ABSTRACT

In hot-swap circuits, series-limiting devices such as MOSFETs are used to control start-up inrush and fault currents. During these transient events, the MOSFET dissipates power greater than steady-state and can well exceed the thermal limits of the MOSFET. These factors require consideration when selecting the MOSFET. This application report describes the steps required to properly choose a MOSFET that can meet the power dissipation requirements under all of the event areas. An example using the Texas Instruments TPS2490 hot-swap controller and International Rectifier IRF540NS MOSFET is discussed in this document. Figure 1 shows the schematic of this circuit.

1 Protection from the Power Supply and Inductive Kick

To protect the MOSFET from inductive transients, a designer must consider the MOSFET device drain-to-source voltage ($V_{ds}$) rating. When voltage transients occur as the MOSFET shuts off during faults, large current changes can occur in a short time, resulting in a voltage spike due to parasitic circuit inductances (PCB, wiring, interconnect, and MOSFET leads). In the Figure 1 example with the IRF540NS, the current through the MOSFET is limited to approximately 125 A during an output short due to saturation. By noting that the internal drain inductance of this transistor is 4.5 nH, the internal source inductance is 7.5 nH, the fall time is 35 ns, and $V = L \frac{di}{dt}$, the voltage across the transistor from inductive kick during the clearing of a fault can be about 43 V. (This calculation neglects additional parasitic inductance because it is designed for a worst-case scenario of $I_d$ for a junction temperature of 175°C.) For the example with the TPS2490, the power supply is 48 V. Therefore, the MOSFET needs a $V_{ds}$ or $V_{dss}$ rating of at least 43 V + 48 V or 91 V. The IRF540NS meets this specification with a $V_{ds}$ rating of 100 V.

Further input protection may still be required for the MOSFET. Depending on the particular design, it may be advisable to use a transient voltage suppressor (TVS) diode. This diode shunts excess transient current to control the peak voltage and offer protection for the downstream circuit. In this example, the TPS2490 uses an SMAJ60A TVS diode.
Gate-to-Source Voltage ($V_{gs}$)

The designer must ensure that the MOSFET can handle the maximum gate driver output voltage of the hot-swap controller. MOSFETs with a ±20-V limit are common and are usually sufficient. For the TPS2490, the maximum gate output voltage is 16 V. Therefore, it is advised to use a MOSFET with $V_{gs\,\text{max}}$ of 20 V.

If such a rating is infeasible for a particular design, a gate-to-source clamp Zener diode can be used. This can be accomplished with the use of the BZX84C7V5 gate clamp diode with the TPS2490 as mentioned in the applications section of its data sheet. Also note that gate drivers are capable of providing sizable currents that require series impedance before the diode for protection of the diode itself.

2 Thermal Protection

One of the most important characteristics of a transistor in a hot-swap application is its ability to dissipate the power of the specific application without overheating. The device needs to withstand steady-state, start-up and fault power dissipation.

Initial Calculations: Finding necessary $R_{\text{dson}}$ of MOSFET

From Figure 1, this application calls for an input voltage $V_{CC}$ of 48 V with a 4-A nominal output current, (and a peak current limit of 5 A). To determine the amount of power the MOSFET must dissipate, first determine a starting value of $R_{\text{dson}}$. $R_{\text{dson}}$ needs to have a maximum limit because the design needs to prevent a sizable voltage drop across the transistor to preserve efficiency. From the TPS2490 design tool, the maximum $R_{\text{dson}}$ based on efficiency can be found as:

$$R_{\text{dson\,(max)\,\text{eff}}} = (1 - \left(\frac{E_{\text{ff}}}{100}\right)) \times \left(\frac{V_{CC\,\text{max}}}{\text{I}_{\text{load}}}\right) - R_{\text{sense}}$$

$$R_{\text{dson\,(max)\,\text{eff}}} = (1 - \left(\frac{98}{100}\right)) \times (48 \div 4) - 0.01 = 0.23 \Omega$$

Where:
- $E_{\text{ff}}$ = Desired efficiency in percent
- $V_{CC\,\text{max}}$ = Maximum power supply voltage
- $I_{\text{load}}$ = Maximum continuous load current
- $R_{\text{sense}}$ = Sense resistor value

Furthermore, $R_{\text{dson\,(max)}}$ also needs to satisfy a PG (power good) requirement for this device. This requirement can be seen as follows:

$$R_{\text{dson\,(max)\,\text{PG}}} = \left(\frac{\text{PG}_{\text{thrshld}}}{\text{I}_{\text{final}}}\right)$$

$$R_{\text{dson\,(max)\,\text{PG}}} = \left(\frac{0.8}{5}\right) = 0.16 \Omega$$

Where:
- $\text{PG}_{\text{thrshld}}$ = Minimum power good threshold voltage
- $\text{I}_{\text{final}}$ = Final current limit set point

The maximum value for $R_{\text{dson}}$ is limited by the minimum of these two calculations; so, $R_{\text{dson\,(max)}}$ is 0.16 Ω. The preceding calculations are merely to find a starting value of $R_{\text{dson}}$ with which to iterate. The $R_{\text{dson}}$ limit must be met at the highest operating junction temperature.

Now that minimum ratings for $V_{ds}$ and $V_{gs}$ have been established and a maximum rating for $R_{\text{dson}}$ has been calculated, a choice can be made for a preliminary transistor to place in the design for verification. The IRF540NS is chosen for this application with $V_{dss} = 100$ V, $V_{gs} = \pm 20$ V, and $R_{\text{dson}} = 44$ mΩ at 25°C.

Verifying Initial Transistor Choice: Steady State

The data sheet of the IRF540NS shows that the maximum junction temperature ($T_j$) is 175°C. The designer must target the maximum junction temperature based on the particular derating rules and reliability requirements. A good initial value is 125°C if these are not specified. For transient conditions, consider it acceptable to have a junction temperature of 150°C. These margins are based off the Telcordia SR-332 long-term reliability metrics for a ten-year life with a 90% confidence level. This provides a margin of safety in the analysis. If calculations exceed these design limits, a larger MOSFET capable of dissipating more heat may need to be chosen.

For the steady-state case, $T_j$ (operating) yields the following:
\[ T_{j(op)} = \left( T_{A_{\text{Max}}} + R_{\theta JA} \times R_{\text{dson-temp}} \times I_{\text{load}}^2 \right) \]

(3)

Where:
- \( T_{j(op)} \) = the operating junction temperature
- \( T_{A_{\text{Max}}} \) = the maximum ambient temperature at which the device is expected to run for long periods continuously: 70°C (Note: this number is based on the extreme operating case of a common application: telecommunications buses and equipment.)
- \( R_{\theta JA} \) = the junction to ambient thermal resistance for the particular board/copper configuration specified (from MOSFET data sheet) (40°C/Watt)
- \( R_{\text{dson-temp}} = R_{\text{dson}} \) at the junction temperature the device is running (from graph on the MOSFET data sheet multiplied by \( R_{\text{dson}} \) at 25°C, approximately = 1.4 \times 44 \text{ m\Omega} = 61.6 \text{ m\Omega} \) at assumed \( T_J \) of 90°C) (Note: this leads to an iterative calculation.)
- \( I_{\text{load}} \) = the maximum continuous load current (4 A from Figure 1)

\[ T_{j(op\_steady\_state)} = \left( 70 + \left( 40 \times 0.0616 \times \left( 4 \right)^2 \right) \right) = 109°C \]

(4)

After updating the assumed \( T_J \) to 109°C, \( R_{\text{dson-temp}} \) can be updated, and the calculation can continue to be iterated until convergence. This eventually leads to a \( T_{j(op\_steady\_state)} \) of about 133°C. This temperature is higher than the design goal of 125°C, so it can be inferred that the MOSFET does not fall into the specification to last for ten years with 90% confidence at the most extreme telecommunications operating temperature. However, it also will not fail immediately as it does not closely approach or surpass 175°C. This may be more of a concern for some and not others. Therefore, the designer must consider what a realistic long-term operating temperature is and what kind of lifetime the application needs to have.

**Verifying Initial Transistor Choice: Output Fault and Inrush Current**

Again, when looking at output faults or inrush current during start-up, the key is to analyze the junction temperature and current limit.

**Output Faults:**

One of the key pieces of information needed when determining whether a transistor can handle the thermal stresses presented in a design is the time it takes to shut off the transistor during a fault. For the TPS2490, an initial shutoff occurs when the fault is first recognized and then the controller checks for a time to see if the fault is still present. This time is referred to as the fault timer period. The fault-retry duty cycle is quite small, (1.0% maximum). This small duty cycle often reduces the average short-circuit power dissipation to levels associated with normal operation and eliminates special thermal considerations for surviving a prolonged output short.

Because it has already been verified that the MOSFET can handle normal operation, the only circumstance with which to be concerned in this case is the initial moment that the fault occurs, not the fault-retry. In most applications, this is the only thing to check for in the output fault case because not all controllers have a fault-retry feature.

To check if the MOSFET can withstand a short-circuit, use the following equation:

\[ T_j = T_{j(op\_steady\_state)} + \left( P_d \times Z_{\theta JA\_norm} \times R_{\theta JA} \right) \]

or

\[ T_j = T_{j(op\_steady\_state)} + (P_d \times Z_{\theta JA}) \]

(5)

Where:
- \( T_j \) = the junction temperature
- \( T_{j(op\_steady\_state)} = 133°C \) from the steady-state calculations previously
- \( P_d \) = the power dissipated (calculated via \( P_d = I_{\text{fault}} \times V_{\text{fault}} \))
- \( Z_{\theta JA\_norm} \) and \( Z_{\theta JA} \) = the normalized and absolute transient thermal impedance (characteristic of MOSFET displayed on a graph in the relevant data sheet)
- \( R_{\theta JA} \) = the junction to ambient thermal resistance (from MOSFET data sheet) (40°C/Watt)
The transient thermal impedance is provided in the form of a graph that gives the thermal impedance versus power pulse duration and duty cycle. The graph’s single-pulse data is appropriate for many hot-swap applications. Such a graph for the IRF540NS for this example appears in Figure 2:

![Graph of Transient Thermal Impedance](image)

**Figure 2. Transient Thermal Impedance (IRF540NS)**

Many manufacturers give the transient thermal impedance of either the junction-to-case ($Z_{θ_{JC}}$), the junction-to-ambient ($Z_{θ_{JA}}$), or the junction-to-lead ($Z_{θ_{JL}}$) interface. The familiar $R_{θ_{JA}}$ is simply the steady-state value of $Z_{θ_{JA}}$, which is sometimes presented as normalized to $R_{θ_{JA}}$. Although $Z_{θ}$ is used as a variable, it is not a complex impedance, but is a factor that relates the peak junction temperature to the dissipation of a rectangular power impulse or train of impulses.

From the TPS2490 data sheet, the large overload response time to gate low, turning the MOSFET off, is 1.2 µs.

Note: This number is under specific test conditions; specifically $V_{sense} = 200$ mV. For small overloads, such as when $V_{sense}$ is 57 mV, this response time can be slower, closer to 2 µs to 2.5 µs. In Figure 15 of the TPS2490 data sheet, with the time scale at 1 µs/division, this response to gate low is approximately 2.5 µs. Further, the turnoff delay time of the IRF540NS is 39 ns and its fall time is 35 ns. In this way, the short-circuit current lasts for an estimated 2.574 µs. In Figure 2, the shortest pulse duration is 10 µs, which is used now to demonstrate the calculation. Because this example deals with a single pulse, look at the lowest curve at 10 µs, yielding a $Z_{θ_{JC}}$ of about 0.022°C/W.

To calculate the short-circuit current, consider the following at a $T_j$ of 133°C from the preceding calculations. (Note: $R_{θ_{JL\_temp}}$ now equals 98.56 mΩ.) Initially, it may seem that the current is merely:

$$I_{fault} = \frac{48V}{(0.01\ \Omega + 0.09856\ \Omega)} = 442 \text{ amps}$$

(6)

However, during this short, the MOSFET receives nearly the entire 48-V supply voltage from drain-to-source. Looking at the 175°C Id-Vds curve of the IRF540NS with a 15-V gate voltage, the maximum current is limited to approximately 125 A as the MOSFET enters saturation.

Another thing to consider is that even an $I_{fault}$ of 125 A may not necessarily be achieved during an output short. Due to inductance in the lines, the current may not necessarily be able to get to such a level in a few microseconds as the inductance naturally limits rapid changes in current. Further, impedance in the lines causes voltage drops, so that 48 V does not truly occur across the MOSFET. For calculation purposes, however, $I_{fault}$ is set to 125 A as a worst-case scenario. For power dissipation purposes, assume that this is equivalent to a constant current of half of this, or 62.5 A.

In this way, the equations become:

$$P_d = I_{fault\_avg} \times V_{fault} = 62.5A \times 48V = 3000 \text{ watts}$$

$$T_j = T_{j\_cp\_steady\_state} + (P_d \times Z_{θ_{JC}}) = 133 + (3000 \times 0.022) = 199°C$$

(7)
Once again, the design goal for long-term reliability has been exceeded, and it has exceeded the operational limit of 175°C. However, consider that these calculations use $Z_{\theta JC}$ at 10 µs and not 2.574 µs. Also consider that the time axis of the transient thermal impedance plot extends further to the left for shorter pulse durations, and note that the $Z_{\theta JC}$ is much lower. If it is lower by a large enough factor for a pulse duration of 2.574 µs, the junction temperature will be low enough during this fault to meet the design goal.

This is a realistic assumption by viewing the transient thermal impedance plot of another power MOSFET; the IRF1324S is shown in Figure 3. (Notice that $Z_{\theta JC}$ is about 7 times smaller at 2.5 µs than at 10 µs for a single pulse.)

$$T_j = T_{j(op\_steady\_state)} + (P_d \times Z_{\theta JC}) = 133 + (3000 \times 0.0031) = 142.3°C$$

This now yields a $Z_{\theta JC}$ of approximately 0.0031°C/W.

Therefore, $T_{j(op\_fault)}$ is about 142°C and within the design limits.

Inrush Current on Start-up:

By design, hot-swap controllers have built-in inrush current-limiting features. The TPS2490 takes this a step further with a constant power engine that limits power dissipation through the MOSFET. This creates an advantage over linear foldback in that it yields the maximum output current from a device over the full range of $V_{ds}$ while still protecting the device and the MOSFET.

In general, to determine if the chosen MOSFET can withstand start-up conditions, note that two regions of the start-up response must be considered. First, the current exceeds the current-limit threshold. This changes the temperature by the difference between steady-state and fault junction temperature; so, the initial $T_j$ point can be assumed to be 79°C. However, unlike a fault, the MOSFET does not shut off completely. In this second region, the MOSFET maintains the current at its limit of 5 A in this example until the output capacitor is fully charged. As this capacitor charges, the voltage difference across the MOSFET decreases, and the power dissipated decreases as well. As such, a waveform of $V_{ds}$ across the MOSFET appears as a negatively sloped triangle with a peak of 48 V. Figure 4 shows a plot of start-up from the TPS2490 data sheet, where VCC-OUT is $V_{ds}$. 
For power dissipation calculations, this plot of $V_{ds}$ is equal to the average seen as a rectangular waveform of a constant 24 V.

For the TPS2490, the output capacitor is 220 µF.

$$I = C(dV/dt) \Rightarrow \text{Charge time} = CV/I = \frac{220 \times 10^{-6}}{5} \times 48 = 2.112 \text{ ms}$$ \hspace{1cm} (9)

Note that $Z_{\theta JC} = 0.6$ for the 2.112-ms, single-pulse transient.

$$P_d = I_{\text{CurrentLimit}} (V_{ds}) = 5 \times 24 = 120 \text{ watts}$$

$$T_{J_{\text{inrush}}} = T_{J_{\text{initial}}} + (P_d \times Z_{\theta JC}) = 79 + (120 \times 0.6) = 151^\circ C$$ \hspace{1cm} (10)

Because this $T_{J_{\text{inrush}}} = 151^\circ C$ is very close to the transient design limit of 150°C, this verifies that the MOSFET is suitable for this start-up inrush event.

**Additional Methods**

Another method that is commonly used to test if a MOSFET can withstand certain DC or single-pulse currents or powers is through the use of a safe operating area (SOA) curve. These SOA curves usually assume a junction-temperature rise from a 25°C ambient to 150°C or 175°C. System-level thermal requirements often require operation at higher starting temperatures, and so data from the graph must be adjusted for a lower temperature rise as such:

$$\text{SOA}_T = \text{SOA}_{J_{\text{MAX}}} \times \frac{T_{J_{\text{MAX}}} - T}{T_{J_{\text{MAX}}} - T_{A}}$$ \hspace{1cm} (11)

where SOA$_T$ represents the SOA capability at arbitrary temperature T, SOA$_{J_{\text{MAX}}}$ represents the capability at a specific point on the manufacturer’s SOA curves, and $T_{J_{\text{MAX}}}$ and $T_{A}$ represent the peak and ambient junction temperatures assumed on the curves (e.g., 175°C and 25°C). SOA curves tend to mix die-heating and pad- or leadframe-heating effects. They do provide a quick way of verifying a design, if the curves for the expected fault duration are provided.

**SOA Derating Example**

Assume that you want to see if the IRF540NS can withstand start-up with the following conditions:

- $P_d = 120$ W, pulse width = 2.112 ms, operating junction temperature = 79°C, $T_{J_{\text{MAX}}} = 175^\circ C$, and $V_{IN_{\text{MAX}}} = 48$ V.

1. Using Figure 5, determine that at 48 V, for a period of 2 ms, a current of 5 A is allowed.
2. Calculate:

\[ SOA_T = SOA_{JMAX} \times \frac{T_{JMAX} - T}{T_{JMAX} - T_A} \]

\[ SOA_T = (48 \, V \times 5 \, A) \times \frac{175^\circ C - 79^\circ C}{175^\circ C - 25^\circ C} = 153.6 \, W \]  (12)

3. Because this result is greater than \( P_D \) in the beginning of the example, the device survives with some margin.
3 Conclusion

This application report shows how to verify the robustness of a transistor in a typical hot-swap application. Because the MOSFET has physical limits, one can analyze the voltage, current, power, and temperature that the design will place on the transistor. By using manufacturer data such as transient thermal impedance plots and safe operating area curves, one can visualize the MOSFET performance and have a quick reference tool to check designs. Further, with features such as power-limiting and current-limiting in devices such as the Texas Instruments TPS2490 hot-swap controller, analysis such as this becomes less important as the stresses placed on the external MOSFET are less.

4 References

1. *Hotswap Design Using TPS2490/91 and MOSFET Transient Thermal Response* application report (SLVA158)
2. TPS2490 / TPS2491 Design-In Calculation Tool (SLVC033)
3. TPS2490/TPS2491, Positive High-Voltage Power-Limiting Hotswap Controller data sheet (SLVS503)
4. IRF540NS/IRF540NL Power MOSFET data sheet, PD–91342B, International Rectifier
5. IRF1324S-7PPbF Power MOSFET data sheet, PD–97263A, International Rectifier
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