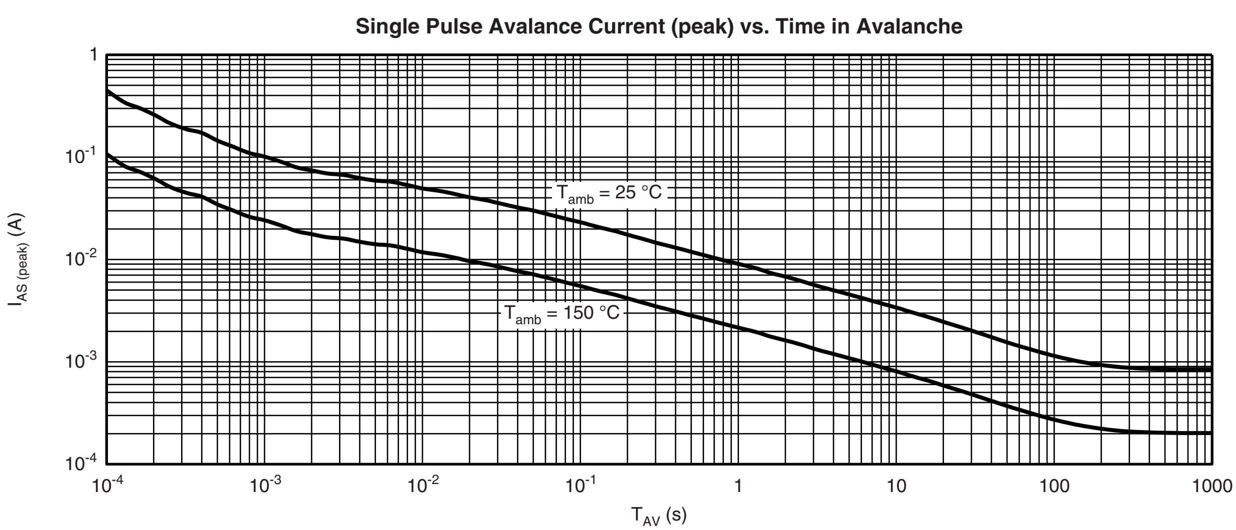

Fig. 2 - I_{AV} vs. T_{AV} - Single Pulse Avalanche Current vs. Time in Avalanche Characteristics

APPLICATION NOTE

Power MOSFET in UIS/Avalance Applications

I_{AS} VS. L - SINGLE PULSE AVALANCHE CURRENT VS. INDUCTANCE

The first step is to extract the permissible value of inductor, L (mH) corresponding to T_{AV}.

Using the basic Ohm's Law equation for the inductor:

V = L x dI/dt Equation (7)

Where

V = Voltage across the inductor in volts
L = the inductance in Henry
dI/dt = rate of change of current A/s

Rearranging Equation (7) for the value of inductance in avalanche condition:

L (mH) = [(V_{BR} (V) x T_{AV} (s))/I_{AV} (A)] x 1000 Equation (8)

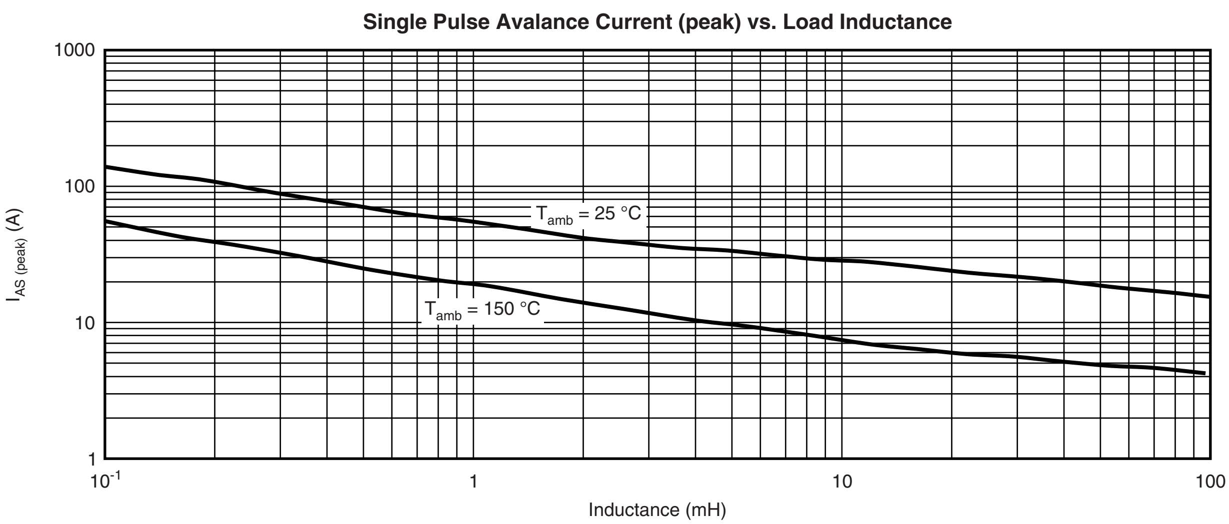

Fig. 3 - I_{AV} vs. L (mH) - Single Pulse Avalanche Current vs. Inductance, L (mH) Characteristic

Figure 3 is the plot for maximum single pulse avalanche current vs. inductance

I_{AV} (A) vs. L (mH) for ΔT = 150 °C or T_{amb} = 25 °C

I_{AV} (A) vs. L (mH) for ΔT = 25 °C or T_{amb} = 150 °C

The values are extracted for an inductor value range 0.1 mH to 100 mH, which covers most of the applications.

E_{AS} VS. $T_{J\ (Start)}$ - SINGLE PULSE AVALANCHE ENERGY VS. STARTING JUNCTION TEMPERATURE

Single pulse avalanche energy, E_{AS} vs. starting junction temperature, $T_{J\ (Start)}$ for the value of single pulse avalanche current, I_{AV} at 90 A, 30 A. and 15 A. These values are chosen to cover the most practical range of avalanche current; around 80 %, 30 %, and 15 % of drain current rating respectively. These characteristics enable user to limit the total avalanche pulse energy from both the staring junction temperature and peak avalanche current.

Extract database for E_{AS} (mJ) corresponding to $T_{J\ (Start)}$ (°C) for I_{AV} = 90 A

Rearrange equation (2) by substituting $T_{J\ (Start)}$ for T_{amb} and T_J (max.) = 175 °C

ΔT (°C)= 175 (°C) - $T_{J\ (Start)}$ (°C) Equation (9)

While maintaining the temperature rise, ΔT = 150 °C, i.e., $T_{J\ (Start)}$ = 25 °C

Extract Single Pulse Avalanche Energy, E_{AS} (mJ) as follows:

E_{AS} (mJ) = P_D (W) x T_{AS} (s) x 1000 Equation (10)

Power MOSFET in UIS/Avalance Applications

Substitute PD(W) from Equation (3)

E_{AS} (mJ) = [ΔT (°C)/$R_{th(j-a)}$ (°C /W)] x T_{AV} (s) x 1000

E_{AS} (mJ) = [150 (°C)/$R_{th(j-a)}$ (°C /W)] x T_{AV} (s) x 1000 Equation (11)

Substitute the values of $R_{th(j-a)}$ (°C/W) and T_{AV} (s) corresponding to I_{AS} = 90 A from single pulse database developed in equation (1) above. The equation simplifies to:

E_{AS} (mJ) = [175 (°C) - $T_{J\ (Start)}$ (°C)/0.0642 (°C/W)] x 0.0005 (s) x 1000 Equation (12)

Similarly, substitute the values of $R_{th(j-a)}$ (°C/W) and T_{AV} (s) corresponding to I_{AS} = 30 A from single pulse database developed in (1) above. The equation simplifies to:

E_{AS} (mJ) = [175 (°C) - $T_{J\ (Start)}$ (°C)/0.198 (°C/W)] x 0.005 (s) x 1000 Equation (13)

Similarly, substitute the values of $R_{th(j-a)}$ (°C/W) and T_{AV} (s) corresponding to I_{AS} = 15 A from single pulse database developed in (1) above. The equation simplifies to:

E_{AS} (mJ) = [175 (°C) - $T_{J\ (Start)}$ (°C)/0.3826 (°C/W)] x 0.032 (s) x 1000 Equation (14)

Figure 4 shows plot of E_{AS} (mJ) vs. $T_{J\ (Start)}$ (°C) ranging from 25 °C to 175 °C.

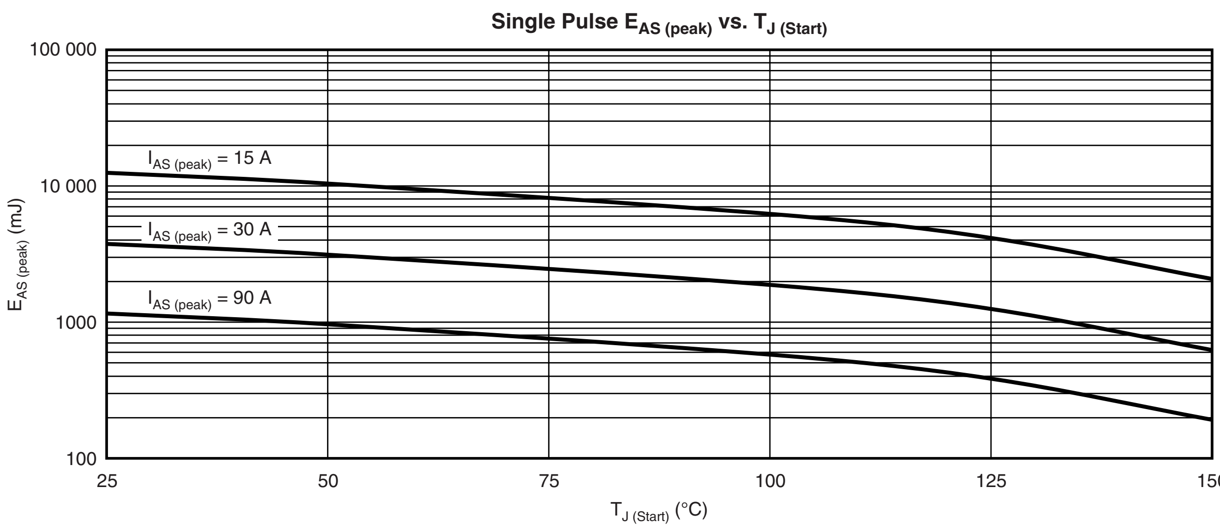

Fig. 4 - E_{AS} (mJ) vs. $T_{J\ (Start)}$ (°C) - Single Pulse Avalanche Energy vs. Starting Junction Temperature (°C) Characteristic

REPETITIVE, MAXIMUM AVALANCHE PULSE CURRENT, I_{AR} VS. TIME IN AVALANCHE, T_{AV} FOR SINGLE PULSE AND 0.02 DUTY CYCLE TO 0.5 DUTY CYCLE

This characteristic helps to relate the repetitive peak current to the value of time in avalanche at different duty cycle ratios.

Using Equation (1) extract junction to ambient thermal transient impedance characteristics for duty cycles 0.02, 0.05, 0.1, 0.2, and 0.5 (from datasheet)

$R_{th(j-a)}$ (°C /W) vs. T_{AV} (s) 0.02 duty cycle

$R_{th(j-a)}$ (°C /W) vs. T_{AV} (s) 0.05 duty cycle

$R_{th(j-a)}$ (°C /W) vs. T_{AV} (s) 0.1 duty cycle

$R_{th(j-a)}$ (°C /W) vs. T_{AV} (s) 0.2 duty cycle

$R_{th(j-a)}$ (°C /W) vs. T_{AV} (s) 0.5 duty cycle

Using Equation (6) for single pulse for different duty cycles 0.02 to 0.5 extract

I_{AR} (A) corresponding to T_{AV} (s) for ΔT = 150 °C

T_J (max.) = 175 °C

Power MOSFET in UIS/Avalance Applications

T_{amb} or $T_{J\ (Start)}$ = 25 °C
While maintaining the temperature rise, ΔT = 150 °C

I_{AR} (A) = 2 x (150 (°C)/$R_{th(j-a)}$ (°C /W))/1.3 x 40 (V) for $T_{J\ (Start)}$ 25 °C Equation (15)

See figure 5.
Similarly, extract I_{AR} (A) corresponding to T_{AV} (s) for ΔT = 25 °C
T_J (max.) = 175 °C
T_{amb} or $T_{J\ (Start)}$ = 150 °C
While maintaining the Temperature Rise, ΔT = 25 °C

I_{AR} (A) = 2 x (25 (°C)/$R_{th(j-a)}$ (°C /W))/1.3 x 40 (V) for $T_{J\ (Start)}$ 150 °C Equation (16)

See figure 6

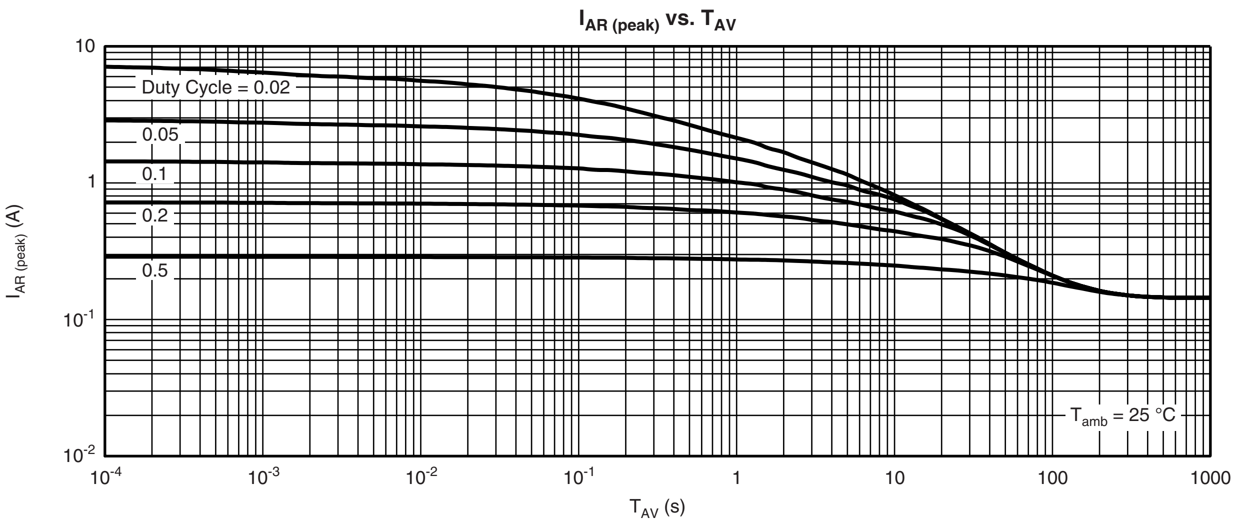

Fig. 5 - Shows plots of I_{AR} (A) vs. T_{AV} (s) for T_{amb} = 25 °C or ΔT = 150 °C for duty cycles 0.02 to 0.5

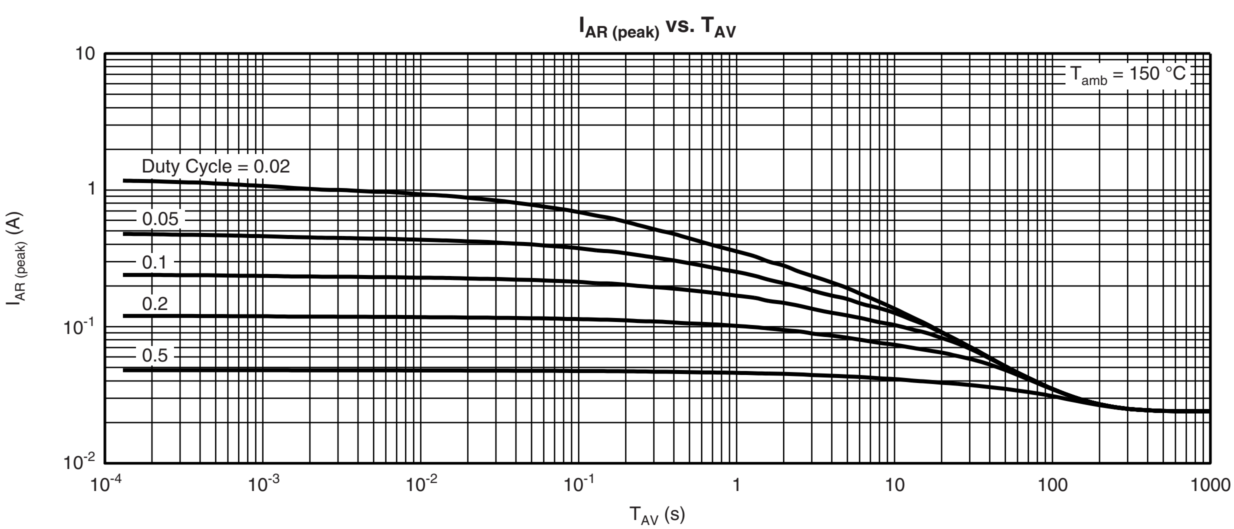

Fig. 6 - Shows plots of I_{AR} (A) vs. T_{AV} (s) for T_{amb} = 150 °C or ΔT = 25 °C for duty cycles 0.02 to 0.5

Power MOSFET in UIS/Avalance Applications

SUMMARY

Extensive testing is required to determine if a MOSFET can sustain a given repetitive UIS operating condition. The above approach, which relies on datasheet information including maximum and steady-state junction temperature, junction-to-ambient thermal resistance, and normalized thermal transient impedance junction to ambient characteristics $Z_{th(j-a)}$ of the device on a standard PC board assembly, allows us to estimate device performance in both single pulse and repetitive avalanche mode operation.

The characteristics shown in figures 2, 3, and 4 enable a designer to relate the ability of the system to handle peak single pulse avalanche current, I_{AS}, versus time, and shows the corresponding useable maximum inductance values and maximum single pulse energy.

The characteristics shown in figures 5 and 6 show the impact of repetitive peak avalanche current, I_{AR} versus time in avalanche, T_{AV} at $T_{J\ (Start)}$ 25 °C, and 150 °C.

The superior performance of real-life automotive printed circuit board designs can indirectly provide additional safe design headroom when these guidelines are followed.

A robust design should include recirculation components to quench the energy stored in the inductor and thus minimize the stress upon and risk of failure for the MOSFET.

Designers should also take care that optimization and cost-cutting measures do not result in overstressing the MOSFET.

The power MOSFET's capability to survive UIS is determined by the thermal capabilities of the device itself and the PCB assembly. In practical and sound designs, the MOSFET needs to operate within its thermal limits as determined by such parameters as circuit inductance, avalanche energy, time in avalanche, duty cycle, current and voltage rating, in addition to the transient thermal properties of the MOSFET and the PCB assembly.

The author would like to thank Ibrahim Darwish for his valuable technical inputs to this article.

REFERENCE

[1] Vishay Siliconix Power MOSFET SQM110N04-03 Datasheet URL: www.vishay.com/doc?68605

[2] Vishay application note AN601 "Unclamped Inductive Switching Rugged MOSFETs for Rugged Environment" Application Note URL: www.vishay.com/doc?70572