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APPLICATION NOTE 5599

Enhance PA Performance and System Efficiency with Bypass Mode in Hysteretic Step-Down Converters

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Abstract: This application note illustrates how using a hysteretic step-down converter instead of the battery itself to power the RF PA greatly improves PA efficiency and extends battery life. The basics of this converter along with the importance and benefits of using bypass mode are discussed.

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Introduction

A hysteretic DC-DC step-down converter has been widely used in 2G/3G/4G RF power amplifiers (PAs) as a replacement for a direct battery supply to the PA's DC supply. By dynamically adjusting the PA supply voltage and bias current, this approach dramatically improves PA efficiency and extends battery life. A bypass mode with a bypass field-effect transistor (FET) or a bypass low dropout (LDO) regulator also reduces dropout voltages across the step-down converter and enhances the output current capability. Together, these functions lower the battery shutdown point and extend battery life.

The increased system efficiency by using a hysteretic step-down converter does, admittedly, involve a trade-off in voltage headroom. This application note discusses how a bypass mode with a bypass FET or a bypass LDO can be integrated into the hysteretic step-down converters to optimize PA performance.

Basics of a Hysteretic Step-Down Converter

A PA step-down converter differs from a traditional step-down converter that powers a digital processor core in several important ways. The PA converter offers dynamic output voltage control for continuous PA power adjustment; high efficiency over a wide output voltage/current range; a fast turn-on time and settling time for output voltage change; low dropout and 100% duty cycle operation; and low output voltage ripple.

In contrast, Maxim's modern hysteretic step-down converters dynamically control the DC supply voltage to the PA. (See the Appendix for a list of Maxim's hysteretic step-down converters.) The converter output voltage is adjusted by an independent DAC-controlled analog input in proportion to different RF transmitting power levels. The converter uses output voltage ripple to control when the high-side and low-side switches are turned on and off. It uses an error comparator without a fixed-frequency clock instead of an error amplifier with compensation. Therefore, the hysteretic converter's key significant advantage over a fixed-frequency PWM converter is its major improvement in transient response. Unlike a fixed-frequency converter, the hysteretic converter reacts immediately to any output voltage/load transient without having to wait for a new clock pulse or for the error amplifier output to move. With high efficiency, high switching frequency, and a 100% duty cycle, the hysteretic converter is a perfect candidate to power the PA.

The Importance of a Bypass Mode

Using a hysteretic step-down converter instead of the battery itself to bias the PA does, admittedly, raise one issue: the efficiency improvement sacrifices voltage headroom. Inserting the converter between the battery and the PA usually removes at least 200mV or more of headroom.

Let's look at an example of the hysteretic step-down converter. To transmit 32dBm RF power on a certain PA module, the recommended V_{CC} and I_{CC} are 3.4V and 1130mA, respectively. Assume that the MAX8989 internal pFET on-resistance (R_{ON}) is 175mΩ and that the inductor used has 200mΩ direct current resistance (DCR). Then the total voltage drop across the pFET and inductor is:

$$(175m\Omega + 200m\Omega) \times 1.13A = 424mV \qquad \text{(Eq. 1)}$$

To sustain a 3.4V V_{CC}, the battery voltage must be above 3.824V, which shortens talk time. To overcome this issue, a bypass mode is implemented. Essential components of this bypass mode are the bypass FET and bypass LDO. We examine each in turn.

Use a Bypass FET to Lower the Dropout Voltage

The MAX8805W hysteretic step-down converter has a bypass mode with a bypass FET. As the battery voltage drops and the converter approaches the dropout region, its internal bypass FET connects the PA directly to the battery when $V_{REFIN} > 0.372 \times V_{IN}$. **Figure 1** demonstrates the performance difference when the bypass is enabled or disabled.

Without the bypass FET, the dropout voltage after the converter enters 100% duty cycle is:

$$V_{DROPOUT} = (R_{ON\text{-}PFET} + DCR_{IND}) \times I_{OUT} \qquad \text{(Eq. 2)}$$

With the bypass FET, the dropout voltage becomes:

$$V_{DROPOUT} = (R_{ON\text{-}BYP} // (R_{ON\text{-}PFET} + DCR_{IND})) \times I_{OUT} \qquad \text{(Eq. 3)}$$

Where $R_{ON\text{-}PFET}$ is 180mΩ and $R_{ON\text{-}BYP}$ is only 60mΩ.

Using a 3.4V battery, the MAX8805W's output voltage is 3.23V without the bypass FET and 3.37V with the bypass FET. The bypass FET thus improves the 140mV voltage headroom by lowering the dropout voltage.

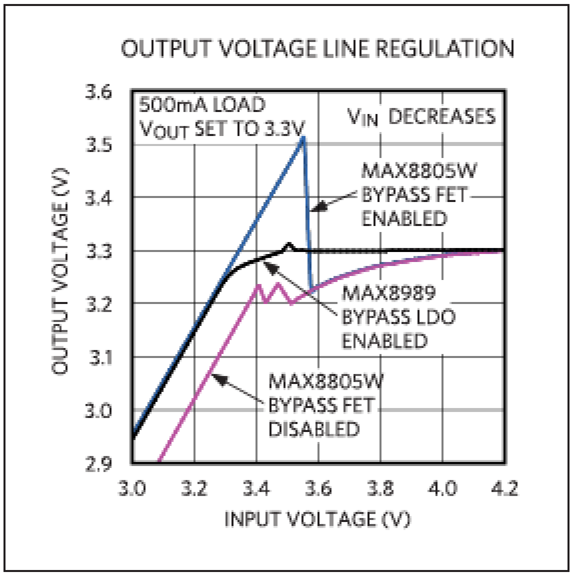

Figure 1. Data from the MAX8805W show how a bypass FET affects output voltage line regulation.

The bypass FET increases the converter's output-to-battery voltage in the dropout region. The trade-off is a voltage jump at the transition from the regulation region to the dropout region instead of the smooth transition shown in Figure 1. To obtain a smooth transition from the regulation region to the dropout region, a low dropout linear regulator (a bypass LDO) in parallel with the step-down converter is introduced into hysteretic converters.

Use a Bypass LDO to Remove Voltage "Jump"

Figure 1 also shows the improvement of a bypass LED over a bypass FET. This LDO provides a smooth transition between step-down regulation and operation in dropout. Two bypass LDO examples are presented using the MAX8989 and the MAX8951.

We start by looking at the MAX8989, where the relationship between the output voltage and REFIN voltage is:

$$V_{OUT} = 2 \times V_{REFIN} - 0.5 \times DCR_{IND} \times I_{OUT} \qquad \text{(Eq. 4)}$$

When the MAX8989 output voltage drops by more than 50mV due to load regulation ($0.5 \times DCR_{IND} \times I_{OUT} > 50mV$) and the output voltage is above the linear bypass enable threshold (1.4V, typ), the bypass LDO supplies supplementary current to the output to keep the output voltage in regulation.

Figure 2 illustrates the effect of the bypass LDO on output voltage regulation. Here, the bypass LDO is disabled in the case of V_{REFIN} = 0.4V; for V_{REFIN} = 0.9V, the bypass LDO begins operation when the output voltage drops 50mV and the load regulation ramps down at a slower rate. Two 4.7µH inductors (a

TOKO® DFE252012C series inductor and a TDK® VLS252015ET series inductor) are used and noted in Figure 2. With different inductors, the bypass LDO starts at the same 50mV point. But since the TDK inductor has bigger DCR and causes a higher voltage drop across the inductor, the bypass LDO begins operation at a lower output current.

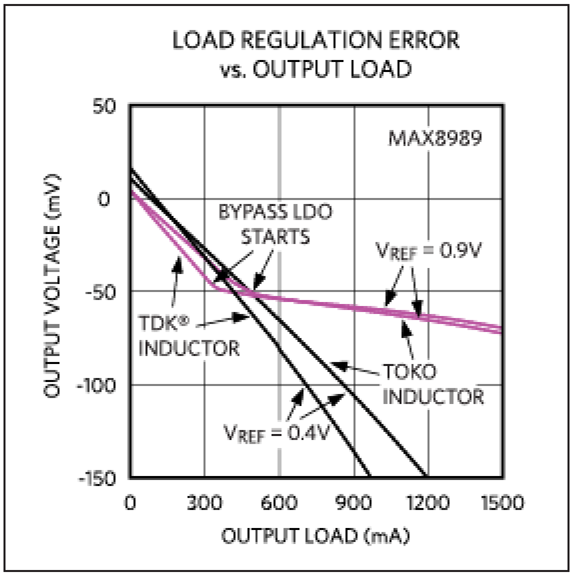

Figure 2. Data show the load regulation error versus output load for the MAX8989.

When the output current exceeds the step-down converter's current limit, the bypass LDO provides supplementary current to the output, thereby ensuring a stable output voltage. The bypass LDO does not provide any supply current before the step-down converter reaches its current limit. While the linear bypass regulator is sourcing current, the step-down converter continues to supply most of the load to maximize efficiency.

The MA8951 has separate input supplies for the hysteretic step-down converter (IN1) and bypass LDO (IN2). **Figure 3** illustrates the IN1/IN2 supply-current delivery versus output load. The converter reaches its current limit at 1.3A load. Above a 1.3A load, the IN2 supply picks up the load and provides the supplemental current to the output. Therefore, with a bypass LDO, the inductor with a lower saturation current rating can be used in higher current PA applications.

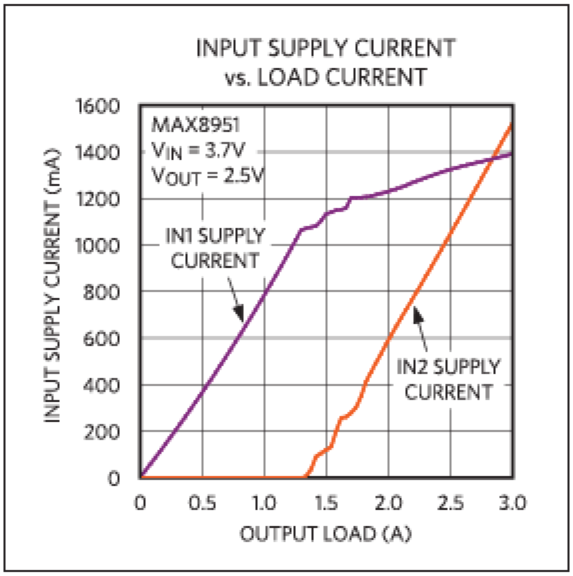

Figure 3. Data show the input supply current versus load current for the MAX8951.

A bypass LDO also enables a faster output voltage transient response. Using the same setup for the MAX8989 described above, tests are done by stepping the REFIN voltage to get a 1V to 3V output voltage change. After the output voltage rises above the bypass enable threshold, the bypass LDO starts and ramps up the output voltage at a faster rate. The MAX8989's overall settling time from 1V to 3V is less than 8µs, while this time for the MAX8805W is more than 16µs. Compare **Figure 4** and **Figure 5** for the devices' difference in the output voltage transient response.

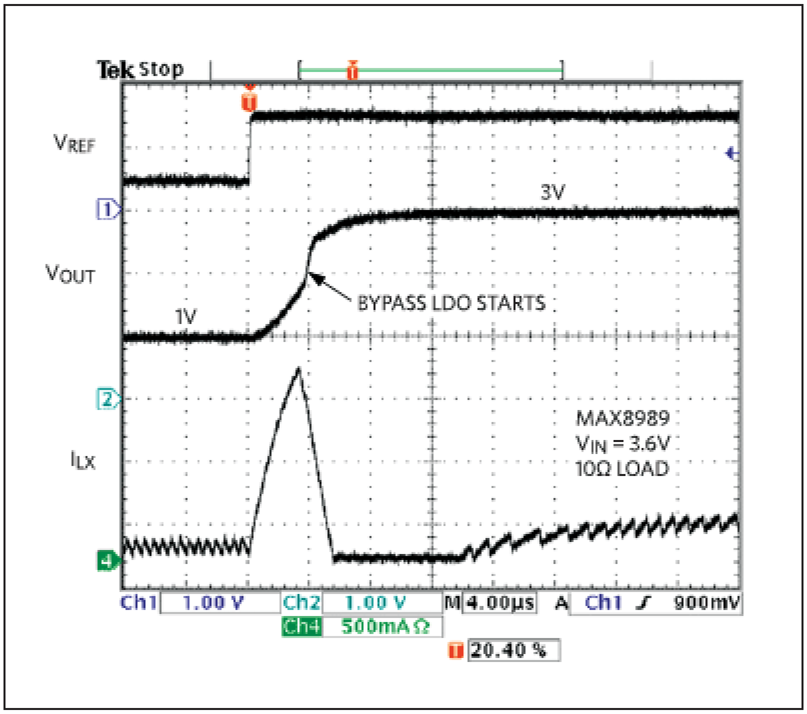

Figure 4. The output voltage transient response for the MAX8989 shows a settling time of less than 8µs.

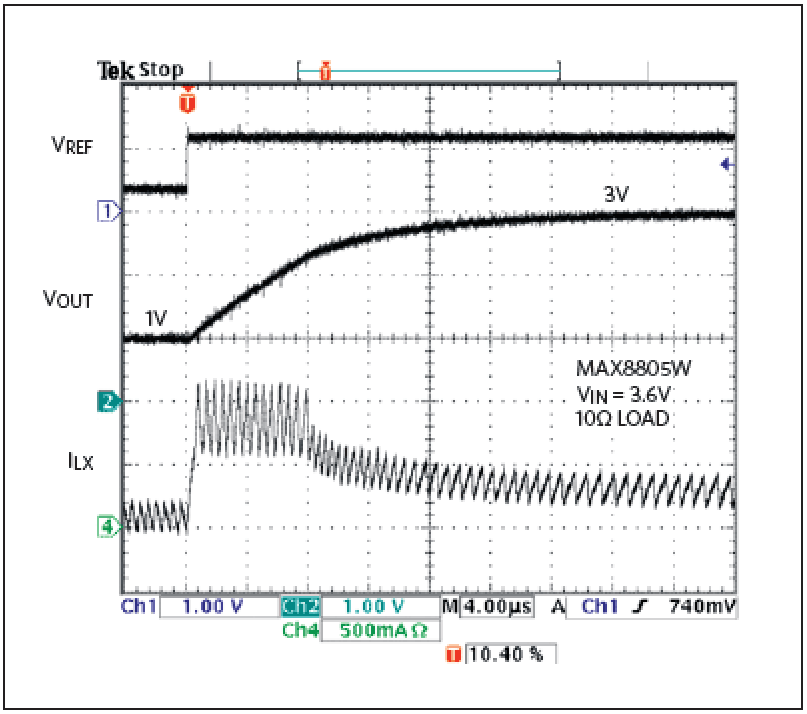

Figure 5. The output voltage transient response for the MAX8805W shows a settling time of more than 16µs.

Conclusion

Hysteretic step-down converters with either a bypass FET or a bypass LDO both optimize the PA performance and improve the system efficiency which extends battery life. A bypass LDO offers advantages over a bypass FET, specifically a smoother transition between step-down regulation and dropout as well as a faster transient response. These performance benefits make a step-down converter with a bypass LDO an ideal candidate for PA power applications.

Appendix: Hysteretic Step-Down Converters

Table 1 lists the hysteretic step-down converters that have been discussed in this application note as well as additional Maxim converters.

Table 1. Hysteretic Step-Down Converters

Part	Switching Frequency (MHz)	L (µH)	C_{IN} (µF)	C_{OUT} (µF)	Bypass Mode
MAX8581	1.5	3.3	2.2	2.2	FET
	2.5	1.5			
MAX8805	2	2.2	2.2	2.2	FET
	4	1.0			

MAX8896	2	2.2	4.7	4.7	FET
MAX8951	2	2.2	4.7	4.7	LDO
MAX8989	2	4.7	4.7	4.7	LD

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Related Parts		
MAX8581	2.5MHz/1.5MHz Step-Down Converters with 60mΩ Bypass in TDFN for CDMA PA Power	Free Samples
MAX8805	600mA/650mA PWM Step-Down Converters in 2mm x 2mm WLP for WCDMA PA Power	
MAX8896	Dual PWM Step-Down Converter in a 2mm x 2mm Package for WCDMA PA and RF Power	
MAX8989	Multimode PA Step-Down Converter with Linear Bypass Mode	Free Samples

More Information
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