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APPLICATION NOTE 4883

# Oscilloscope Math Functions Aid Hot-Swap Circuit Analysis

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*Abstract: Digital oscilloscopes are the norm in most engineering labs, but the chances are that you have not fully explored their features. Among the more interesting features of a digital oscilloscope is the "math" channel, which can be applied in novel ways to simplify and expand the analysis of hot-swap and load-switching circuits. This application note shows how to connect the oscilloscope's probes to a hot-swap circuit to obtain accurate values for MOSFET power dissipation and load capacitance. The MAX5976 hot-swap solution serves as the example device.*

A similar version of this article appeared in the October 1, 2011 issue of *Test & Measurement World* magazine.

## Introduction

Among the more interesting features of a digital oscilloscope is the "math" channel, which can be applied in novel ways to simplify and expand the analysis of hot-swap and load-switching circuits. With clever use, oscilloscope math functions enable the calculation of load capacitance or reveal the transient power dissipation in a MOSFET during startup or shutdown. Math functions can yield detailed real-world information about hot-swap circuit parameters that are otherwise subject to approximations and estimates. Such information is invaluable, both for design and for troubleshooting of hot-swap and load-switching circuits.

This application note shows how to connect the oscilloscope's probes to a hot-swap circuit to obtain accurate values for MOSFET power dissipation and load capacitance.

## Oscilloscope Setup

For simplicity in this demonstration, we chose the MAX5976 hot-swap solution, which combines an internal MOSFET switching element with the current-sensing and driver circuitry necessary to implement a complete power-switching circuit. (The following test method also applies to hot-swap control circuits built from discrete components.) By connecting scope probes to the hot-swap circuit as shown in **Figure 1**, the oscilloscope can access the signals needed for calculations. Voltage probes connected to the input and output provide the voltage drop across the MOSFET; a current probe offers the easiest way to sense load current through the MOSFET.

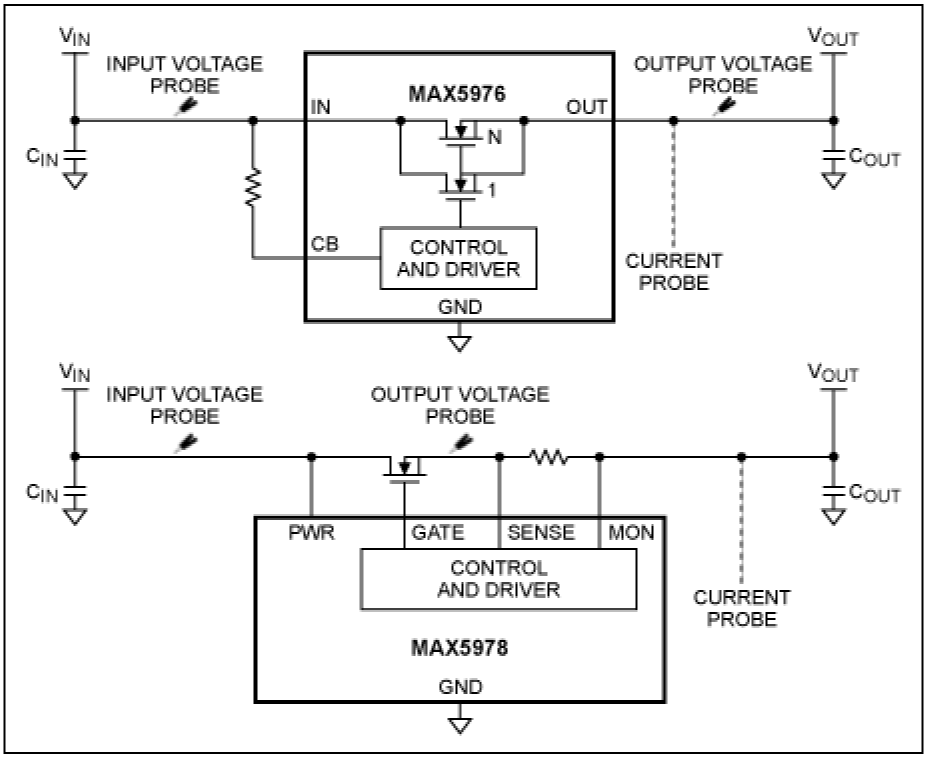
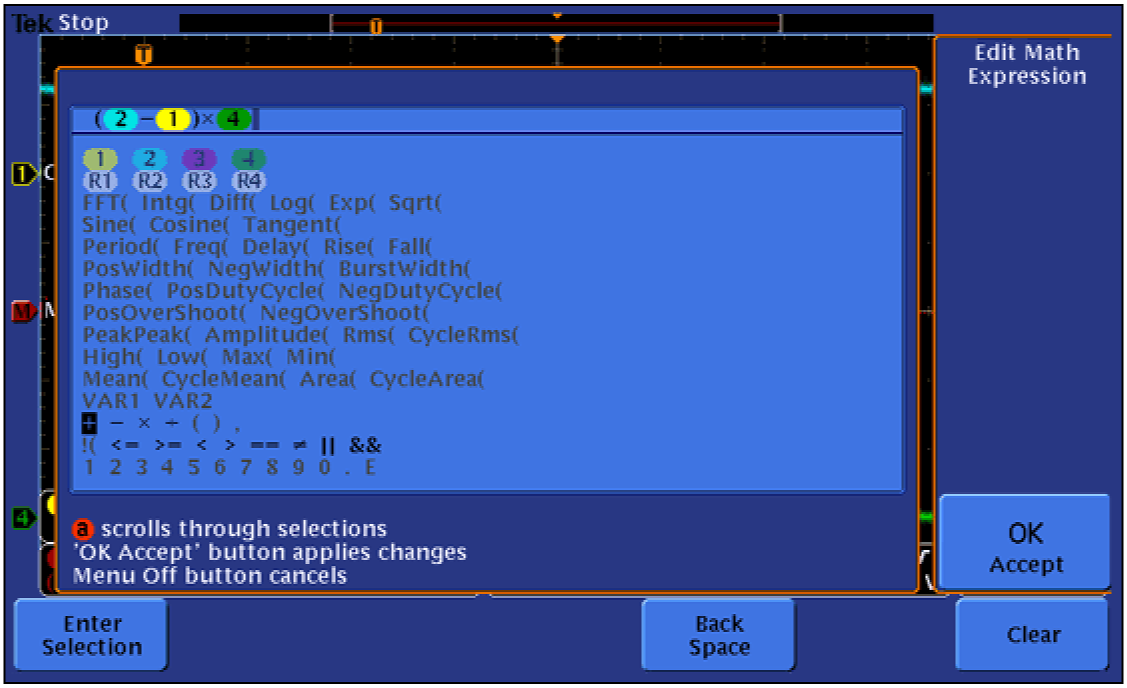


*Figure 1. Scope probes connect to the MAX5976 and MAX5978 hot-swap circuits. These oscilloscope connections obtain waveforms that feed the scope's advanced math function.*

Note that the same basic connections apply for a nonintegrated hot-swap circuit. Connect the input- and output-voltage probes before and after the MOSFET (internal to a MAX5976, external to a MAX5978), and place the current probe in series with the circuit's current-sense resistor. To get an accurate measure of current flowing through the switch element itself, you should place the current probe after the input bypass capacitance and before the output capacitance.

## MOSFET Power Dissipation

Power dissipation in the switch element (typically an n-channel MOSFET) is the product of drain-to-source voltage ($V_{DS}$) and drain current ($I_D$). In our test setup, $V_{DS}$ is the difference between channel 2 and channel 1, and $I_D$ is measured directly by the current probe. The oscilloscope used in this example (a Tektronix® DPO3034) has a math trace that is configured through an advanced math menu (**Figure 2**).



a scrolls through selections
'OK Accept' button applies changes
Menu Off button cancels

*Figure 2. This menu lets you edit math expressions in the advanced math function of a DPO3034 digital oscilloscope.*

To measure power dissipation in the MOSFET, simply enter an expression that subtracts channel 1 from channel 2. Multiply the result by the current-probe signal. When the hot-swap circuit is enabled, its output voltage rises toward the input potential at a particular dV/dt slew rate. The load-capacitance charging current ($I_D$) flows through the MOSFET according to:

$$I_D = C_{OUT} \times dV/dt$$

Capturing this startup event on the oscilloscope yields the waveforms of **Figure 3a**, for which output capacitance is 360µF and $V_{IN}$ = 12V. The MAX5976 limits inrush current to 2A. Note that the power waveform is a decreasing ramp, starting at 12V × 2A = 24W and falling to 0W as the output rises to 12V. That behavior is exactly what we expect for a hot-swap circuit charging the load capacitance with a constant current.

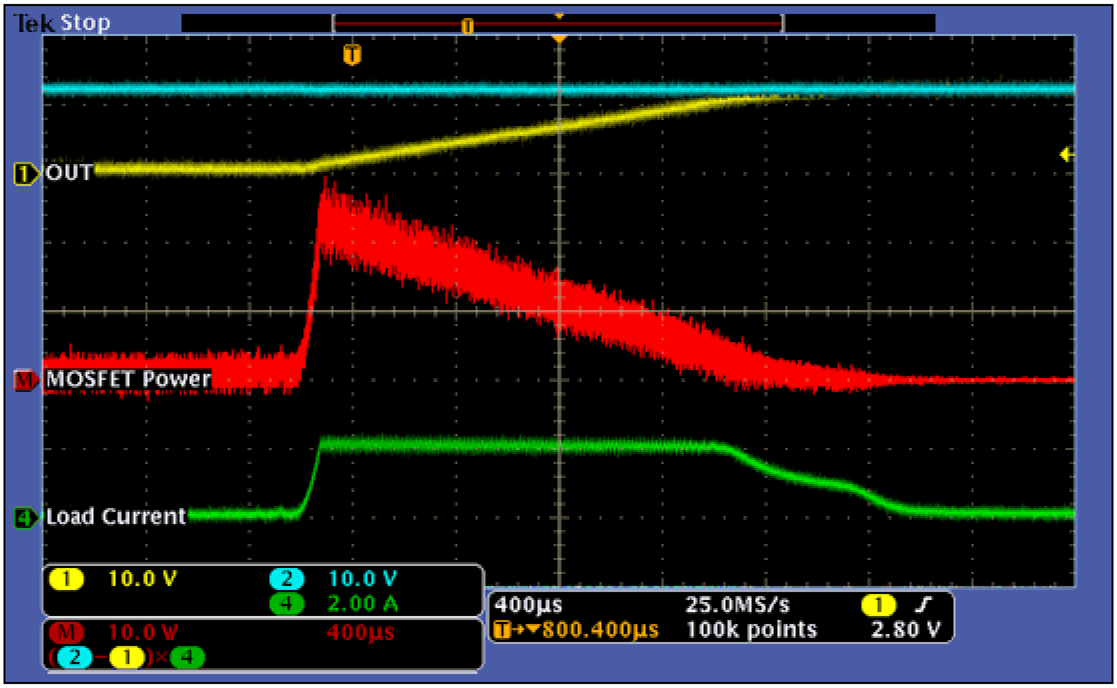


*Figure 3a. The MOSFET power dissipation for the circuit of Figure 1 is shown (red trace) for* $C_{OUT}$ = *360µF. Inrush current is clamped to 2A.*

Power waveforms measured in this way can be used to determine whether the MOSFET is within its safe operating area (SOA), or to estimate the rise of its junction temperature by referring to relevant charts in the MOSFET data sheet. Determining the waveform directly from actual measurements eliminates the error inherent in approximating power dissipation. Moreover, the power waveform can be accurately captured during a startup event for which neither the inrush current nor the dV/dt is constant (**Figure 3b**).

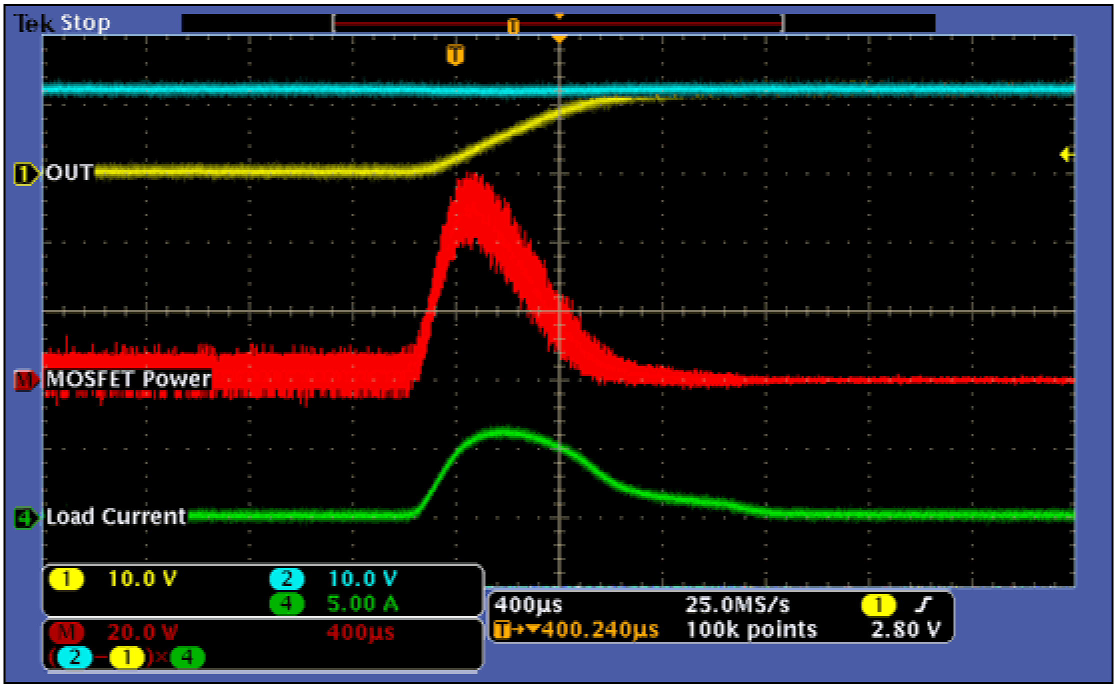


*Figure 3b. A power waveform is accurately captured during a startup in which neither the inrush current nor the dV/dt is constant. Here the inrush current is unclamped.*

If the math function in your oscilloscope includes an integration operand, this waveform calculation can be taken one step further to show the total energy deposited in the MOSFET during any event that results in significant power dissipation in the FET. **Figure 4** applies the integration function to the MOSFET's power information.

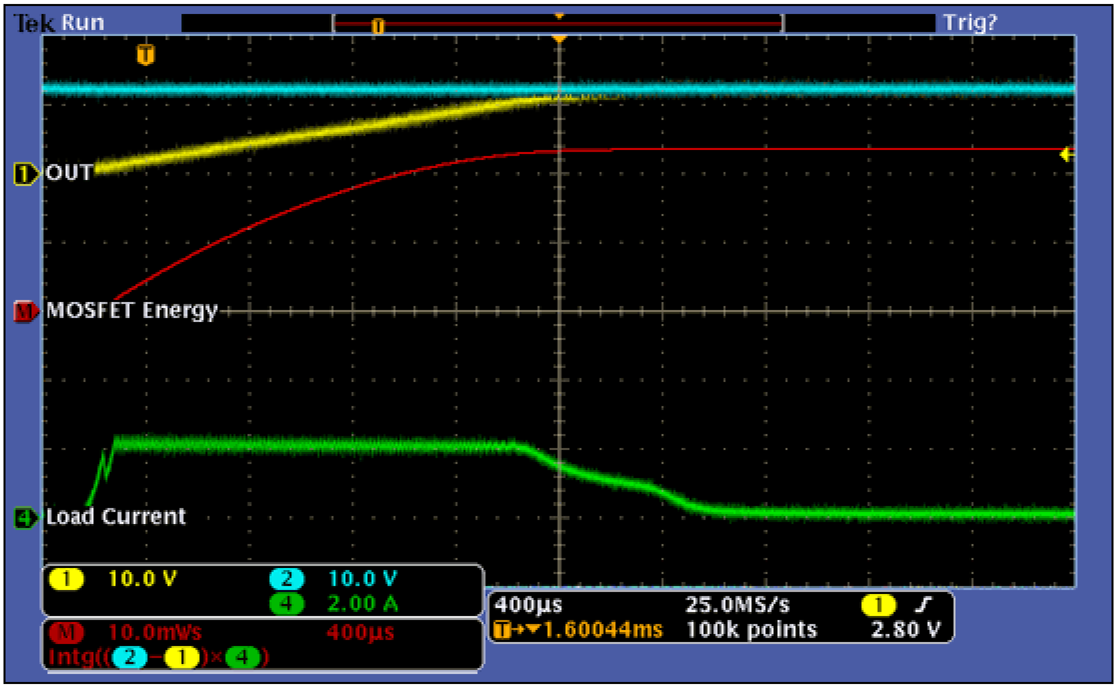


*Figure 4. Integration of power dissipation yields the total energy deposited in the MOSFET of Figure 1*

*during startup.*

As in Figure 3a, $C_{OUT}$ is 360µF and the inrush current is clamped to 2A. Because the power waveform has a triangular shape with a startup duration of about 2ms, we expect about 24W/2 × 2ms = 24mJ of energy to be converted to heat in the MOSFET. Indeed, the math channel's integral of power reaches almost exactly 24mWs (= 24mJ) of energy at the end of the startup event!

Obviously, this technique can also be applied to other transient conditions that affect the MOSFET, such as a shutdown and short-circuit or overload events. Such detailed power and energy information can be used to make precise calculations of pulse duration and single-pulse power when checking the MOSFET's SOA and thermal characteristics.

## Measuring Load Capacitance

Among the math functions of a digital oscilloscope, the integration operand can also be used to measure hot-swap load capacitance—provided that the resistive load current is small during startup.

Capacitance is the amount of charge stored per volt applied to the capacitor; charge is simply the time integral of current. Therefore, by integrating the hot-swap inrush current and dividing by the output voltage, an oscilloscope's math function can measure the total load capacitance with surprising accuracy. In **Figure 5a**, the hot-swap controller is enabled with three ceramic output capacitors, each with a nominal value of 10µF. The math trace is initially meaningless because of the divide-by-zero problem before $V_{OUT}$ rises. However, when $V_{OUT}$ exceeds zero, the math channel quickly converges to a measured capacitance of approximately 27µF. Note that the math function units for this integral are not represented properly—modern digital scopes are amazing, but they still cannot read our minds or understand our intentions!

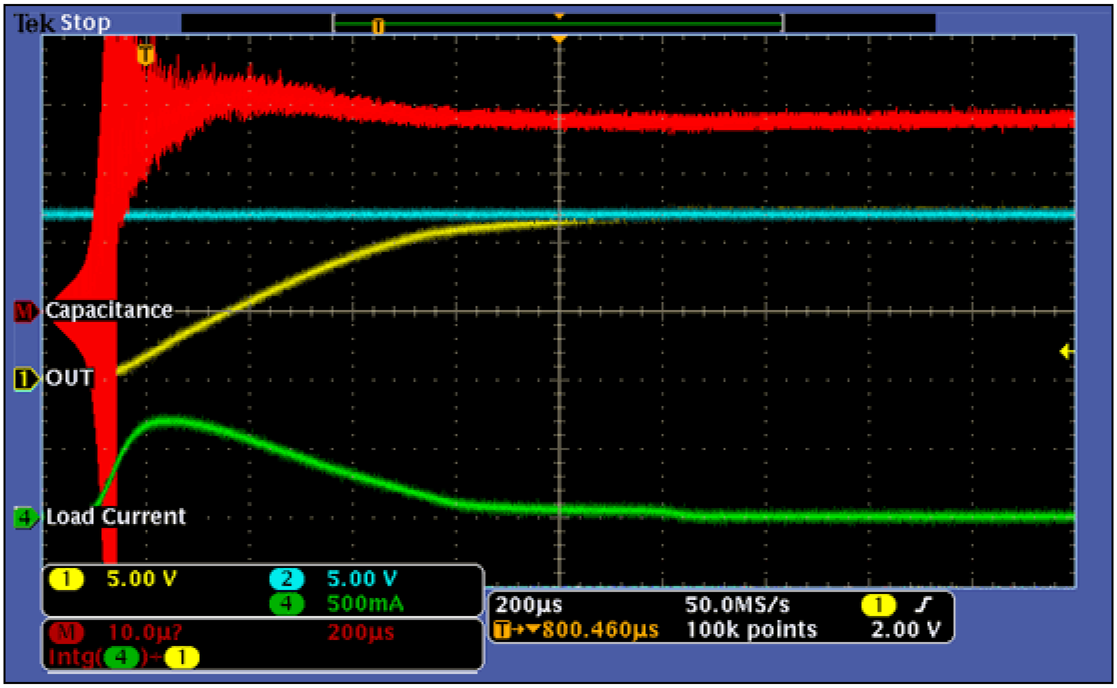


*Figure 5a. Output capacitance measurement from Figure 1 with $C_{OUT}$ = 30µF.*

**Figure 5b** repeats the experiment of Figure 5a, but with an additional aluminum electrolytic capacitor of nominal value 330µF added to the output. Note that as the startup event ends, the math trace shows a measured output capacitance of approximately 360µF—almost exactly what we expect. Remember that a resistive load degrades the accuracy of these capacitance measurements by drawing current that is not stored in the capacitor. For short-duration measurements, however, the results can still be very useful.

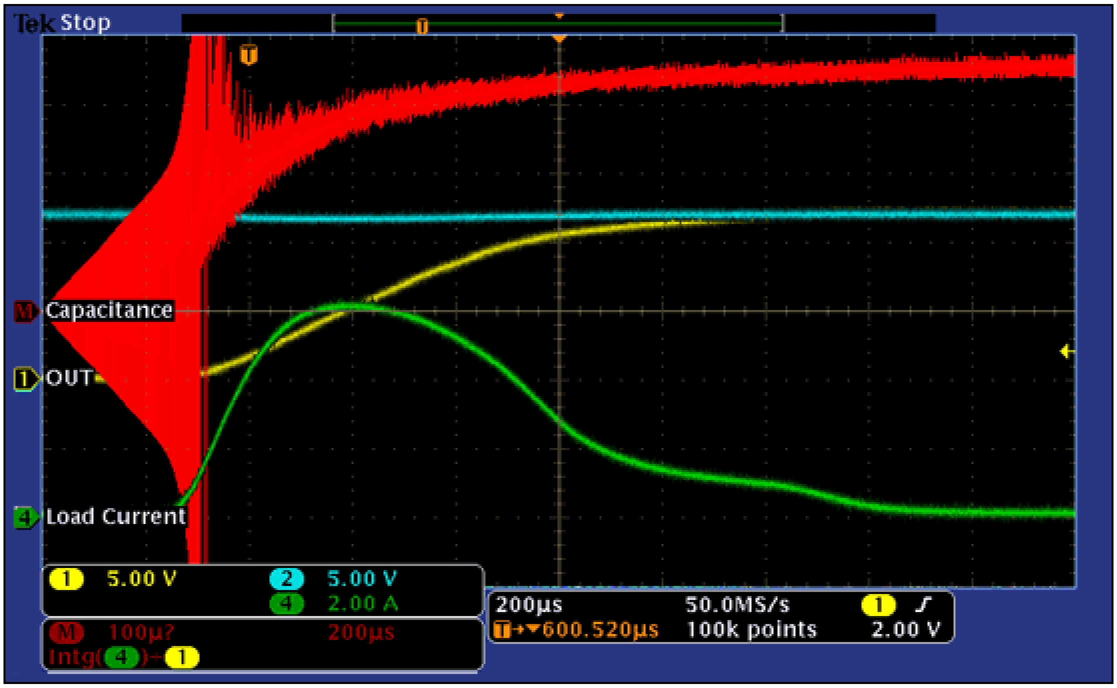


*Figure 5b. Output capacitance measurement from Figure 1 with $C_{OUT}$ = 30µF + 330µF.*

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