Maxim > Design Support > Technical Documents > Application Notes > Amplifier and Comparator Circuits > APP 4326
Maxim > Design Support > Technical Documents > Application Notes > Power-Supply Circuits > APP 4326

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APPLICATION NOTE 4326

Reduce Standby Power Drains with Ultra-Low-Current, Pulse-Frequency-Modulated (PFM) DC-DC Converters

By: Javier Monsalve Kägi, Senior Member of Technical Staff, Applications
Jose Miguel de Diego, Escuela Técnica Superior de Ingeniería, Bilbao, Spain
Jose Ignacio Garate, Escuela Técnica Superior de Ingeniería, Bilbao, Spain
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Abstract: This article explains how to reduce the level of low-current consumption in isolated DC-DC power supplies and how to improve the performance of those supplies under no-load conditions. Sensitive to today's need for innovative "green" solutions, the discussion especially focuses on ways to extend the battery life of battery-powered electronic devices and communication-system devices with discontinuous transmission.

This article was also featured in Maxim's Engineering Journal, vol. 65 (PDF, 756kB).

A Japanese version of this article appeared in the *EDN Japan Power Supplement*, December, 2008.

Today, many industrial systems employ battery-powered sensors and transponders to eliminate expensive cable installations and to reduce overall system power consumption. These industrial systems typically have an active mode and a standby mode. In active mode the sensor delivers data to the transponder (a radio modem) which transmits the data to a host system. In standby mode the transponder and sensor go to sleep for a fixed or variable time period. This start-and-stop operation, often referred to as a discontinuous operating mode, maximizes the battery life of the device.

For an application like a watering system that leverages GSM radio modules for the sensors, maintenance costs would be high if the batteries powering the GSM radios had to be replaced every few days, or even every few weeks. Since such a system spends most of its time in standby or sleep mode, minimizing the power drain from the battery when no activity is taking place would go a long way toward extending battery life. In this system no-load quiescent current becomes a key design consideration, and for safety concerns, galvanic isolation is an important aspect of the design.

To address these concerns, designers must focus on the design of the DC-DC converter to ensure that it consumes as little current as possible during no-load conditions. All DC-DC converters, even during standby, can consume significant quiescent current. One commercial power-supply module (the RECOM® R-78A3.3-1OR), for example, draws about 7mA under no-load conditions. However, with some attention to topology and careful design, an isolated DC-DC converter module with a no-load current drain of less than 1mA can be implemented.

The 30x difference in current drain can translate into reduced battery replacements. For example, even if the system's batteries are rechargeable, then additional recharge cycles might be needed if the higher current-drain supply is used. Moreover, batteries that are recharged often, wear out sooner and end up in landfills. Similarly, if the device employs one-time-use batteries, they will discharge sooner with a higher standby current and get discarded more frequently.

While there are several approaches to the challenge, this article looks at the use of pulse-frequency modulation (PFM) to achieve a 1700:1 ratio between the device's on and standby states.

System Characteristics

Typical power consumption versus time looks like the graph in **Figure 1**. Here the load current spikes during operation or active charging, and then drops when the device is idle. The idle current, I_Z, must be minimized to reduce battery drain and extend battery life and standby time. Thus, the isolated DC-DC converter needs ultra-low-current consumption when no load is connected, and should also provide high isolation from input to output. Ideally, the converter should also offer high-conversion efficiency and a small footprint.

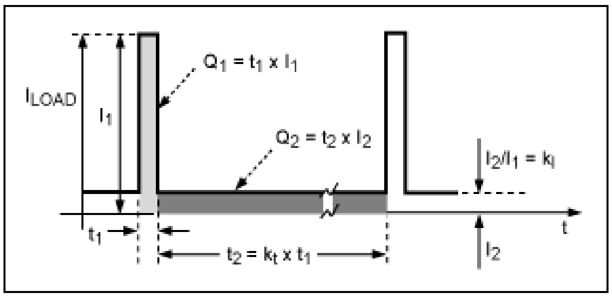


Figure 1. The relationship between the on and standby states of a communication device with discontinuous transmission.

The typical commercial DC-DC converters listed in **Table 1** show input currents of 7mA to 40mA when no load is connected with an input of 12V. These converters traditionally employ pulse-width-modulation (PWM) controllers. However, PWM controllers always have an active oscillator, even when there is no load, and that oscillator continually draws current from the battery.

Table 1. Characteristics of Commercial DC-DC Converters

Manufacturer	Model	V_{IN} (V)	V_{OUT} (V)	I_{OUT} (A)	I_{IN} (I_{OUT} = 0, mA)	η (%)	Isolation
Traco® Electronic AG	TEN 5-1210	12	3.3	1.2	20	77	√
XP Power	JCA0412S03	12	3.3	1.2	38	83	√
RECOM International Power	RW-123.3S	12	3.3	0.7	21	65	√
C&D Technologies®	HL02R12S05	12	5	0.4	40	60	√
Bourns® Inc.	MX3A-12SA	12	3.3	3.0	11	93	
RECOM International Power	R-78A3.3-1	12	3.3	1.0	7	81	

A PFM Controller Topology

An alternative approach is to use a DC-DC converter that employs a pulse-frequency-modulation (PFM) controller.[1] A PFM controller uses two one-shot circuits that only work when the load drains current from the DC-DC converter's output. The PFM is based on two switching times (the maximum on-time and the minimum off-time) and two control loops (a voltage-regulation loop and a maximum peak-current, off-time loop).

The PFM is also characterized by control pulses of variable frequency. The two one-shot circuits in the controller define the T (maximum on-time) and the T (minimum off-time). The T one-shot circuit

ON OFF ON

activates the second one-shot, T_{OFF}. Whenever the comparator of the voltage loop detects that V_{OUT} is out of regulation, the T_{ON} one-shot circuit is activated. The time of the pulse is fixed up to a maximum value. This pulse time can be reduced if the maximum peak-current loop detects that the current limit is surpassed.

The quiescent current consumption of a PFM controller is limited only to the current needed to bias its reference and error comparator (10s of µA). In contrast, the internal oscillator of a PWM controller must be turned on continuously, leading to a current consumption of several milliamps. The implementation presented in this article keeps the current consumption to less than 1mA at 12V by using a PFM controller topology.

Field systems such as the watering system must endure harsh environments, and thus the DC-DC converter in those systems should be galvanically isolated. A transformer provides the isolation, but the challenge is to feed back the voltage reference from the secondary side to the primary side without breaking the isolation. The most common approach solves the problem by using either an auxiliary winding or an optocoupler.

The power-supply topology is a step-down approach; the battery pack used by the application has a nominal voltage of 12V, while the internal electronic circuits in the system operate at 3.6V, nominal. **Figure 2** shows the schematic diagram of the DC-DC switching regulator and the bill of materials with component values is provided in **Table 2**. When the control loop is regulating the voltage, the optocoupler requires a constant current through the LED on the primary side of the transformer. The lower limit of the current is fixed by the optocoupler's CTR at low bias currents (63% at 10mA, and 22% at 1mA) and by a reduction of the response time (2µs at 20mA and 6.6µs at 5mA).

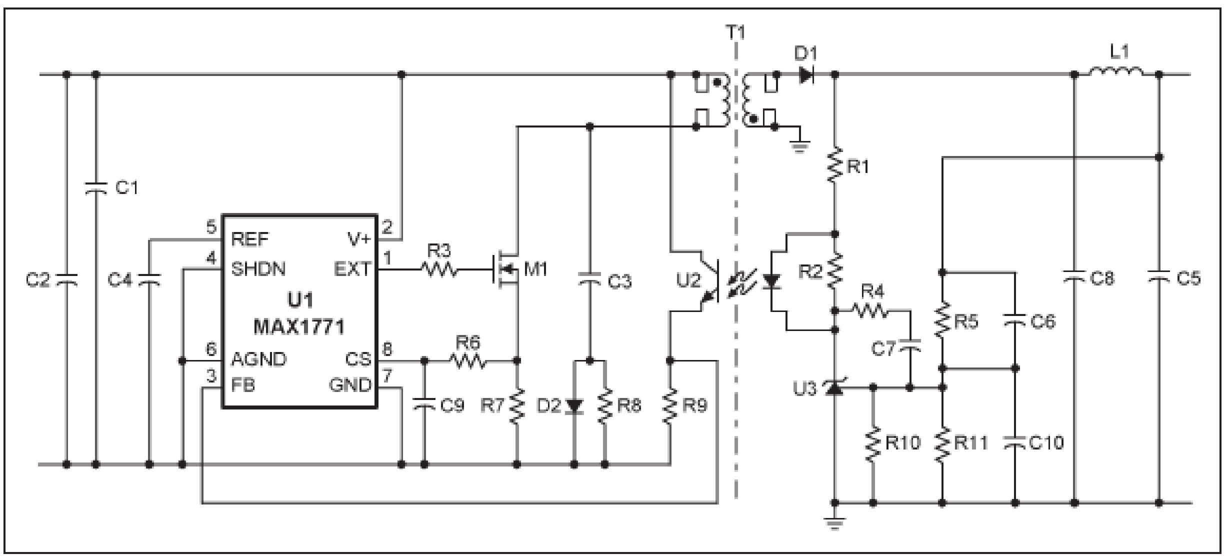


Figure 2. Schematic of an isolated PFM flyback DC-DC converter.

Table 2. Component Bill of Materials for PFM Flyback DC-DC Converter

Reference	Values	Description	Manufacturer
C2	470µF 25V	CEL 470µF, 25V, +105°C, 10mm x 10mm SMD	UUD1E471MNL1GS (Nichicon®)
C10	180pF	CS 180p C COG, 50V 0603/1	GRM39 COG 181 J 50 PT (Murata®)
C1, C4, C7	100nF 16V	#CSMD 100nF K X7R 16V 0603/1	GRM39X7R104K16PT (Murata)
C5, C8	100µF 16V 0.1Ω	CEL TAN 100µF ±20% E 16V 0.1Ω	T495D107K016ATE100 (Kemet®)
C6	100pF	CS 100p C COG 50V 0603/1	GRM39 COG 101 J 50 PT (Murata)

C3	1nF 50V	#CS 1n M X7R 50V 0603/1	GRM39 COG 271 J 50 PT (Murata)
C9	150pF	CS 150p C COG 50V 0603/1	GRM39 COG 151 J 50 PT (Mutata)
D1	MBRS230LT3G	D Schottky 2A, 30V SMB	MBRS230LT3G (ON Semiconductor®)
D2	MBRA160T3G	D Schottky 1A, 60V SMA	MBRA160T3G (ON Semiconductor)
L1	22µH 1.2A 0.19Ω	L SMD 22µH, 1.2A, 0.19Ω	SRR0604-220ML (Bourns®)
M1	IRFR120	Q IRFR120 DPAK 8.4A, 100V, 0.270Ω, nMOS	IRFR120 (Int. Rectifier)
R1, R6	680Ω	RS 680R J 1/16W 0603/1	RK73B 1J T TD 680 J (KOA Speer®)
R9, R2	100kΩ	#RS 100K F 1/16W 0603/1	RK73H 1J T TD 1003 F (KOA Speer)
R3	10Ω	#RS 10R J 1/16W 0603/1	RK73B 1J T TD 100 J (KOA Speer)
R4	4.7kΩ	#RS 4K7 J 1/16W 0603/1	RK73H 1J T TD 4701 J (KOA Speer)
R5	390kΩ	#RS 390K F 1/16W 0603/1	RK73H 1J T TD 3903 F (KOA Speer)
R7	0.047Ω	RS R047 J 1206 /1	SR73 2B T TD R047 J (KOA Speer)
R10	270kΩ	RS 270K F 0603 /1	RK73H 1J T TD 2703 F (KOA Speer)
R11	820kΩ	RS 820K F 0603 /1	RK73H 1J T TD 8203 F (KOA Speer)
R8	100Ω	#R SMD 100R-J 1206/1	RK73B 2B T TD 101 J (KOA Speer)
T1	EP10 3F3	T SMD EP10 3F3 NUCTOR	CSHS-EP10-1S-8P-T (Ferroxcube®-Nuctor)
U1	MAX1771	DC-DC controller	Maxim Integrated Products
U2	TLV431A	U TLV431A V.REF 1.25V SOT23-5	TLV431ACDBVR (Texas Instruments™)
U3	SFH6106-2	#U SFH6106-2 OPTO 63-125%, 5.3kV SMD-4	SFH6106-2 (Vishay®)

The current consumption of the output voltage-divider (formed by resistors R5 and R11) is fixed to 7µA. Because of this, the 0.5µA required by the reference input plus its thermal deviation does not significantly affect the output voltage. Additionally, the voltage measured at the divider output does not suffer a relevant delay, thanks to the low-input capacitance. This latter fact precludes the need for a capacitive divider to reduce the input capacitance of the precision reference. In the optocoupler, the phototransistor draws 60µA ($|I_{FB}|$ < 60nA), which translates into a current flow through the LED of less than 230µA (CTR ~26%).

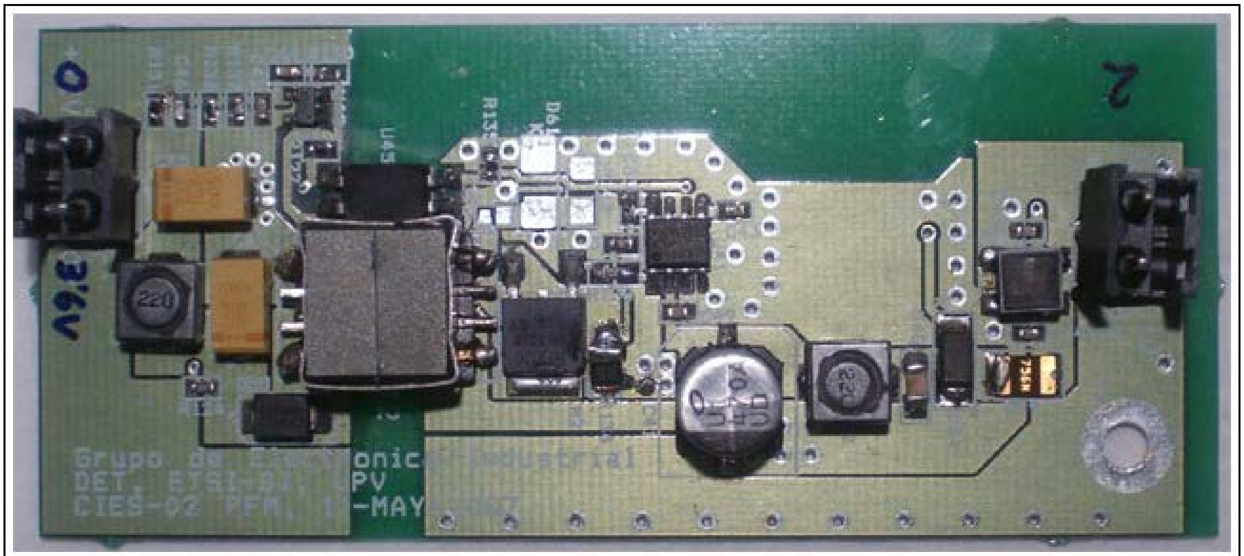
Controlling It All

To implement a PFM controller, the MAX1771 BiCMOS step-up, switch-mode power-supply controller (U1) can be used to provide the necessary timing. The MAX1771 offers improvements over prior pulse-skipping control solutions: reduced size of the inductors required, due to a 300kHz switching frequency; the current-limited PFM control scheme achieves 90% efficiencies over a wide range of load currents; and a maximum supply current of just 110µA. Besides these advantages, the main characteristics of the MAX1771 in a nonisolated application are: 90% efficiency with load currents ranging from 30mA to 2A; up to 24W of output power; and an input-voltage range of 2V to 16.5V.

The resistances of the voltage-control loop have been chosen to have the highest possible values. This decision represents a trade-off between current consumption and loop stability. As a result, the current through the voltage-divider is less than 7µA. Since the filtering capacitors are nonideal, capacitor leakage current must be added to this current. In this design, filter capacitor-leakage current in C5 and C8 is less than 20µA. If lower leakage is required, these caps could be upgraded to ceramic capacitors with the following characteristics: 100µF, 6.3V, X5R, and 1206 size (Kemet C1206C107M9PAC). Using ceramic capacitors reduces the capacitor leakage to just a few microamps. Note, however, that the ceramic capacitors cost about

3x that of the tantalum capacitors, and that difference would increase the system cost.

Figure 3 shows the prototype PFM DC-DC converter that draws a quiescent current of just 0.24mA. The board measures less than 50mm by 30mm, can deliver 3.6W with an input-voltage range of 10V to 15V (12V nominal), and operates at a switching frequency of 300kHz. The converter can supply a maximum constant output current of 1A while delivering a regulated output of 3.6V. Employing a flyback topology (step down) with both current and voltage feedback control, the converter output is galvanically isolated from the input.



More detailed image (PDF, 4.59MB)

Figure 3. Top view of the DC-DC PFM converter prototype for wireless applications.

The prototype can be used in various wireless applications that operate in a discontinuous transmission mode. The current consumption of the modules can peak at 3A, and the maximum mean current is 1A. To reduce the current peaks and avoid the problems that they generate in the performance of the radio, the techniques described in references 2 and 3 are used. Additionally, some basic guidelines suggest that designers should use high-value capacitors that have low series resistances.

Qualifying Design Performance

To verify the performance of the power supply, the following parameters are measured: the input voltage, V_{IN}; the input current, I_{IN}; the nominal output voltage, V_{OUT}; the load current consumption, I_{OUT}; and the efficiency of the power supply. **Tables 3** and **4** show the measurement results, including the losses on the common-mode input filter and the losses of the protection circuitry. It is also important to remember that power supplies handling low power levels are not as efficient as power supplies handling higher loads. The higher-load power supplies are usually synchronous, which helps to reduce the losses in the active devices.

Table 3. Current Consumption Under a No-Load State for Different Input Voltages

V_{IN} (V)	I_{IN} (mA)	V_{OUT} (V)	I_{OUT} (A)
10.0	0.244	3.615	0
12.0	0.239	3.615	0
15.0	0.227	3.615	0

The current consumption of the power supply with a PFM control scheme has been reduced to 0.24mA. Due to component values selected, however, the control loop may oscillate during certain load conditions. To prevent self-oscillation, designers must account for the various tolerances of the components in a production environment. Thus, the values of the resistors and capacitors used in the loop must be selected with care.

Table 4 provides the values for the input and output parameters of the power supply at various load conditions. The optimum efficiency is reached at normal conditions and within the nominal load range.

Table 4. Efficiency at Nominal Voltage for Different Loads

V_{IN} (V)	I_{IN} (mA)	V_{OUT} (V)	I_{OUT} (A)	Efficiency (%)
12.0	0.24	3.615	0	0
12.0	61	3.615	0.14	69.14
12.0	83	3.615	0.2	72.59
12.0	121	3.615	0.3	74.69
12.0	160	3.615	0.4	75.31
12.0	200	3.615	0.5	75.31
12.0	240	3.615	0.6	75.31
12.0	281	3.615	0.7	75.04
12.0	323	3.615	0.8	74.61
12.0	367	3.615	0.9	73.88
12.0	411	3.615	1.0	73.30

The efficiency of the DC-DC converter with no load is represented as zero (**Figure 4**), because the current consumed by the wireless device in standby mode and referred to the 3.6V output side is below 140µA. This current is negligible when compared to the 0.24mA of the power supply's input-current consumption under no-load conditions.

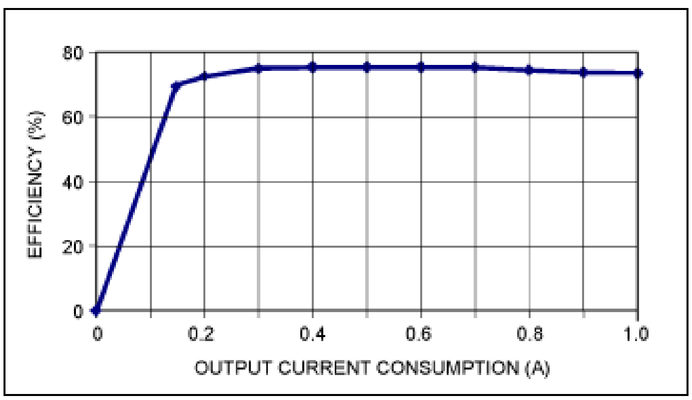


Figure 4. Efficiency of the power supply for different load conditions at the input nominal voltage (12V).

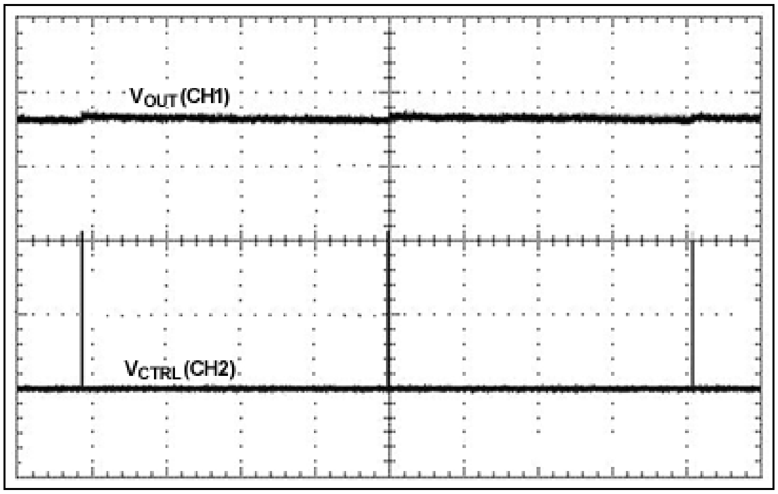


Figure 5a. Output voltage and control voltage without load (10ms/div, CH1 1V/div, and CH2 5V/div).

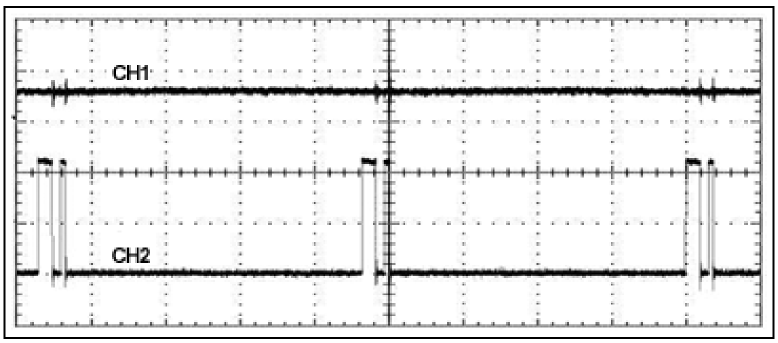


Figure 5b. Output voltage and control voltage for 0.1A load (20ms/div, CH1 1V/div, and CH2 5V/div).

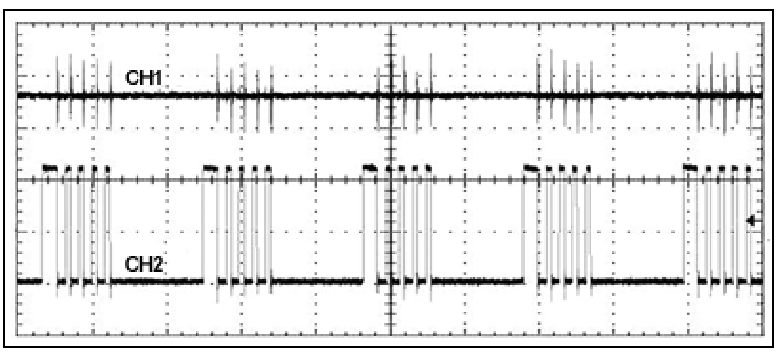


Figure 5c. Output voltage and control voltage for 0.5A load (20ms/div, CH1 1V/div, and CH2 5V/div).

The waveforms in **Figures 5a**, **b**, **c**, and **d** show the output voltage and control voltage for various loads; the control pulses at the gate of the switching device become more frequent as the load increases. The converter prototype shows the signals at no load, 100mA, 500mA, and 1A current loads. The scope traces graphically illustrate the operation of the PFM control scheme. The lower scope trace is scaled by 5x to make it more visible. The X axis represents the time and the Y axis the voltage.

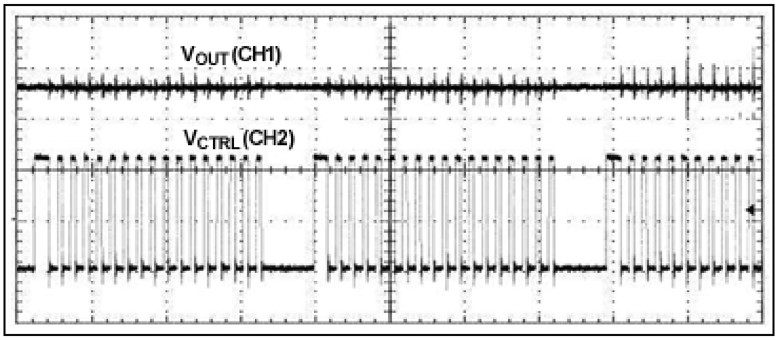


Figure 5d. Output voltage and control voltage for 1A load (20ms/div, CH1 1V/div, and CH2 5V/div).

Summary

Initial industry surveys indicate that the best commercial isolated DC-DC converters for power supplies with low current consumption under no-load conditions typically have about 20mA minimum current consumption. With minimal effort, however, designers can use a PFM scheme to implement a low-I_Q, isolated power supply that has the lowest current consumption on the market. The no-load current consumption of the power supply presented here is only 0.24mA.

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MAX1651	5V/3.3V or Adjustable, High-Efficiency, Low-Dropout, Step-Down DC-DC Controller	Free Samples
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