

Understanding ECO-MODE™ Operation

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ABSTRACT

The efficiency of dc/dc converters is defined as:

$$\eta = \frac{PowerOut}{PowerIn} = \frac{PowerOut}{PowerOut + PowerDissipated} \quad (1)$$

To maximize efficiency, the output power must be maximized or the power dissipation must be minimized. When the load current is low, the output power will also be low, so the only way to increase efficiency at light loads is to reduce power dissipation in the converter. The losses in a dc/dc converter can generally be divided into three categories; conduction loss, switching loss and quiescent loss. Conduction losses occur as the result of the direct current flowing through resistive elements, primarily the high and low side switching elements and the output inductor. These will naturally decrease as the load current decreases. Quiescent losses are those associated with the internal losses of the converter control. These losses are mostly constant and fixed for a particular controller. Switching losses occur during the switch transition times. So long as the converter is switching, they will occur and are independent of load current.

Certain SWIFT™ dc/dc converters feature a unique low power operating mode called Eco-mode™. This mode is designed to allow higher efficiencies at low output currents than would normally be achievable. Since the conduction losses and quiescent losses are generally fixed for a given load, Eco-mode™ increases efficiency by reducing switching losses at low output currents.

The SWIFT™ devices that implement Eco-mode™ can be divided into two families. One family comprises of the mid-range input voltage devices; TPS54231, TPS54232, TPS54233, TPS54331 and TPS54332. The second family comprises of the wide-range input voltage devices; TPS54040, TPS54060, TPS54140 and TPS54160. The general characteristics for each device is given in [Table 1](#). Characteristic data that is presented for a particular device is representative for that device family unless otherwise specified.

NOTE: There is more than one type of Eco-mode™ control. This application note specifically addresses Eco-mode™ operation activated by minimum COMP clamp voltage. It is not applicable to Eco-mode™ activated by zero crossing switch current or other any other method.

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1 Current Mode Control

For the SWIFT™ devices that feature Eco-mode™, current mode control is utilized. Each individual switching pulse is terminated when the peak current as determined by the COMP pin voltage is reached. During normal operation, increasing the load current above the output current of the supply causes the output voltage to drop slightly. This is sensed by the error amplifier which increases the COMP voltage. Now the on-time of the switching cycle is extended as the inductor current ramps up to the new peak current as set by the COMP pin voltage. When the load current is decreased, the converse takes place. The output voltage slightly increases, and the error amplifier reduces the COMP pin voltage. The on-time of the switching cycle is reduced as the inductor needs less time to ramp up to the lower set peak current. The relationship between peak switch current and COMP voltage is controlled by the COMP to switch current transconductance, gm_{PS} . The units are A/V and represent the change in peak current per unit step of COMP pin voltage. The gm_{PS} value for each Eco-mode™ device is shown in Table 1. This list is not inclusive of all existing and future devices, but is a sample showing typical characteristics.

Table 1. Eco-mode™ Device Characteristics

Device	Input Voltage Range	Rated Current	gm_{PS}	I_Q
TPS54040	3.5 - 42 V	0.5 A	1.9 A/V	116 μ A
TPS54060	3.5 - 60 V	0.5 A	1.9 A/V	116 μ A
TPS54140	3.5 - 42 V	1.5 A	6 A/V	116 μ A
TPS54160	3.5 - 60 V	1.5 A	6 A/V	116 μ A
TPS54140A	3.5 - 42 V	1.5 A	6 A/V	116 μ A
TPS54160A	3.5 - 60 V	1.5 A	6 A/V	116 μ A
TPS54240	3.5 - 42 V	2.0 A	10.5 A/V	138 μ A
TPS54260	3.5 - 60 V	2.0 A	10.5 A/V	138 μ A
TPS54231	3.5 - 28 V	2.0 A	9 A/V	75 μ A
TPS54232	3.5 - 28 V	2.0 A	10 A/V	85 μ A
TPS54233	3.5 - 28 V	2.0 A	9 A/V	75 μ A
TPS54331	3.5 - 28 V	3.0 A	12 A/V	110 μ A
TPS54332	3.5 - 28 V	3.0 A	12 A/V	82 μ A

2 Eco-mode™ Operation

As the output load current is lowered, the required peak current on each switching cycle is lessened and the COMP pin voltage is reduced by the error amplifier in the closed loop system. To enter Eco-mode™ operation, all which is required is that the converter is in regulation and the COMP pin voltage is lowered to 0.5 V nominal. When this occurs, the COMP pin voltage is clamped at 0.5 V, the high side FET is inhibited from switching and the device enters a low power consumption sleep mode. In sleep mode, the device only draws 116 μ A of quiescent current. Since the device is not switching, the output voltage will start to decay as energy is drawn from the output capacitors to supply the load current. As the output voltage decreases, the control loop will sense the decreased voltage at VSENSE and start to drive the COMP pin above the Eco-mode™ threshold voltage. At this time the device will leave sleep mode and resume switching, charging the output back to the desired output voltage level. Once the output is charged, the peak current demand will decrease and the COMP pin voltage will begin to fall back towards 0.5 V. When the COMP pin voltage reaches that point the device will then stop switching and enter sleep mode.

So Eco-mode™ consists of two states; a low power sleep mode where the output discharges and a period of switching where the output is recharged. The efficiency gains are due to the lack of switching losses and low quiescent current during the sleep time portion of Eco-mode™ operation.

3 Eco-mode™ Efficiency Gains

Figure 1 shows a typical improvement in light load efficiency that is potentially available with Eco-mode™. In the efficiency graphs, three devices are plotted; TPS54140, TPS54331 and TPS54620. For each efficiency plot, the input voltage is 12 V and the set output voltage is 3.3 V. The TPS54140 and TPS54331 both feature Eco-mode™ operation while the TPS54620 does not. The TPS54620 is rated for 6 A output and will offer higher efficiencies at higher output currents, but is shown here to compare light load performance against Eco-mode™ devices.

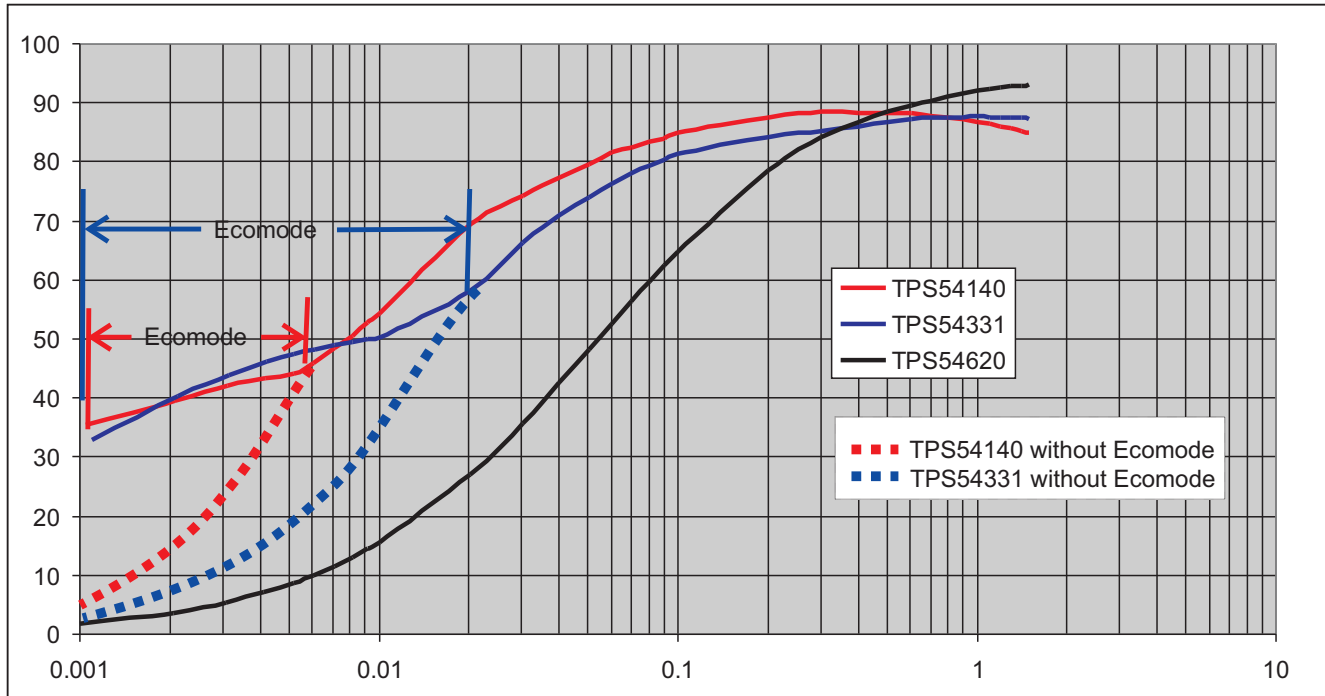


Figure 1. Eco-mode™ Efficiency Comparison

In the example above, Eco-mode™ operation begins at approximately 20 mA for the TPS54331 and 6 mA for the TPS54140. The dashed lines represent the projected efficiency for the TPS54331 and TPS54140 if Eco-mode™ were not present. You can see that for operation without Eco-mode™, efficiency falls off rapidly at light loads, decreasing to near 0 % at 1 mA. With Eco-mode™ operation, the efficiency remains above 30 % at 1 mA load and is significantly higher than the TPS54620 at load currents below 300 mA.

4 At What Current Does Eco-mode™ Operation Begin?

In theory, Eco-mode™ operation is straight-forward. The peak output current is proportional to the COMP voltage by a factor of gm_{PS} , when the COMP voltage falls to 500 mV, the device enters Eco-mode™. The output current of the converter is the peak current minus one half of the peak to peak inductor current. In actual practice, the Eco-mode™ threshold is much more difficult to predict. There are several design details internal to the integrated circuits which contribute to this uncertainty.

In a closed loop system the actual value of the COMP pin voltage is not important, only the transconductance gain characteristic. Internally, the output of the transconductance error amplifier is biased so that the COMP pin voltage is in the linear region for most of the output current operating range. So while gm_{PS} is a characterized parameter, the actual peak current corresponding to a COMP pin voltage of 0.5 V can only be estimated. Figure 2 shows the COMP pin voltage to peak current characteristic for the TPS54140. The performance is typical for this family of devices. The ratio of peak current to COMP voltage (gm_{PS}) is fairly constant above 240 mA. The measured gm_{PS} is about 5.1 A/V compared to the specified gm_{PS} of 6 A/V. At peak currents below 240 mA, the power stage transconductance is non linear down to the COMP pin clamp voltage.

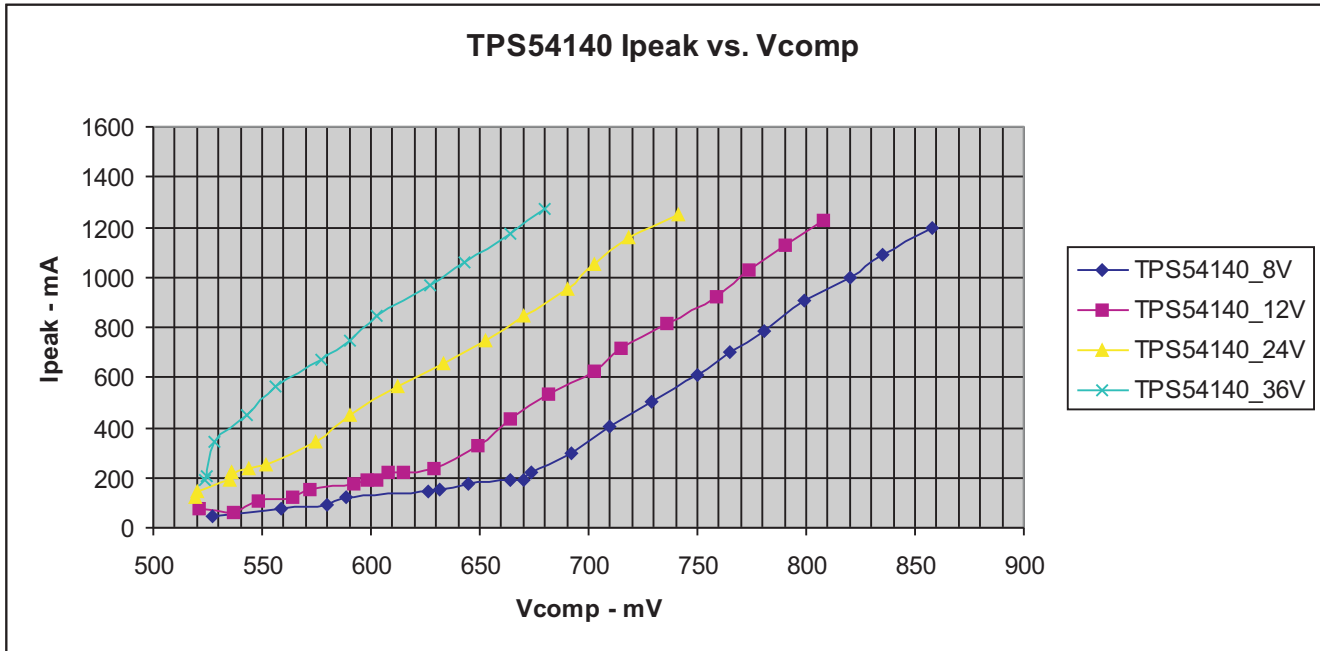


Figure 2. TPS54140 Typical Transconductance Curves

Figure 3 shows the COMP pin voltage to peak current characteristic for the TPS54331. The performance is typical for the TPS54331 family of devices. The ratio of peak current to COMP voltage ($g_{m_{PS}}$) is fairly constant above 650 mA to 800 mA, depending on the input voltage. The measured $g_{m_{PS}}$ is about 10 A/V compared to the specified $g_{m_{PS}}$ of 12 A/V. At peak currents below 650 mA to 800 mA, the power stage transconductance is non linear down to the COMP pin clamp voltage. Since the TPS54331 is a higher current device, the transconductance is higher and the bias point is also set higher to allow operation in the linear region for a wider portion of the output current range.

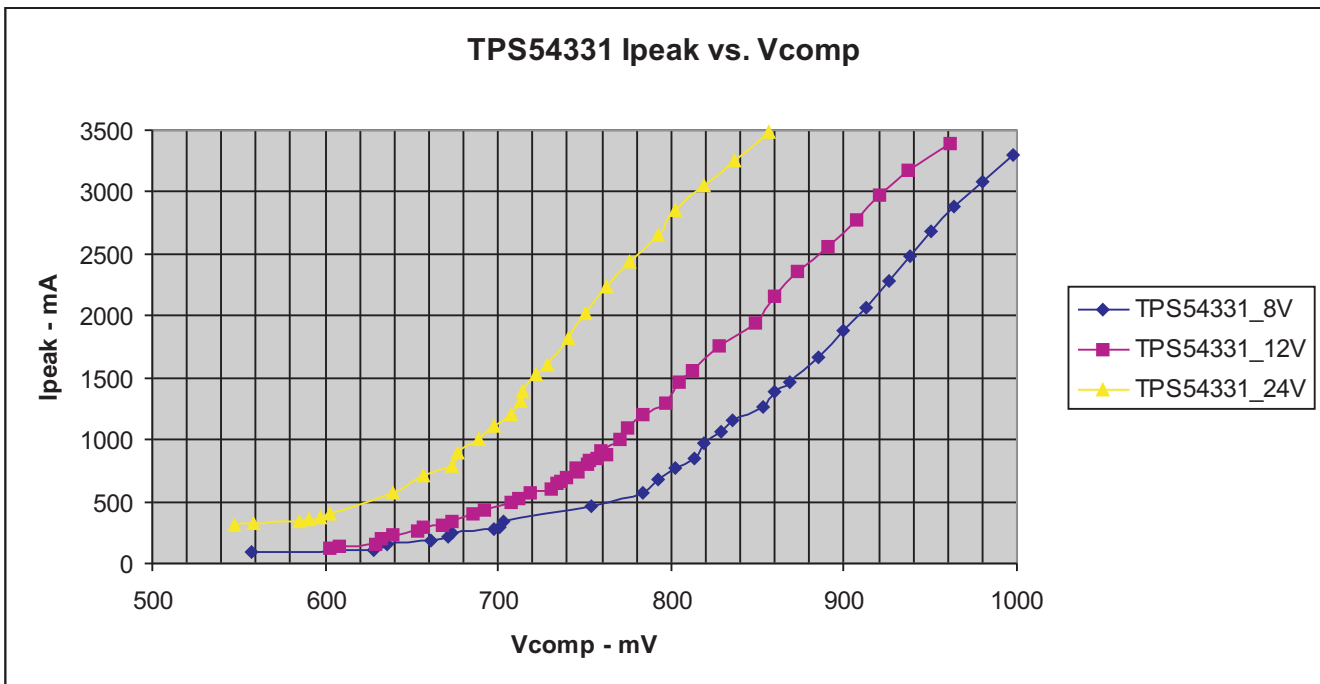


Figure 3. TPS54331 Typical Transconductance Curves

Figure 2 and Figure 3 above show that the linear relationship between the COMP pin voltage and peak switch current breaks down at lower currents. These lower current ranges are exactly the currents where Eco-mode™ operates. There is an additional observation that we can make from Figure 2 and Figure 3. The user can observe that there is shift in the transconductance curves with input voltage. This is not directly related to input voltage, but rather to duty cycle (V_{OUT} / V_{IN}). For current mode control, it is necessary to provide slope compensation to ensure stability at duty ratios above 50%. For the Eco-mode™ devices, slope compensation starts at 10% duty ratio, and increases as the duty ratio increases. Slope compensation effectively subtracts from the peak current obtainable for any particular cycle as the on time increases. The effect is that at higher duty cycles, a higher COMP pin voltage is required for a given peak current as shown in the above curves. This also changes the peak current at the COMP clamp voltage.

Not only is the power stage transconductance non linear, but the actual COMP pin clamp voltage is not fixed at 500 mV. Actual test data reveals that the average COMP pin clamp voltage is typically 541 mV for all Eco-mode™ devices. The variation on clamp voltage is shown depends on the device family. For the TPS54140 and other devices of that family, the standard deviation is 0.007 mV, while for TPS54331 devices, the standard deviation is 26 mV. Also while the TPS54140 clamp voltage is very stable across the operating temperature range, the TPS54331 devices may vary from 403 V to 603 mV typical.

As shown, there are three main components to variation Eco-mode™ threshold current; transconductance non-linearity, slope compensation effects, and variation in the COMP pin clamp voltage. Figure 4 shows the actual measured peak current at the Eco-mode™ start threshold for a typical TPS54140 and TPS54331 design. For these circuits, the COMP pin clamp voltage was 0.527 V for the TPS54140 and 0.553 V for the TPS54331. So with only the variation due to slope compensation, the Eco-mode™ threshold current can vary over a wide range. There is additional variation due to COMP clamp voltage variation as well. This variation is shown in Figure 4.

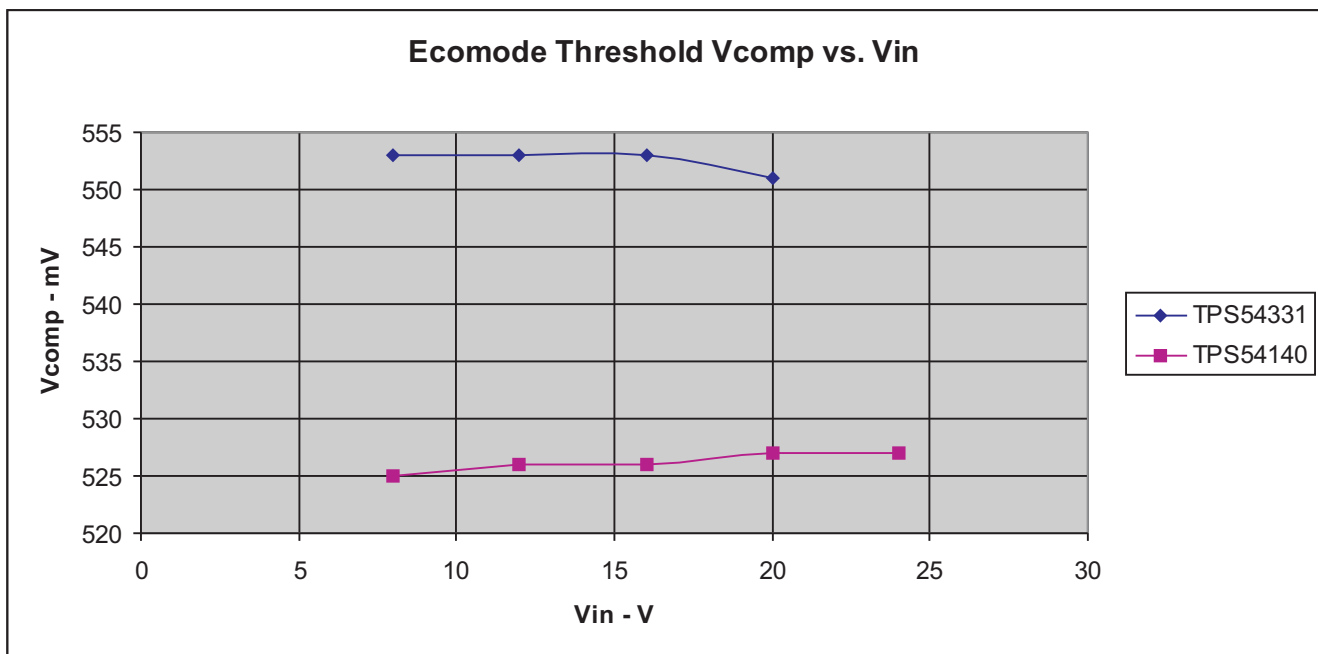


Figure 4. COMP Pin Clamp Voltage vs Input Voltage

Typically, the peak current threshold will be 150 to 160 mA, but may vary over the range of 20 to over 500 mA. Realize also that this is peak switch current not load current. The actual load current where Eco-mode™ is activated will depend the output inductor value as well. The peak switch current is:

$$I_{swpk} = I_{load} + I_{lpp} / 2 \quad (2)$$

So, the load current at which Eco-mode™ is activated will be reduced from the peak switch current by ½ the peak-to-peak inductor current. Measured data confirms this performance. The typical peak switch current and actual output currents at various input voltages for the TPS54140 and TPS54331 are shown in Figure 5

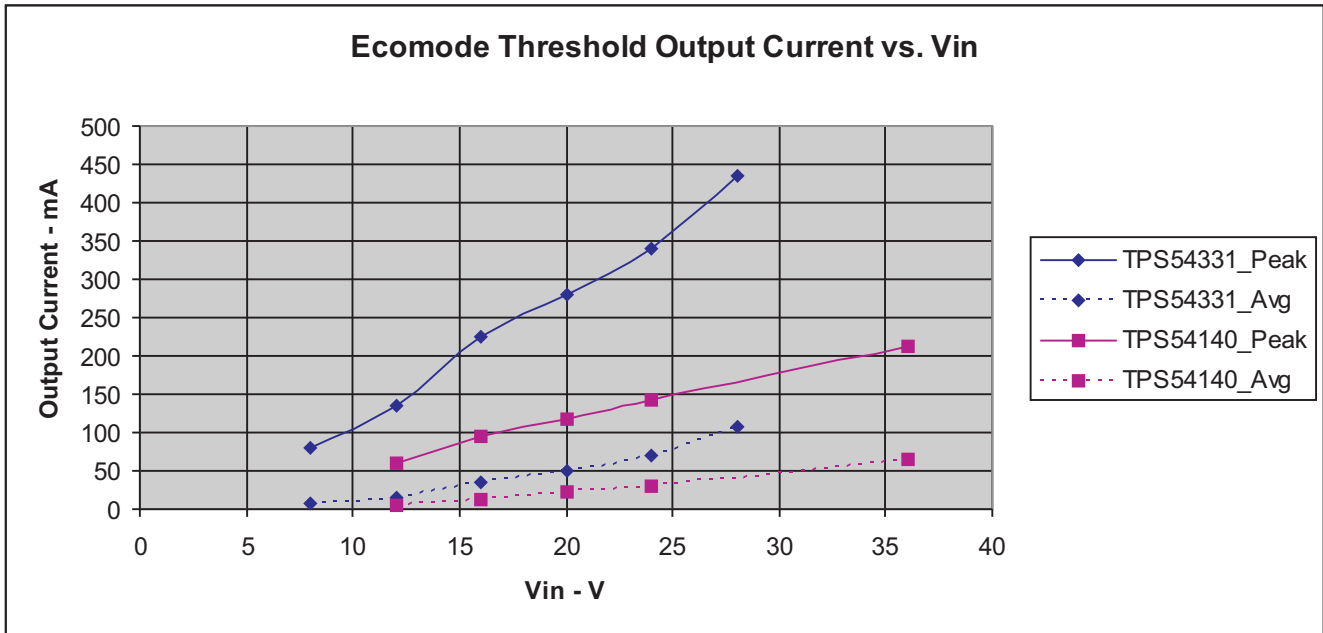


Figure 5. Eco-mode™ Output Current and Peak Switch Current

5 Trade Offs

There are trade offs involved with Eco-mode™ operation. First, during Eco-mode™ operation the output ripple voltage is increased. During sleep time, the device is not switching and the output is allowed to decay until the COMP pin voltage rises above the clamp voltage. Compare the output ripple voltage during continuous conduction operation in Figure 6 to the output ripple in Eco-mode™ operation in Figure 7. For both figures, the top trace is V_{OUT} , the middle trace is inductor current and the bottom trace is the switching node (PH) voltage.

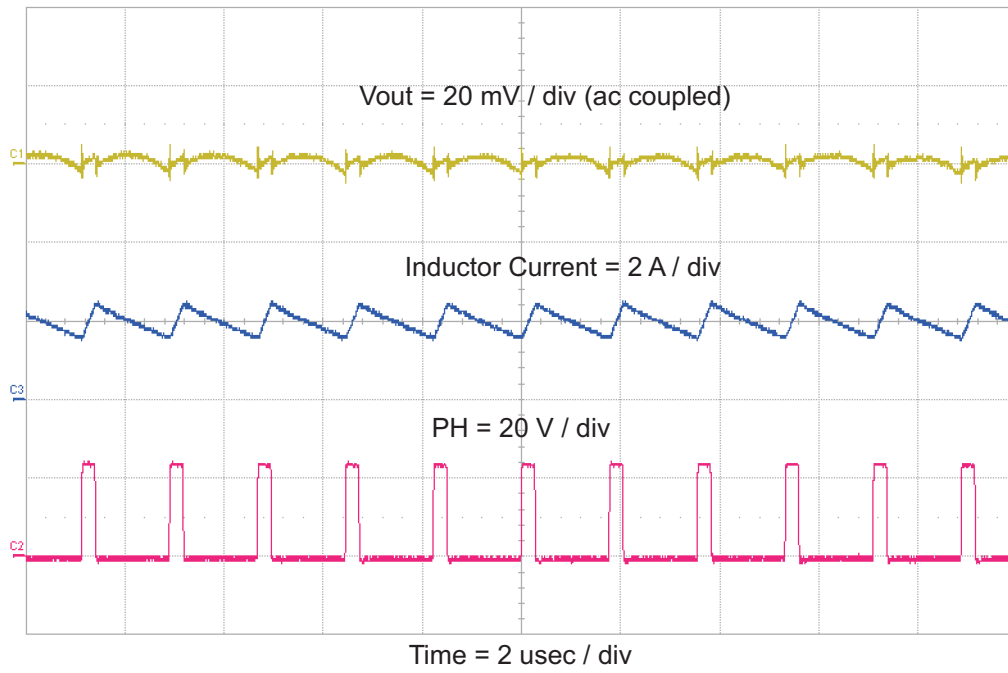


Figure 6. Output Ripple Voltage in Normal PWM Operation

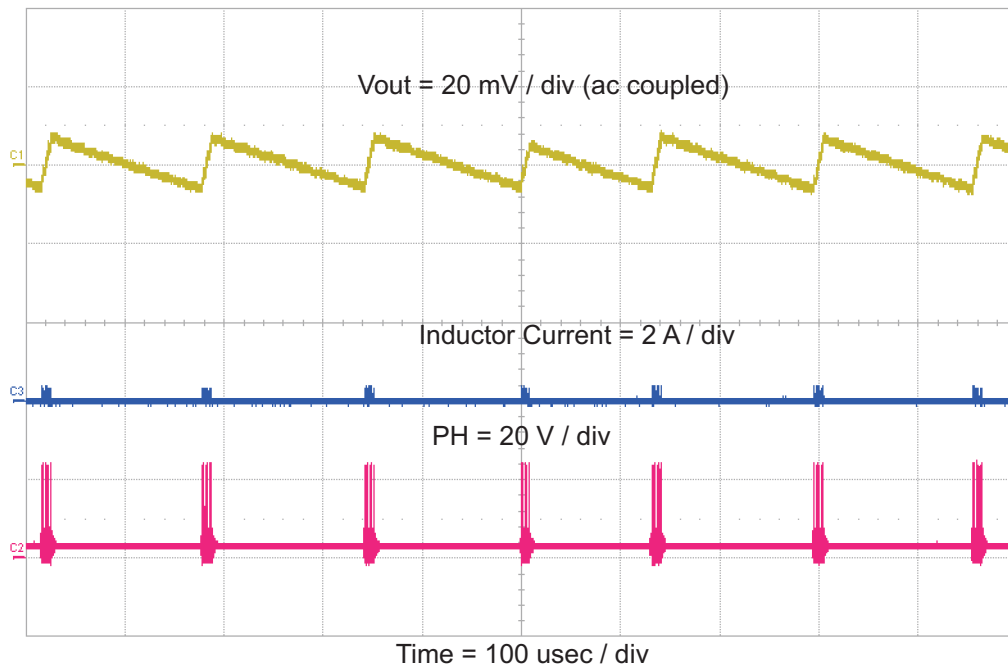


Figure 7. Output Ripple Voltage in Eco-mode™ Operation

Transient response will also degrade somewhat when the current step load change crosses the Eco-mode™ threshold. Figure 8 and Figure 9 show the transient response differences. During Eco-mode™ operation, the COMP pin voltage is clamped at 0.5 V. When the load step crosses the Eco-mode™ threshold the error amplifier may take some time to force the COMP pin voltage above the clamp voltage and allow switching to resume. During this time the output voltage may undershoot more than if the Eco-mode™ threshold is not crossed.

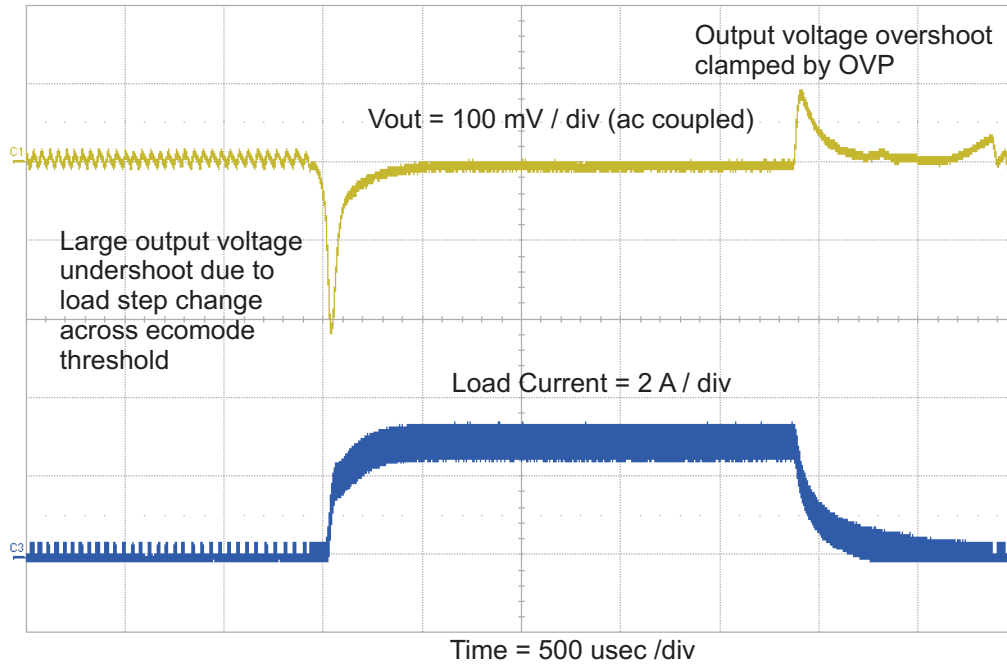


Figure 8. Transient Response, 10 mA to 3 A Load Step

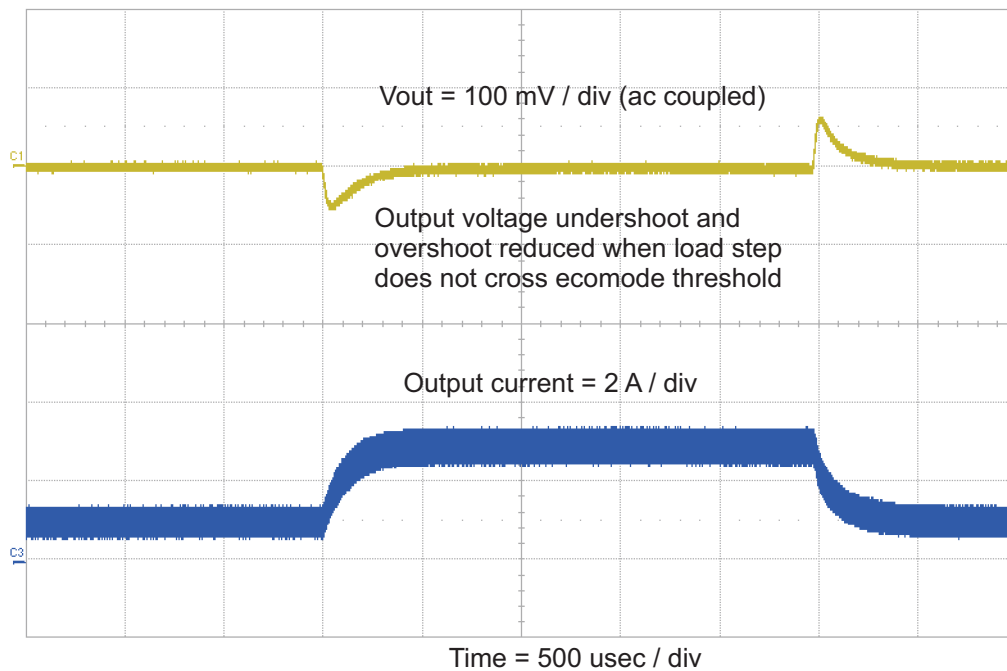


Figure 9. Transient Response, 1 A to 3 A Load Step

6 Conclusion

Eco-mode™ provides distinct efficiency advantages at low output current levels. The load current at which Eco-mode™ operation begins is difficult to predict and depends on several factors that are inherent in the device design. These factors include non-linearity in the power stage transconductance, effects of slope compensation and variation in the actual COMP pin clamp voltage. There are tradeoffs to consider. Transient response can be worse as well as output voltage ripple. Additionally, the switching waveform is not continuous as the device will not switch during the energy saving sleep time. If light load efficiency is an important concern, Eco-mode™ can provide a real benefit.

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