TITLE:
Ultra Low Quiescent Current Consumption Isolated PFM Power Supplies under No-Load Condition

ABSTRACT
The present paper focuses on low current consumption isolated DC-DC power supplies under no-load condition for electronic devices. It is specially devoted to battery powered electronic devices and communication system devices with discontinuous transmission.
As a result of previous work where power supplies, with high efficiency and low current consumption under no-load conditions, were studied and analyzed, we present here a practical design that reaches the technology limits of isolated power supplies under no-load condition. The design has been implemented with a commercial control device. It has three communication modules and it is intended for remote control of electromechanical actuators and electronic sensors in harsh environment applications.

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TOPIC
The main topic of the article is RENEWABLE ENERGIES, and is applicable to the particular topics of "Energy conversion, conservation and energy efficiency" and "Energy saving policy. Energy storage. Batteries"

KEY WORDS
Voltage conversion, Voltage Regulation, Current consumption, Discontinuous loads
PFM (Pulsed Frequency Modulation)

INTEREST OF THE ARTICLE
The present work provides technical and practical knowledge to design ultra-low power consumption isolated power supplies for communication and control electronic devices, particularly to those fed through batteries and with discontinuous loads.

MAIN CONTRIBUTIONS
- Define the minimum current consumption under no-load conditions, of isolated DC-DC converters.
- Design and development of the isolated DC-DC converter with the lowest power consumption of the market.

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***Abstract*— The present paper focuses on low current consumption isolated DC-DC power supplies under no-load condition for electronic devices. It is specially devoted to battery powered electronic devices and communication system devices with discontinuous transmission.**

As a result of previous work where power supplies, with high efficiency and low current consumption under no-load conditions, were studied and analyzed, we present here a practical design that reaches the technology limits of the isolated power supplies under no-load condition. The design has been implemented on a commercial control device. It has three communication modules and it is intended for remote control of electromechanical actuators and electronic sensors in harsh environment applications.

I. Introduction

The present paper completes the research carried out in previous work [8] and [9] about low consumption power supply systems under discontinuous loads with input current ratios between on and standby state of 1700 to 1, i.e, power supply systems with standby current consumption of 0.06% of the consumption at maximum load. Figure 1 illustrates the shape of the current consumption of and electronic device with discontinuous loads. Fig. 1 also shows the relationship between the current consumption at maximum peak current and in standby mode. As Fig. 1 shows, the consumption in standby has more weight over the total consumption than the instantaneous peak consumption during the on state.

This research tries to define the minimum current consumption that could be obtained with the actual technology.

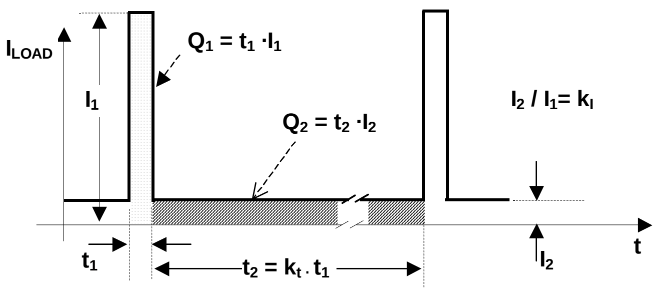
A PWM (Pulse Width Modulator) controller, like the one described on [8] and [9], always has an active oscillator even when there is no load at the output of the DC-DC converter.

The solution with a PFM (Pulse Frequency Modulation) controller uses two one-shot circuits that only work when the load drains current from the output of the DC-DC converter.

The current consumption of a PFM controller is generated by the leakage current of the electronic devices, which means only tenths of micro amps. On the other hand, the internal oscillator of a PWM controller must be turned on continuously, which leads to an additional current consumption of several milliamps.

II. State of the Art

The study and analysis of the state of the art of power supplies for battery powered devices is done bearing in mind the following technical aspects:



Fig, 1: Relationship between on and standby states of a communication device with discontinuous transmission

-- Ultra low current consumption without load
-- Isolation

Efficiency and size, although significant, are here considered as less relevant.

Table I shows the technical details of commercial DC-DC converters with similar voltage and current characteristics. Even the non-isolated converters have high consumption without load.

Based upon this information the first objective in the first implementation [8] was the design and development of an isolated DC-DC converter with a no-load consumption through the input below 12mA@12V. This was accomplished with a standard control topology based on a PWM controller.

TABLE I
CHARACTERISTICS OF COMMERCIAL DC-DC CONVERTERS

Manufacturer	Model	Vi (V)	Vo (V)	Io (A)	Ii (Io=0) (mA)	η (%)	Isol.
TRACO POWER	TEN 5-1210	12	3.3	1.2	20	77	yes
XP Power	JCA0412S03	12	3.3	1.2	38	83	yes
RECOM	RW-123.3S	12	3.3	0.7	21	65	yes
C&D Technologies	HL02R12S05	12	5	0.4	40	60	yes
BOURNS	MX3A-12SA	12	3.3	3.0	11	93	no
RECOM	R-78A3.3-1	12	3.3	1.0	7	81	no

The implementation presented in this paper has the objective of highlighting the details for the design and development of an isolated DC-DC converter, with a consumption below 1mA@12V, using a non-standard PFM controller topology.

The questions to be considered to fulfill the two main requirements are:

-- Isolation.
-- Control scheme of the switched regulator.
-- Characteristics of the control loops.

A. Isolation

The isolation between the input and the output is done with the help of a transformer. If the configuration of the switching power supply is a "flyback" or an inverter, the inductance of the transformer is used to store the energy.

The problem is how to feedback the voltage reference from the secondary to the primary side without breaking the isolation. The most common technique solves the problem with an auxiliary windinging or an optocoupler [3].

The auxiliary winding option has several drawbacks. It increases the complexity of the transformer, and it does not provide enough accuracy in the output voltage at low output voltages and with discontinuous loads.

The optocoupler, when the control loop is in regulation, requires a constant current trough the LED on the primary side of the transformer. Fig. 2 shows how to minimize the value of the bias current. The lower limit of this current is fixed by the CRT of the optocoupler at low bias currents (63%@10mA and 22%@1mA) and the reduction of the speed response (2µs@20mA and 6.6µs@5mA). There is another limitation, which is the minimum bias current of the error comparator of the voltage control loop (TLV431 I_{kmin} = 100µA).

The voltage divider that measures the output voltage has to be made with high value resistors in order to minimize their current consumption (R131 and R137). The maximum value of resistance is set considering the input current of the voltage reference, U42, (typically I_{ref} = 0.5µA) and its input capacitance. The input capacitance may introduce delays that must be adjusted with extra capacitive dividers.

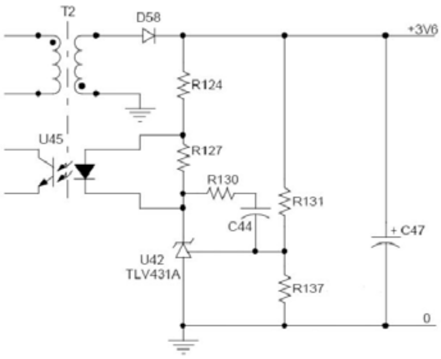


Fig. 2: Regulation loop with error comparator and output voltage divider

The output filtering capacitor (C47 of Fig. 2), tends to be of high value. The only alternative are electrolytic capacitors. These must be chosen with low ESR, (Tantalum, OsCon, Organic Al., etc.), and considering that their leakage current (Kemet T495 100uF 16V I_L=16uA@25°C and 160µA@85°C) could be relevant in certain conditions.

B. Control Circuit

1) The PWM (Pulsed Width Modulation) controller in current mode is the most common control scheme of switching power supplies [12]. The inductance load current is controlled by means of a pulse of variable amplitude and constant frequency [15].

It is possible to stop the oscillator in a PWM controller whenever the loads are low, but this leads to an asynchronous operation of the controller. Also it is not clear how to start again the oscillator when the voltage is out of regulation.

As this is the control scheme of a previous work, more detailed information can be found in the references [8] and [9].

2) The PWM control scheme is suitable for current loads with low variations. If the load is low or even null, the current consumption of the power supply itself becomes relevant and penalizes the consumption of the DC-DC converter in standby mode.

The alternative control scheme for null or low loads is the PFM. It is intended for low quiescent current and applications where there is no required isolation. 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 for having control pulses of variable frequency. The operation mode of PFM control scheme could be found in the application notes [4] [5] or [13].

In essence, a PFM has two one-shot circuits: one defines TON (maximum on-time) and the other TOFF (minimum off-time). The TON one-shot circuit activates the second one-shot. Whenever the comparator of the voltage loop detects that V_{OUT} is out of regulation, the TON one-shot circuit is activated. The time of the pulse is fixed up to a maximum value. This time could be reduced if the maximum peak current loop detects that the current limit is surpassed.

Once the TON one-shot circuit stops, the TOFF one-short circuit starts its operation and the control voltage is held to zero. After this TOFF time, the TON one-short circuit either: stays off if the output is in regulation, or turns on if the output voltage is out of regulation, i.e., below the nominal output voltage.

Fig. 3 represents the waveforms of the input current, I_{IN}, control voltage, V_{CTRL}, and the inductor current, I_L, for different loads. Fig. 4 shows a detailed PFM controller.

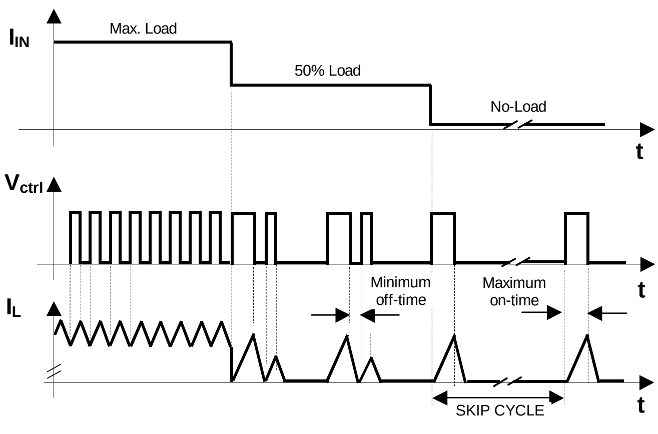


Fig. 3: Inductor current and voltage control waveforms of a PFM controller

With low loads or under no-load state the TOFF on-shot circuit is activated and the control device only lets the current flow to the inductor when an output voltage threshold is reached. If there is enough load, the circuit will use the maximum on-time mode, which works similar to a PWM. Hence the PFM control scheme has two modes of operation:

-- Continuous conduction. With high output loads the power supply operates in continuous conduction mode. In this mode, current always flows in the inductor, and the control circuit adjusts the switch duty cycle to maintain regulation without exceeding the switch current capability. This provides good load-transient response and high efficiency.

-- Discontinuous conduction. In this mode, when the load is close to zero or low, the current through the inductor starts at zero, rises to a peak value, then ramps down to zero. Although efficiency is still good the output ripple increases slightly. This ringing is to be expected and poses no operational problems. The ringing appears at the voltage output as a voltage ripple with a long period (see V_{OUT} on Fig. 8).

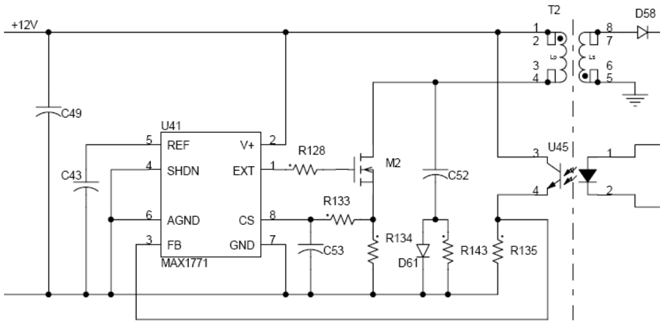


Fig. 4: Detail of a PFM controller

The advantage of PFM over PWM is PFM's lower current consumption under no-load conditions. The voltage control frequency is lower with light loads, so that the power loss associated with switching is less than that of a comparable fixed-frequency PWM system. So the main advantage of the PFM is its efficiency under no-load conditions, i.e., its low quiescent current. The PFM activates the internal electronic circuits only when the voltage is below the comparison level. The only current consumption is generated by the parasitics of the passive components, the leakage currents of the active devices and the consumption of the control electronics.

The disadvantage of the PFM is the variable frequency operation of the control circuitry, thus the EMC is trickier to solve. Nevertheless the energy og the EMC is distributed along the spectrum instead of being placed on a fixed frequency, which has certain advantages.

III. Objective

The main objective is to define the isolated power supply architecture, for battery powered electronic devices with discontinuous loads, that provides the lowest current consumption.

The second objective is to design an isolated power supply with a non-standard isolated PFM controller in current mode for a commercial application. The power supply designed must fulfill the requirements of current consumption and in doing so the technology limits must be reached. Also, the electronics components must be standard to ease the industrialization.

IV. Description

Due to the harsh environment where the device is going to be used, , there is need for galvanic isolation. The power supply topology is a step-down because the battery pack of the application has a nominal voltage of 12V and the internal electronic circuits operate at 3.6V nominal. Fig. 5 shows the schematic diagram of the DC-DC switching regulator designed.

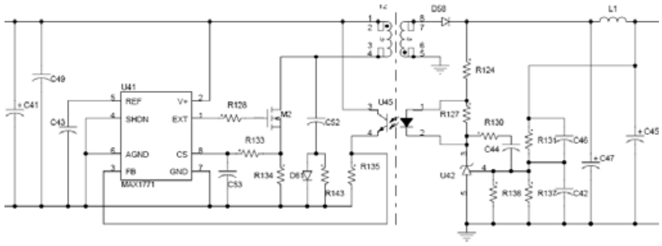


Fig. 5: Schematic of an isolated PFM flyback DC-DC converter.

To develop the circuit, several alternatives to the PFM controller and the precision reference where examined. The other components were chosen for minimum current consumption.

A. *Error Comparator*

The precision reference is used as an error comparator and could be implemented, for example, with the classic IC TL431. In this application it could not be used because V_{REF} = 2.5V which makes the comparison voltage, $V_{A\text{-}Kmin}$, very similar to the output voltage of 3.6V. $V_{A\text{-}Kmin}$ is equal to V_{REF} plus the voltage drop on the optocoupler LED, U45, and the voltage drop on R124.

There are several alternatives to the TL431; one of the most suitable integrated circuits is the MAX8515A from Maxim. This IC has a reference voltage of 0.6V with a 1% tolerance in the temperature range of –40 to +85°C. If a lower output voltage was required, this circuit is the best option, because the $V_{A\text{-}Kmin}$=V_{REF} ($V_{A\text{-}Kmin}$ = 0.2V) does not represent a limitation.

The option finally chosen was the TLV431C because it is available thru several manufactures and its characteristics are good enough to fulfill the output voltage and precision requirements (V_{REF} =1.24V, 1% tolerance from 0 to 70°C).

The current consumption of the output voltage divider is fixed to 7μA. Because of this, the 0.5μA required by the reference input plus its thermal deviation, do not affect much the output voltage. Also the voltage measured does not suffer a relevant delay, thanks to the low input capacitance. This fact precludes the need of a capacitive divider to reduce the input capacitance of the precision reference.

In the optocoupler, the phototransistor drains 60μA, ($|I_{FB}|$ < 60nA) which leads to a current flow through the LED of less than 230μA (CTR ~26%).

B. *PFM Controller*

The alternative chosen is the MAX1771. It is a BiCMOS, step-up, switch-mode power-supply controller. It offers certain improvements over prior pulse-skipping control solutions. These advantages are the reduced size of the inductors required due to its 300kHz switching frequency;

the current-limited PFM control scheme which allows 90% efficiencies over a wide range of load currents; and the maximum supply current of 110µA. Maxim has another controller with a current consumption around 16µA (MAX1556).

Besides these advantages the main characteristics of the MAX1771 in a non-isolated application are: 90% efficiency from 30mA to 2A load current, up to 24W of output power and input voltage range of 2V to 16.5V.

C. *Voltage reference and filtering capacitors.*

The resistances of the voltage control loop have been chosen of the highest possible value, a trade-off between current consumption and loop stability. As a result, the current trough the voltage divider is lower than 7µA. As the filtering capacitors are non-ideal, this current must be added to the capacitors leakage current. The leakage current of the filtering capacitors is lower than 20µA. In order to further reduce this current consumption, the filtering capacitors could be replaced by ceramic ones with the following characteristics: 100µF, 6.3V, X5R and 1206 size (Kemet C1206C107M9PAC).

Fig. 7 shows a detail of the prototype developed. Its dimension are below 50 x 30mm. The technical characteristics of the power supply developed are the following:

-- Power = 3.6W.
-- Input voltage range = 10 to 15V.
-- Nominal input voltage = 12V.
-- Isolated power supply (required galvanic isolation).
-- Flyback topology (step-down).
-- Current and voltage feedback control.
-- PFM control scheme.
-- Switching frequency f_C = 300kHz.
-- Maximum constant output current of 1A.
-- Regulated output voltage = 3.6V.
-- Quiescent input current = 0.24mA.

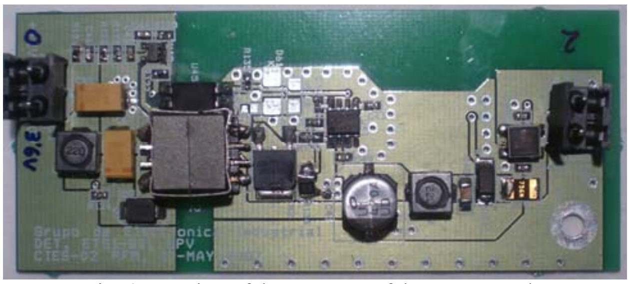


Fig. 6. Top view of the prototype of the power supply

V. .MEASUREMENTS AND RESULTS

The prototype has several wireless modules with discontinuous transmission. The current consumption of the modules reaches a maximum peak of 3A, and the maximum mean current is 1A. To reduce the current peaks and avoid the problems they generate in the performance of the radio, the techniques described in [6] y [7] are used.

The capacitors used are of high value and low serial resistance.

To verify the performance of the power supply the following parameters are measured: the input voltage, V_I, the input current, I_I, the nominal output voltage, V_O, the load current consumption, I_O and the efficiency of the power supply.

Tables II and III show the measurement results performed in the prototype. The measurements include the losses on the common mode input filter and the losses of the protection circuitry. It is also important to highlight and remember that power supplies of low power do not have as good efficiency as power supplies of higher power. High power supplies are usually synchronous, in order to reduce the losses of their active devices.

Table II provides the values of the input and output variables of the power supply under no-load conditions for different input voltages.

TABLE II
CURRENT CONSUMPTION UNDER 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

If this power supply is compared with the design in the previous work [8] [9], it can be seen that the improvement in current consumption is substantial. The current consumption of the power supply, with PFM control scheme, has been reduced to 0,24mA. Eventually the control loop may oscillate in certain load conditions. To prevent self-oscillation, and considering the tolerances in a series production of the components, the values of the resistors and capacitors of the loop must be selected with care.

Table III provides the values of the input and output variables of the power supply at different load conditions. The optimum efficiency is reached at normal conditions with the nominal charge.

TABLE III
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	73.30

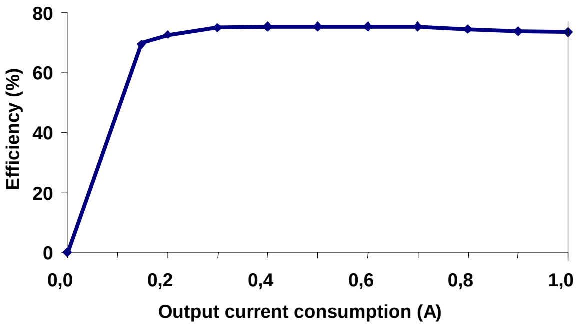


Fig 7. Efficiency of the power supply for different load conditions at the input nominal voltage (12V).

The curve of Fig. 7 shows a graphic of the efficiency behaviour at different loads. The efficiency with no-load is represented as cero because the current consumption of the wireless device, in standby mode and referred to the 3.6V output side, is below 140uA. This current is negligible when compared to the 0.24mA of input current consumption of the power supply under no-load conditions.

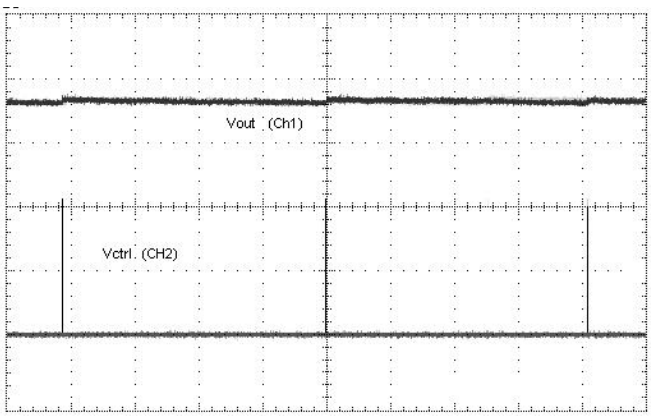


Fig. 8: Output voltage and control voltage without load (10ms/div, CH1 1V/div and CH2 5V/div).

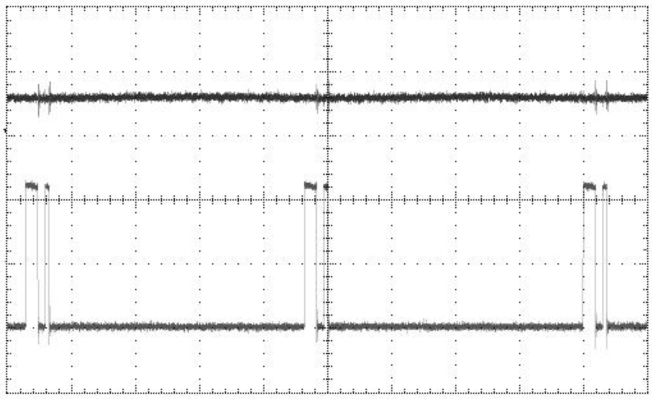


Fig. 9: Output voltage and control voltage for 0.1A load (20ms/div, CH1 1V/div and CH2 5V/div).

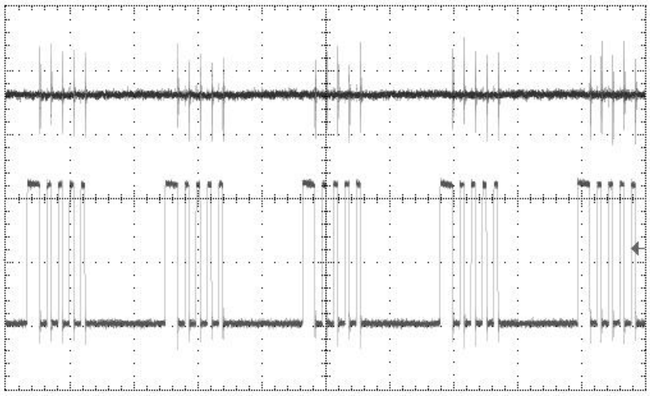


Fig. 10: Output voltage and control voltage for 0.5A load (20ms/div, CH1 1V/div and CH2 5V/div).

The following figures, Fig. 8, 9, 10 and 11, show the output voltage of the power supply and the control voltage applied to the gate of the switching device for no-load, 100mA, 500mA and 1A current output. The pictures illustrate graphically the operation of the PFM control scheme. CH2 of the oscilloscope is on a scale of x5 in voltage. Each square represents a division. The X axis represents the time and the Y axis the voltage.

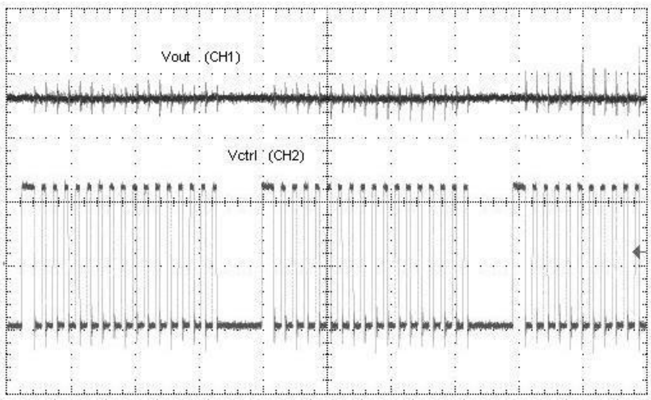


Fig. 11: Output voltage and control voltage for 1A load (20ms/div, CH1 1V/div and CH2 5V/div).

VI. CONCLUSIONS

The objective of designing an isolated power supply with the lowest current consumption under no-load conditions for communication devices has been achieved.

In doing so, a standard application for switching devices has been considered, with a typical 3.6V supply voltage and 1A of maximum current consumption. The study carried out shows that the best commercial isolated DC-DC regulators for power supplies with low current consumption under no-load conditions has a minimum current consumption of 20mA. On the previous work [8] it is showed how it is possible to reduce the power consumption to 5mA with a PWM control scheme.

A low quiescent current consumption isolated power supply has been designed and developed, with the lowest current consumption of the market. The no-load current consumption of the power supply is only 0.24mA.

The prototype shows that the design and development of low quiescent current power supplies must be adapted to each design case due to the control loop characteristics.

Doing so, instabilities and self oscillations in the control loop can be avoided.

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