Improving Voltage Feed Forward

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ABSTRACT

This applications report describes the voltage feedforward function of several TI controllers and how to improve the voltage feedforward performance. This report refers to many buck controller devices offered by Texas Instruments. They and their datasheet references are listed in Table 1 .

1 Improving Voltage Feed-Forward

The TPS4005x/6x and 7x families of synchronous buck controllers are designed to operate over a wide range of input voltages. Compensating wide input voltage mode buck converters can be difficult because the modulator gain changes with input voltage. Modulator gain is defined as the change in DC output voltage per change in the control voltage and in a voltage mode control BUCK is typically given by Equation 1.

$$A_{MOD} = \frac{V_{IN}}{\frac{\delta V_{RAMP}}{\delta t} \times \frac{1}{f_{SW}}} \approx \frac{V_{IN}}{\frac{V_{RAMP}}{D_{MAX}}} \tag{1}$$

In a many controllers, the control ramp (V_{RAMP}) is a fixed peak-to-peak ramp voltage generated by the timing oscillator. The ramp voltage is compared with a control voltage to generate a PWM signal to drive the main and synchronous switches. When the ramp amplitude is fixed, the modulator gain varies directly with the input voltage. In a converter with a fixed ramp amplitude and a 10-V to 40-V supply voltage, the modulator gain varies by 4:1 or 12 dB over the input voltage range. Because modulator gain affects the total loop gain, and thus the loop bandwidth, a designer must compensate the control loop for the entire input range, making error amplifier compensation design more complicated and often forcing lower bandwidth during normal operation to ensure stability at the design limits.

To address these design issues, the TPS4005x/6x/7x families of buck controllers have a voltage feed-forward function that adjusts the ramp amplitude with the input voltage. Figure 1 illustrates how this is accomplished.

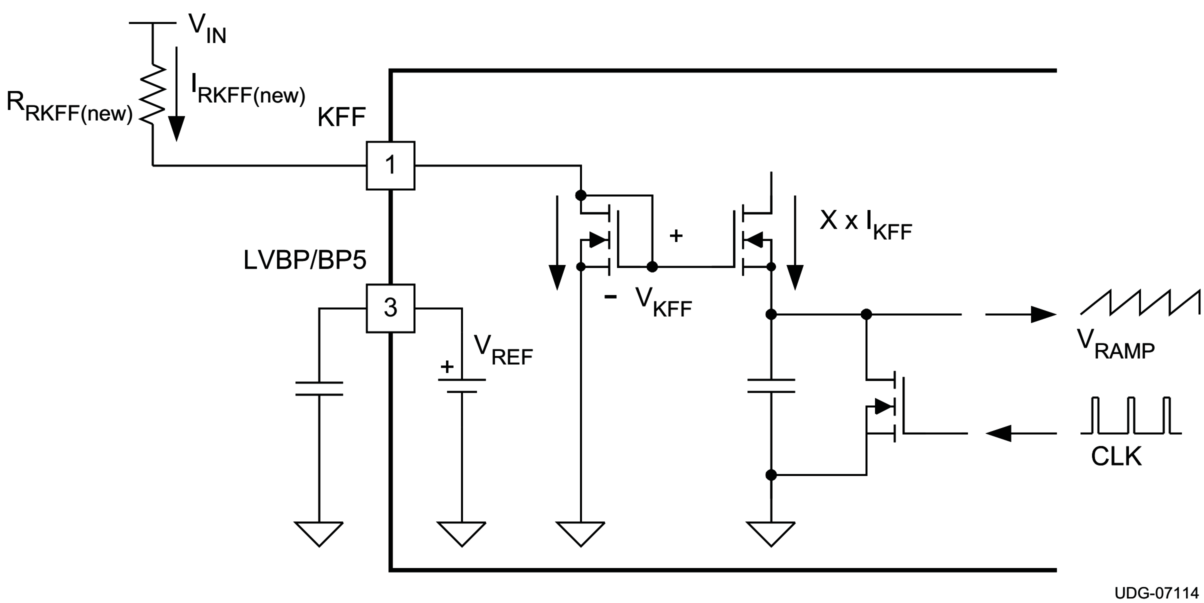

Figure 1. TPS4005X/6X/7X Voltage feed-forward Circuit

In each of these devices, the KFF pin forces a voltage on the pin and mirrors the sink current inside the controller into a fixed capacitor to form the ramp voltage used by the PWM comparator. When this pin is connected to VIN through a fixed resistor, the current through the resistor is approximately proportional to VIN. Combined with the fixed frequency clock, the current produces a voltage ramp whose amplitude is proportional to the current through the resistor, and thus VIN.

In addition to the voltage feed-forward function, the TPS4005x/6x/7x families use the KFF pin for a UVLO function. An internal comparator holds the output drivers off until the ramp voltage exceeds a reference value at the end clock cycle. Because this ramp peak value is dependant on the feed-forward current (I_{KFF}) and the clock period, it provides a frequency dependant undervoltage lockout (UVLO) by requiring a minimum I_{KFF} for the converter to generate output pulses. This allows the user to program the desired UVLO turn-on voltage through feed-forward resistor $_{KFF}$) selection.

The dual functionality of the KFF pin links the UVLO and voltage feed-forward functions. While the feed-forward current adjusts the slope of the ramp voltage, the range of control voltages is fixed by the error amplifier, as a result, the maximum duty cycle drops as the input voltage increases. While this provides an effective volt-second clamp to prevent inductor saturation, it also limits the output to input ratio. Under many conditions this is not an issue because a lower duty cycle is required at higher input voltages. However, in applications requiring high output voltage, low UVLO and a wide input voltage range, a small error term can cause a controller to fall out of regulation at high input voltage.

Inside the integrated circuit, a bias voltage is required to mirror the current. With a voltage present on KFF, I_{KFF} is proportional to V_{IN}-V_{KFF}, creating a small error in the ratio between the output voltage and I_{KFF}. This error term causes the maximum duty-cycle to fall faster than the input voltage rises, resulting in a lower maximum output voltage at high input voltage than at lower input voltage. Figure 2, shows the maximum output voltage ($V_{OUT(max)}$) of a TPS40061 controller at 300 kHz with UVLO set for 10 V, the maximum output voltage drops from almost 9 V at UVLO to 6.24 V at the maximum input voltage of 55 V because of the reduced maximum duty cycle at higher input voltages.

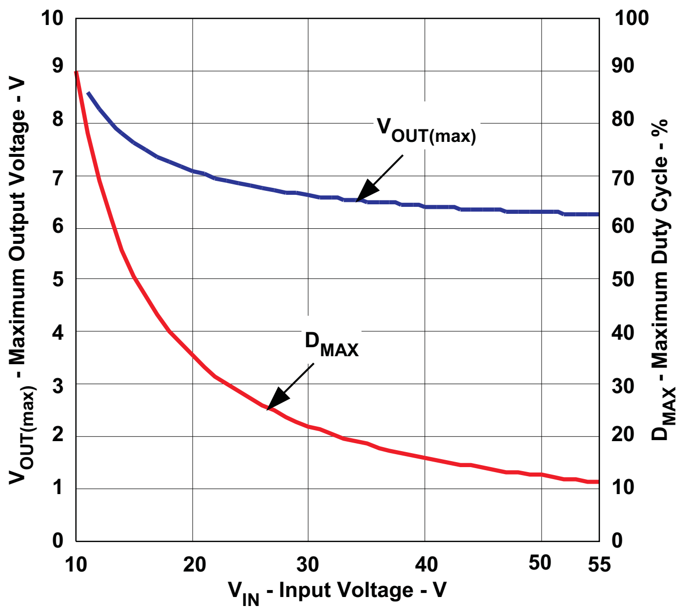

Figure 2. TPS40061 Maximum Duty Cycle and Output Voltage verses Input Voltage (UVLO = 10 V)

When connected as shown in Figure 1 , the current flowing into the KFF pin is given by Equation 2.

$$I_{KFF} = \frac{V_{IN}}{R_{KFF}} - \frac{V_{KFF}}{R_{KFF}} \tag{2}$$

Equation 2 illustrates the small error term generated by the voltage present on the KFF pin. Because this term is constant, it can be cancelled by an additional current $I_{KFF(sup)}$, as shown in Equation 3.

$$I_{KFF} = \frac{V_{IN} - V_{KFF}}{R_{KFF}} + I_{KFF(sup)} = \frac{V_{IN}}{R_{KFF}} \tag{3}$$

To satisfy the desired ratio between I_{KFF} and VIN, the supplemental current must cancel the error term. The required relationship of $I_{KFF(sup)}$ is shown in Equation 4.

$$I_{KFF(sup)} = \frac{V_{KFF}}{R_{KFF}} \tag{4}$$

By adding a single resistor from a low-noise, fixed reference voltage, such as the controller's low-voltage bias pin, the supplemental current can be added to I_{KFF}, improving the voltage feed-forward accuracy and forcing the maximum duty-cycle to track the inverse of the input voltage.

Figure 3 shows the voltage feed-forward circuit with the additional resistor to provide the supplemental current $I_{KFF(sup)}$.

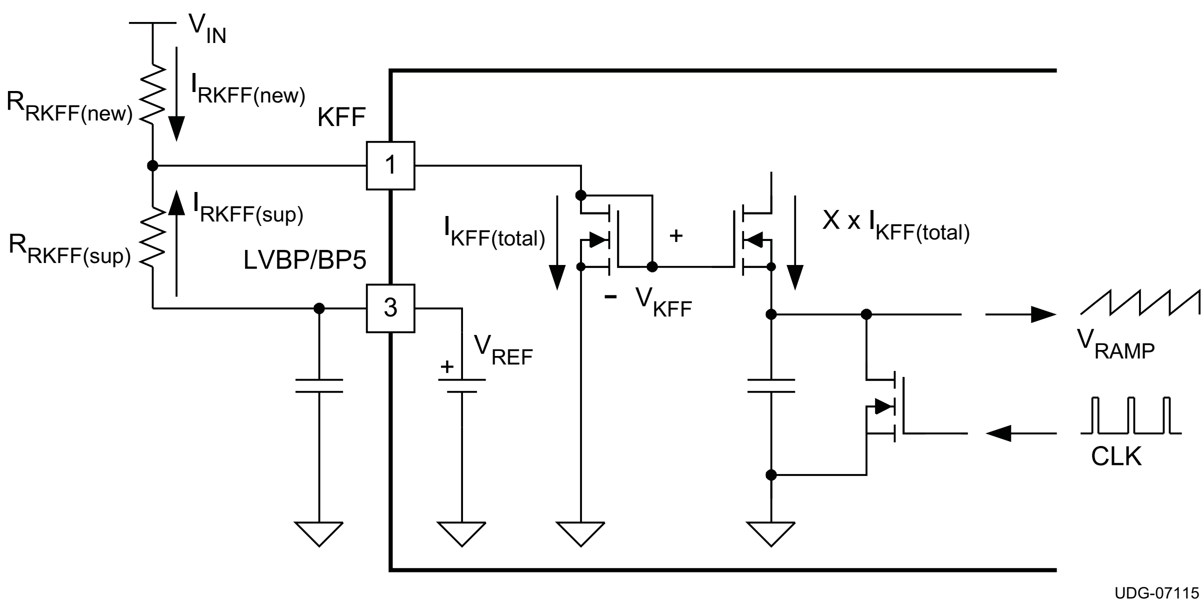

Figure 3. TPS4005X/6X/7X Voltage feed-forward Circuit w/ Supplemental Resistor

Using the circuit from Figure 3 and existing equations from the device datasheets it is possible to select $R_{KFF(new)}$ and $R_{KFF(sup)}$ to provide the same UVLO function previously noted and improve the voltage feed-forward functionality. Before determining the value of the additional resistor, it is necessary to calculate the nominal R_{KFF}. Use the equation found in the device's datasheet because the I_{KFF} required for turn on varies with the device and the switching frequency. This value serves as the basis for selecting a new $R_{KFF(new)}$ and the supplemental $R_{KFF(sup)}$ to provide the same I_{KFF} at UVLO turn-on so the circuit continues to turn-on at the same input voltage.

The goal of the circuit is to provide an I_{KFF} which is directly proportional to VIN and programmed by $R_{KFF(new)}$ as given in Equation 5.

$$I_{KFF(total)} = \frac{V_{IN}}{R_{KFF(new)}} \tag{5}$$

As discussed earlier, the controllers use I_{KFF} to determine the UVLO voltage, because the controller must start at the same UVLO voltage, the current needs to be the same as with the datasheet calculated resistor at the UVLO voltage, as shown in Equation 6.

$$I_{KFF(datasheet)}(UVLO) = I_{KFF(total)}(UVLO) \tag{6}$$

Substituting Equation 2 for the datasheet $I_{KFF(datasheet)}$ and Equation 5 for $I_{KFF(total)}$ both at $V_{VIN} = V_{UVLO}$, resulting in Equation 7.

$$\frac{V_{UVLO} - V_{KFF}}{R_{KFF(datasheet)}} = \frac{V_{UVLO}}{R_{KFF(new)}} \tag{7}$$

If Equation 7 is rearranged and solved for $R_{KFF(new)}$ value to provide the same UVLO voltage as calculated from the datasheet, Equation 8is obtained:

$$R_{KFF(new)} = \frac{V_{UVLO}}{V_{UVLO} - V_{KFF}} R_{KFF(datasheet)} \tag{8}$$

Once $R_{KFF(new)}$ is calculated, it is necessary to calculate the supplemental resistor to solve Equation 4. From the schematic in Figure 3 , $I_{KFF(sup)}$ is given by Equation 9 .

$$I_{KFF(sup)} = \frac{V_{REF} - V_{KFF}}{R_{KFF(sup)}} \tag{9}$$

Substituting Equation 9 into Equation 4, Equation 10 is obtained.

$$\frac{V_{REF} - V_{KFF}}{R_{KFF(sup)}} = \frac{V_{KFF}}{R_{KFF(new)}} \tag{10}$$

Equation 10 is rearranged to solve for R_{KFF}, to produce Equation 11.

$$R_{KFF(sup)} = \frac{V_{REF} - V_{KFF}}{V_{KFF}} R_{KFF(new)} \tag{11}$$

Equation 5 and Equation 7 along with the R_{KFF} equation from the devices' datasheets (see Table 1) provide the necessary values for $R_{KFF(new)}$ and $R_{KFF(sup)}$ to design a programmable UVLO buck controller with improved voltage feed-forward. $R_{KFF(new)}$ and $R_{KFF(sup)}$ provides the same I_{KFF} and UVLO turn-on voltage as the R_{KFF} calculated from the datasheet, but the voltage feed-forward current directly tracks the input voltage providing more accurate voltage feed-forward and a constant maximum output voltage, eliminating the high-voltage drop-out regulation issue with wide-input, high-output voltage converters using the TPS4005x/6x/7x controllers.

In Figure 4 the 82.5-kΩ resistor used for Figure 2 has been replaced with a 124-kΩ resistor and a 57.6kΩ supplemental resistor has been added from the 5-V reference to produce the following $V_{OUT(max)}$ values Figure 2.

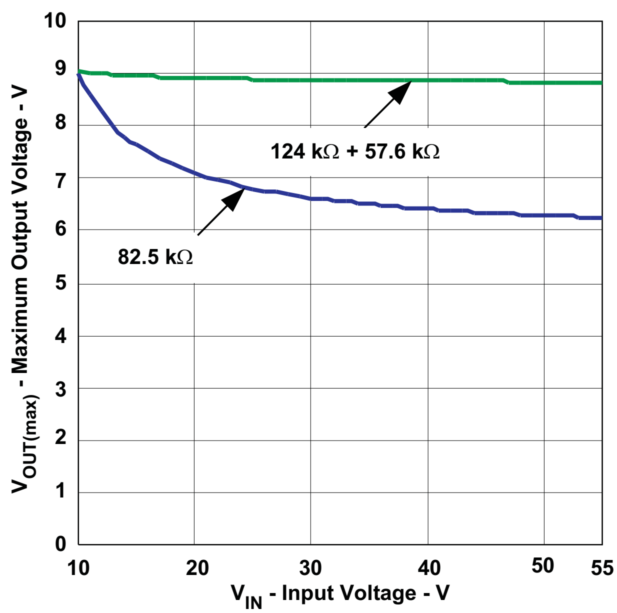

Figure 4. TPS4005X/6X/7X Voltage feed-forward Circuit w/ Supplemental Resistor

A slight dependence on VIN is remains due to the rounding required by the limited resistor value availability, however, even with these values, an output voltage of 8.5 V can now be maintained over the full 10-V to 55-V input range.

Special thanks to Mark Dennis and Norm Mosher of Texas Instruments who originally determined this issue with the Voltage feed-forward Controllers and Pete Goudreau who independently developed this technique, as well as Richard Garvey, Brian Lynch, Ed Walker and Pete Goudreau for reviewing the paper.

2 REFERENCE

Table 1. Device Reference

DEVICE NUMBER	DEVICE NAME	TI LITERATURE NUMBER
TPS40050	Wide Input Synchronous Buck Controller	SLUS540
TPS40051		
TPS40053		
TPS40054	Wide Input Synchronous Buck Controller	SLUS593
TPS40055		
TPS40057		
TPS40060	Wide Input Synchronous Buck Controller	SLUS543
TPS40061		
TPS40070	High Efficiency Midrange Input Synchronous Buck Controller w/Voltage Feed-Forward	SLUS582
TPS40071		
TPS40074	Midrange Input Synchronous Buck Controller w/Voltage Feed-Forward	SLUS617
TPS40075	Midrange Input Synchronous Buck Controller w/Voltage Feed-Forward	SLUS676
TPS40077	High Efficiency Midrange Input Synchronous Buck Controller w/Voltage Feed-Forward	SLUS714

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