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Operation of an inverting *DC-DC* converter with charge pumping and *LDO* in the *LM*27762 microcircuit

The paper focuses on the study of operation of an inverting *DC-DC* converter with charge pumping and *LDO*, which are the part of the combined bipolar secondary power supply *LM27762*. The measurements covered two modes amply included in the range of normalised parameters with input voltages equal to 3.5 and 5.5 V, and output voltages –1.8 and –4.9 V, respectively, as well as the mode with an input voltage of 5.0 V and an output voltage –4.7 V, with a difference in the input and output voltage not exceeding the normalised limit of the voltage drop across *LDO*. Pulsations of voltages were measured at various load currents from 15 to 250 mA at the positive and negative poles of the flying capacitor, at the output of the charge pumping system and, in the latter case, also at the output of the microcircuit. Based on the results obtained, it was shown for the first time how at low load currents up to about 100 mA the charge pumping system operates in the burst mode, and at higher currents, it operates in the charge pumping mode with a constant frequency.

Keywords: microcircuit, *DC-DC* converter, charge pumping, inverter, flying capacitor, *LDO*, burst mode, constant frequency mode

Introduction

Low-noise secondary power supplies find ever wider use in portable mobile devices, such as medical equipment, hand-held instrumentation, wireless communication systems, earphones, and others. The primary power source for such consumers in most cases is lithium-ion batteries or rechargeable storage batteries. Apart from the small size requirement, microcircuits of secondary power supplies face high demands on the output voltage stability, small voltage ripples, and high converter efficiency. One of the microcircuit types providing stabilised voltages of positive and negative polarities are microcircuits with charge pumping.

The majority of the manufacturers of electronic components offer microcircuits intended for constructing either boost converters or buck converters, or polar-inverting converters. There is just a small number of microcircuits that can be used for obtaining regulated unipolar stabilised voltage in the mode of both decrease and increase of the input voltage. Operation of such microcircuits is analysed in [1–5].

The main drawbacks of the microcircuits developed in the early 2000’s and being produced to this day, those that employ a classical technology of charge pumping, are fairly high output voltage ripple, normally amounting to 20...40 mV, and considerable drop of efficiency at deviations of the input/output voltage ratios from the optimal values. Numerous attempts have been made to reduce the output voltage ripples and increase efficiency in different modes. In the microcircuit of unipolar *DC-DC* converter *LTC*3245 (*Linear Technology*), according to the information published in 2013 [6], the charge pumping system, unlike the classical scheme, can operate in two modes. The mode with low output voltage ripples is implemented by means of constant charge pumping frequency. Therewith, the output voltage stabilisation system employs two comparators. Each comparator has an adjustable offset, whose value increases (decreases) proportionally to increase (decrease) of the load current. In this way, output voltage stabilisation is achieved through regulation of charge amount transferred within one cycle. The output voltage ripples in this mode do not exceed 20 mV. However, at low load currents in the mode with constant charge pumping frequency, the efficiency factor is reduced considerably. To increase it, the microcircuit can be set to the pumping mode using a pulse burst (*BURST MODE*). A changeover from one pumping mode to the other can be effected by supplying a logic signal of high or low level to the output of *BURST* microcircuit. It must be pointed out that in the burst mode efficiency increase is accompanied by the growth of the output voltage ripples, which, according to [6], typically amount to 50 mV.

Microcircuits of bipolar *DC-DC* converters employing charge pumping have emerged only very recently. In the search systems and releases of electronic component manufacturers, references to just two microcircuits could be found. It follows from the search results that the first one of them was combined microcircuit *LTC*3260 (*Linear Technology*) [7]. Negative voltage is generated by an inverter with charge pumping, followed by *LDO* (linear stabiliser with low voltage drop), and positive output voltage is generated by positive-voltage *LDO*. In this microcircuit, to obtain a higher efficiency factor, the charge pumping system in the negative voltage generation path, similarly to *LTC*3245, operates in the pulse burst mode under low load currents and in the constant frequency mode under high load currents. In the negative voltage path, *LDO* reduces voltage ripples at the output, which is of special importance for the burst mode. According to the data given in the paper [7], respective ripple amplitude at the microcircuit output is below 10 mV.

A later development of a combined bipolar electric power source employing charge pumping is microcircuit *LM*27762 (*Texas Instruments*), considered in this paper.

The paper is a continuance to the cycle of works [1–5] in which *DC-DC* converters with charge pumping were studied. It reflects the results of the first research stage of bipolar secondary power supplies with charge pumping and focuses on the negative voltage generation only.

Object of study and measurement method

In *LM*27762 specifications, the indicated possible input voltage range is from 2.7 to 5.5 V [8]; therewith, the converter allows to simultaneously obtain two output voltages of positive and negative polarity lying within 1.5...5 V, with load currents up to 250 mA. To generate positive voltage of desired magnitude, *LDO* is used. Negative voltage is obtained by means of inverter followed by *LDO*. This paper only considers operation of that microcircuit section which serves to obtain output voltage of negative polarity.

The operating principle of a charge pumping system with voltage inversion [8], as used in *LM*27762, is shown in Fig. 1. The inverter circuit has three external capacitors: input C_{in}, flying C_1, and capacitor C_{cpout}, preceding *LDO* and sometimes designated in [8] as C_{cp}. Inverted input voltage V_{in} is drawn from input capacitor C_{in}. The charge is transferred to capacitor C_{cpout} by means of four switches *S*1...*S*4 and flying capacitor C_1. The transfer cycle consists of two stages. At the first stage, flying capacitor C_1 is charged from the input voltage on C_{in} at closing of switches *S*1 and *S*3, and at the second stage the charge is transferred from C_1 to C_{cpout} at closing of switches *S*2 and *S*4. Since in this case the positive pole of C_{cpout} is connected to ground, voltage at its negative pole, close to value $-V_{in}$, is supplied to the output and to the regulating system via feedback circuit. The algorithm of regulating system operation is not described in [8]. Determining this algorithm was one of the objectives of this paper.

According to [8], clock frequency of the charge pumping system of negative output voltage is equal to 2 MHz. Such a high clock frequency makes it possible to decrease output

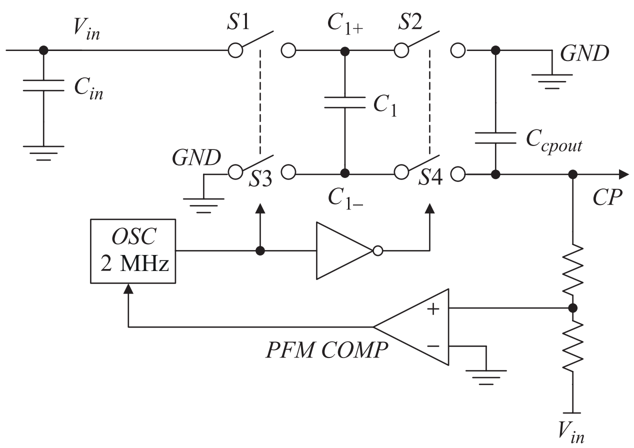

Fig. 1. Voltage inverting principle [8]

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resistance and voltage ripples [8]. Unfortunately, the table of microcircuit electrical characteristics given in [8] is very limited, and the data in it pertain to one case of circuit implementation only, in which input voltage V_{in} = 5 V, the input capacitor and both output ones $C_{in} = C_{out+} = C_{out-}$ = 2.2 μF, flying capacitor C_1 = 1 μF, and capacitor C_{cpout} = 4.7 μF. According to the table of [8], the value of voltage drop across negative *LDO*, given only for one load current of 100 mA and one output voltage of –5 V, is equal to 30 mV. Proceeding from the very limited typical characteristics presented in the graphical form, it just can be concluded that the magnitudes of voltage drop across *LDO* strongly depend on the load current and at 250 mA may reach 100 mV, with output voltage ripples (voltages at *LDO* output) amounting to 1...3 mV.

Analysing all the characteristics of *LM*27762 microcircuit given in [8], it has to be stated that they are plainly insufficient both for determining the algorithms of its operation in different modes and for calculating voltage ripples in different points of its connection layout. This was actually the main objective of research undertaken in this paper.

It was important for the job to have a possibility to avail of a ready-made test printed-circuit board from the *LM*27762 manufacturer – evaluation module *LM*27762EVM [9]. A schematic electrical diagram of this module, with arrangement of check points for connection of instrumentation, is given in Fig. 2.

Since the main causes of voltage ripples in the *LM*27762 microcircuit are accounted for by charge pumping and the regulating system of negative output voltage magnitude, they were the main focus of this paper. To investigate into those causes, measurements of temporal dependencies of voltage at positive U_{flyDC+} and negative U_{flyDC-} poles of 1 μF flying capacitor C_1, with open oscilloscope inputs, were used, as well as alternating component $U_{out\sim}$ of voltage at 4.7 μF capacitor C_{cpout} (see Figs. 1 and 2) with closed oscilloscope input. Voltage at this capacitor is the voltage present at the charge pump regulating system output. It comes to the input of the negative output voltage *LDO*.

Voltage waveforms were recorded with oscilloscope *GDS*-72202 by*GW Instek*, with the use of *FreeWave* software. As a trigger, voltage U_{fly} was normally applied. To ensure high quality of signal recording, the functions of digital filtering and single start, available in the *GDS*-72202 oscilloscope, were used.

In this paper, *LM*27762 microcircuit operation in three different modes was studied. One of the modes was implemented on standard

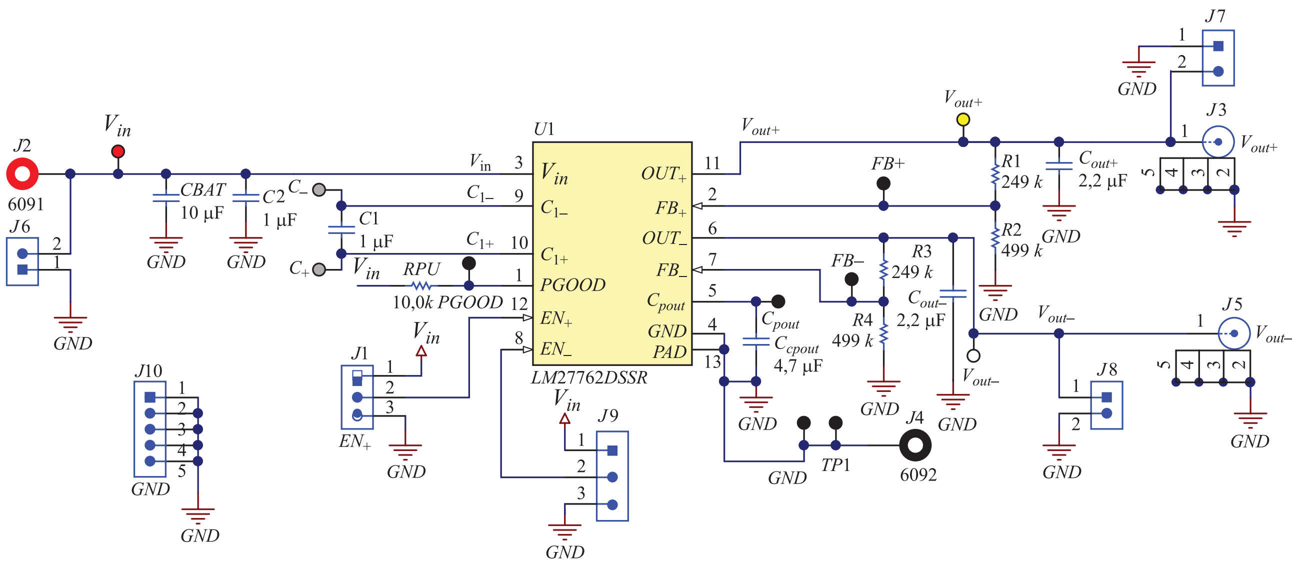

Fig. 2. Schematic of *LM*27762*EVM* module PCB [9]

module *LM27762EVM* in the as-supplied condition, when 249 kΩ and 499 kΩ resistors are used in the regulating system as a voltage divider for the feedback circuit, as shown in Fig. 2. Such divider provides a voltage of 1.8 V at both outputs. In order to implement a typical operation mode of the microcircuit, voltage of 3.5 V was used for this mode as the input voltage.

Measurements in the other two modes were aimed at studying microcircuit operation in the limit cases under high input and output voltages. Those modes, even though called limit ones, do not go beyond the limits specified in the technical documentation [8]. One of them was implemented under input voltage of 5.5 V and output voltage of −4.9 V, and the other under input voltage of 5.0 V and output voltage which decreased from −4.70 to −4.07 V with the increase of load current. The two modes were implemented by replacing resistors in the feedback circuit for resistors with resistance of 82 kΩ and 249 kΩ.

Experiment results

Mode U_{in} **= 3.5 V,** U_{out} **= –1.8 V.** The mode is characterised by a great difference between the input and output voltage magnitudes. Given in Fig. 3 as an example are some of the measurement results for relatively low load currents, equal to 15 and 50 mA. In the left-hand field of the figure, zero levels of signals are shown. Here and below, odd numbers correspond to voltages across the positive or negative pole of the flying capacitor, and even ones, to the AC component of voltage at the charge pumping system output. A digital cut-off filter with frequency of 10 MHz was used in these measurements.

For the load current of 15 mA, five discharge – charge cycles of the flying capacitor and their respective steps at $U_{out\sim}$ can be plainly seen. Under load current of 50 mA, the number of discharge – charge cycles of the flying capacitor increased to 15, while the interval between charge transfer bursts decreased significantly. With further increase of the load current, time

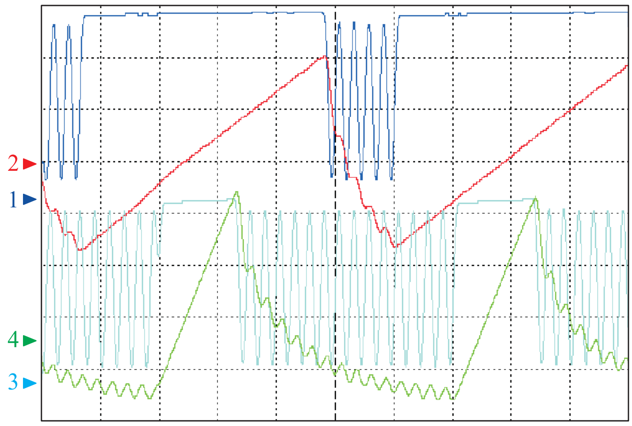

Fig. 3. Signal waveforms (2 μs/div) of voltages U_{flyDC+} (1 V/div) and U_{out}~ (20 mV/div) under different load currents: 1, 2 – 15 mA; 3, 4 – 50 mA

interval between flying capacitor discharge – charge pulse bursts becomes shorter still, and at a certain value of current it disappears altogether.

Fig. 4 shows a comparison between signal waveforms under the currents of 100 mA and 250 mA. Under these currents the flying capacitor discharge – charge cycles occur with a constant frequency equal to 2 MHz.

Along with recording of the U_{flyDC+} signal waveforms across the flying capacitor positive pole, the U_{flyDC-} waveforms were recorded in the paper across the negative pole as well. Fig. 5 shows the waveforms for load current of 50 mA. It can be seen that the results well conform to the data given in Fig. 3 (curves 3 and 4). Fig. 6

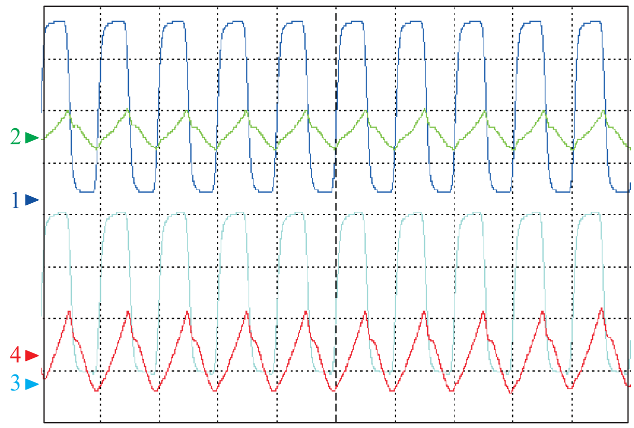

Fig. 4. Signal waveforms (500 ns/div) of voltages U_{flyDC+} (1 V/div) and $U_{out\sim}$ (20 mV/div) under different load currents: 1, 2 – 100 mA; 3, 4 – 250 mA

shows a comparison between signal waveforms under load currents of 50 and 100 mA (burst pumping and constant-frequency pumping).

Mode U_{in} **= 5.5 V,** U_{out} **= –4.9 V.** The measurement results showed that under load current of 15 mA the bursts contain just three cycles of flying capacitor discharge – charge pulses (Fig. 7), whereas under load current of 50 mA, 5 cycles were observed, with the $U_{out\sim}$ decrease over the pumping period amounting to 125 and 160 mV, respectively.

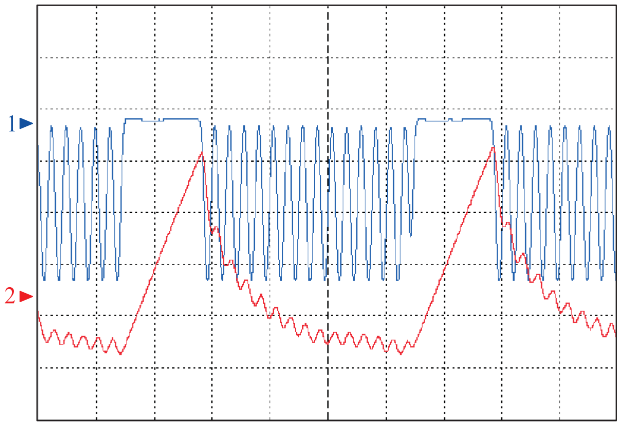

Fig. 5. Signal waveforms (2 μs/div) of voltages: 1 – U_{flyDC-} (1 V/div); 2 – $U_{out\sim}$ (20 mV/div) under load current of 50 mA

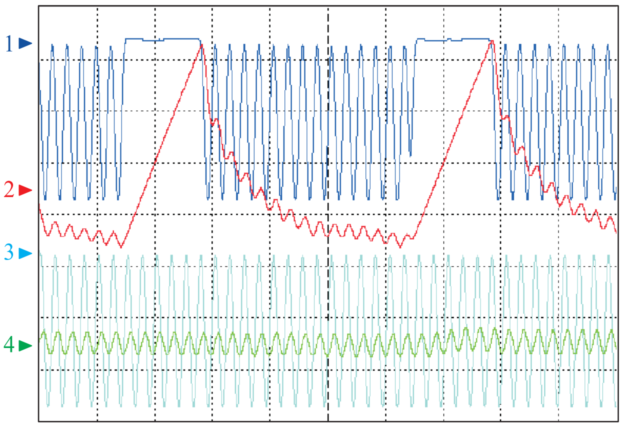

Fig. 6. Signal waveforms (2 μs/div) of voltages U_{flyDC-} (1 V/div) and $U_{out\sim}$ (20 mV/div) under different load currents: 1, 2 – 50 mA; 3, 4 – 100 mA

Under load current of 100 mA, there is a different number of discharge – charge cycles in different bursts. This is demonstrated in Fig. 8. The mode is close to the state of transition from burst pumping to constant-frequency pumping.

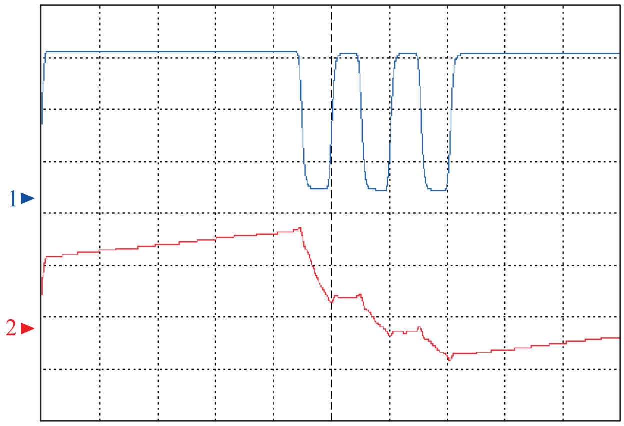

Fig. 7. Signal waveforms (500 ns/div) of voltages: 1 – U_{flyDC+} (2 V/div); 2 – $U_{out\sim}$ (50 mV/div) under load current of 15 mA

Fig. 9 shows a comparison between signal waveforms under the currents of 153 and 220 mA. The pulses follow with the same frequency, but under load current of 220 mA their amplitude is somewhat greater.

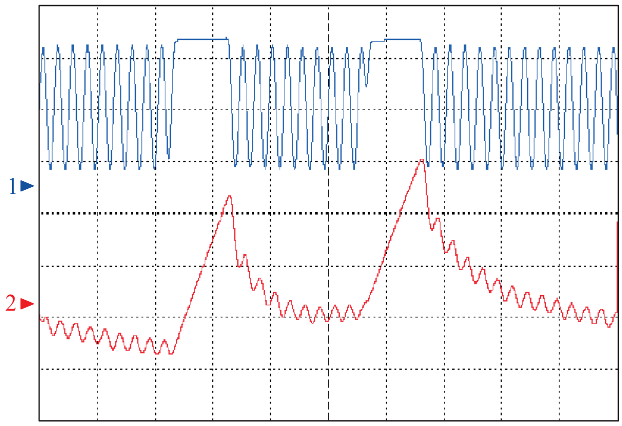

Fig. 8. Signal waveforms (2 μs/div) of voltages: 1 – U_{flyDC+} (2 V/div); 2 – $U_{out\sim}$ (50 mV/div) under load current of 100 mA

Since in many applications of combined *DC-DC* converters, which combine charge pumping with *LDO*, the output voltage ripples are of great importance (see Fig. 2), measurements of such ripples were taken during charge pumping system operation both in the burst mode (low load currents) and in the mode of constant-frequency pumping (high load currents). Two examples of the obtained results are shown in Figs. 10 and 11. It can be seen that in the burst mode the span of output voltage ripples is about 18 mV, with repetition period of about 7 μs, and in the constant-frequency (2 MHz) mode it makes 7 mV.

Mode $\boldsymbol{U_{in}}$ **= 5.0 V,** $\boldsymbol{U_{out}}$ **= –4.7 V.** According to the data provided by the *LM*27762 microcircuit manufacturer [8], with output voltage of −5 V and load current of 100 mA, voltage drop at V_{LDO-} is to amount to 30 mV. Considering this, a mode close to the limit one was selected for the study. It is in this very case, with the same resistors in the feedback circuit and in the absence of load, that voltage settling at the output was equal not to −4.9 V, as was in the previous mode, but to −4.7 V.

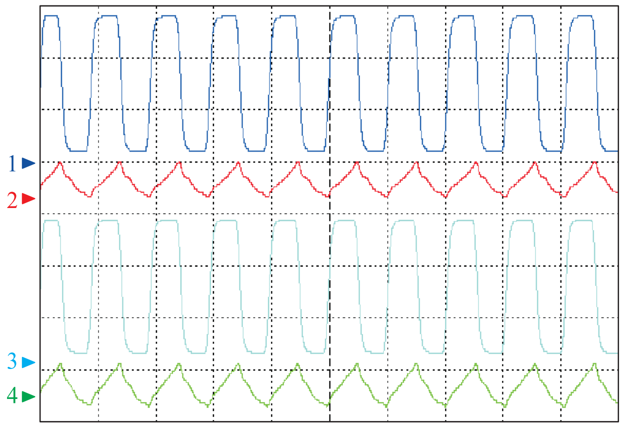

Fig. 9. Signal waveforms (500 ns/div) of voltages U_{flyDC+} (2 V/div) and $U_{out\sim}$ (50 mV/div) under different load currents: 1, 2 – 153 mA; 3, 4 – 220 mA

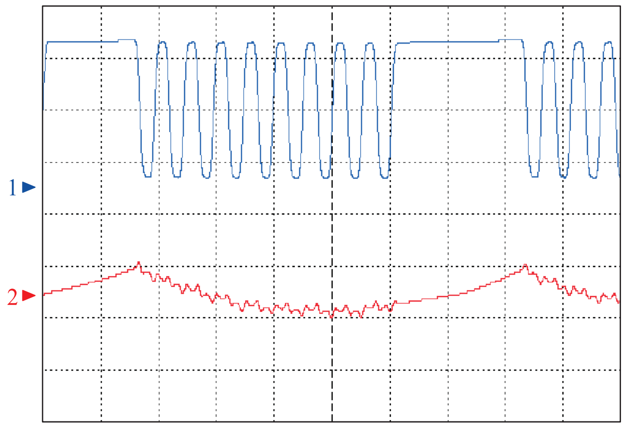

Fig. 10. Signal waveforms (1 µs/div) of voltages U_{flyDC-} (2 V/div) and $U_{out\sim}$ (20 mV/div) under load current of 90 mA

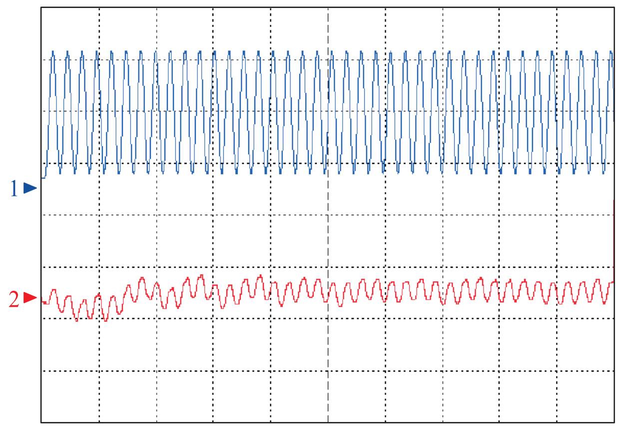

Fig. 11. Signal waveforms (2 µs/div) of voltages U_{flyDC-} (2 V/div) and $U_{out\sim}$ (20 mV/div) under load current of 157 mA

The measurements taken showed that in the absence of load there were just three discharge – charge transfer cycles in the bursts, with the time interval between two consecutive bursts making about 150 µs.

Under load current of 50 mA, there were six discharge – charge transfer cycles, with the time interval between the bursts of about 5 µs.

Under load current of 147 mA, there were no bursts, the discharge – charge cycles followed continuously, and voltage at the microcircuit output decreased to −4.44 V. Under load current of 239 mA, voltage decreased to −4.11 V. Fig. 12 shows a comparison between signal waveforms for load currents of 147 mA and 239 mA.

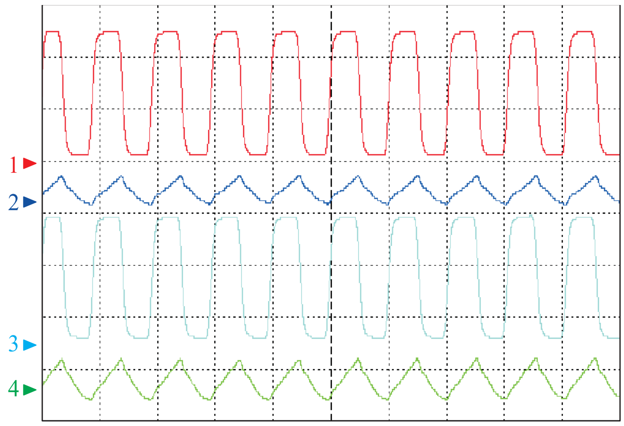

Fig. 12. Signal waveforms (500 ns/div) of voltages U_{flyDC+} (2 V/div) and $U_{out\sim}$ (50 mV/div) under different load currents: 1, 2 – 147 mA; 3, 4 – 239 mA

Analysis of the obtained experimental results

The experimental findings of the study undertaken on the inverting *DC-DC* converter of *LM*27762 microcircuit make it possible to conclude that the information on its operation provided in technical documentation [8] is incomplete and at times incorrect. From the microcircuit description it is impossible to visualise its operation algorithm in different modes. Such information, available in [8], is contained in just two short remarks. The first one is a footnote to the table with electrical characteristics, reading “When V_{IN} = 5.5 V charge pump may enter PWM mode in hot conditions” [8]. The second remark relates to operation with pulse-frequency modulation (PFM): “To minimize quiescent current during light load operation, *LM*27762 allows PFM or pulse-skipping operation. By allowing the charge pump to switch less when the output current is low, the quiescent current drawn from the power source is minimized. The frequency of pulsed operation is not limited and can drop into the sub-2-kHz range when not loaded. As the load increases, the frequency of pulsing increases until it transitions to constant frequency. The fundamental switching frequency in *LM*27762 is 2 MHz” [8]. No registered signal waveforms are given in [8].

The results obtained in this paper show that transition to the PWM mode under the input voltage of 5.5 V is not observed. In none of the microcircuit operation modes PFM is used in the charge pumping system. The discharge – charge cycle frequency is 2 MHz everywhere. Under relatively low load currents, at any values of the input and output voltages (excluding situations when the input voltage exceeds output voltage by a magnitude smaller than voltage drop at *LDO*), the charge pumping system operates in the burst mode, with the discharge – charge cycle frequency in a burst being equal to 2 MHz. The number of pulses in a burst depends on the load current and the upper and lower actuation threshold of the regulating system, which compares feedback voltage with the reference value. The obtained results demonstrate that the difference between the upper and the lower actuation thresholds is great. In the results for the input voltage of 3.5 V and output voltage of −1.8 V, as shown in Fig. 3, under load currents of 15 and 50 mA, it amounts to about 75 mV. In the results for the input voltage of 5.5 V and output voltage of −4.9 VB, as shown in Fig. 7, under load current of 15 mA, it amounts to about 125 mV. Under load current of 50 mA, it is about 160 mV. These are very high values, but the use of *LDO* following charge pumping system makes it possible to reduce ripples to low values of the order of 18 mV, which undoubtedly is a great achievement.

It should be mentioned that, apparently, the mode of a burst of pulses in charge pumping for low load currents was first applied by *Linear Technology* in converter *LTC*3245 [6, 7], receiving the name *Burst Mode® Operation*. Application of a pumping pulse burst under low currents in [6] is implemented on the base of joint use of a conventional system of pumping regulation by the upper and lower limits, together with control and regulation of charge transferred per one cycle. When *LTC*3245 is in the *Burst Mode® Operation*, under light loads, the maximum charge is transferred per one cycle. Regulation of charge current in the burst makes it possible to hold output voltage ripples within 50 mV without the use of *LDO*.

The *LM*27762 manufacturer does not refer to the algorithm of its operation under low currents as the burst mode, but it follows from the measurements taken by the authors of this paper that this is exactly the mode used in this microcircuit. However, voltage ripples at the charge pumping system output are, firstly, much higher in case of *LM*27762 than *LTC*3245, and, secondly, they depend on the load current. The charge transferred per one cycle in the burst mode may depend on a number of factors, in particular, on the resistance of switches, characteristics of the capacitors applied, voltage magnitude at the inverter input, and other. Therefore, control over the amount of transferred charge, or the current during this transfer, is of utmost importance. It would appear that there is no such control in *LM*27762. It is merely the continuous control of the output voltage magnitude that is maintained here. The incomplete last discharge – charge cycles obtained in this paper and shown in some of the figures (see Figs. 5, 6, 8) can be explained exactly by this.

An important item associated with operation of the *LM*27762 microcircuit is its transition, with the load current increase, from the burst mode to the mode of pumping with the constant clock frequency of 2 MHz. Two issues arise here. The first is the transition condition, the second is due to what the constant output voltage is maintained when load current increases. From the findings of this paper it can be seen that with an increase of load current during operation in the burst mode, inter-burst time intervals decrease and the system smoothly transits to the mode of constant-frequency pumping.

As concerns maintaining constant voltage at the output in case of constant pumping frequency, the recorded waveforms of $U_{out\sim}$ demonstrate that with the increasing load current the amplitude of this voltage ripples increases only slightly. Here, maintaining the output voltage constant is provided by *LDO*. When voltage margin at the *LDO* input is small, as it was in the mode with U_{in} = 5.0 V and U_{out} = –4.7 V, with load current increasing, the output voltage decreases.

In conclusion it should be pointed out that the paper reflects on the results of the first stage of experimental research of combined bipolar *DC-DC* converters with charge pumping. This stage covers generation of voltage with negative polarity. At a later stage, it is planned to obtain the necessary results for generated positive voltage and undertake a sufficiently complete simulation of converter operation as a whole.

The research findings presented in the paper were obtained within the framework of the government task order No. 8.5577.2017/8.9 for carrying out a project on the subject “Investigation into noise characteristics and ripples of microcircuits of mobile secondary power supplies”, set by the Ministry of Education and Science of the Russian Federation.

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Работа инвертирующего *DC-DC* преобразователя с накачкой заряда и *LDO* в микросхеме *LM*27762

Представлены результаты исследований работы инвертирующего *DC-DC* преобразователя с накачкой заряда и *LDO*, находящихся в составе комбинированного двухполярного источника вторичного электропитания *LM*27762. Измерения охватывали два режима, входящих с запасом в диапазон нормированных параметров с входными напряжениями, равными 3,5 и 5,5 В, и выходными напряжениями –1,8 и –4,9 В соответственно, а также режим с входным напряжением 5,0 В и выходным –4,7 В с разницей входного и выходного напряжения, не превышающей нормированного предела падения напряжения на *LDO*. Измерялись пульсации напряжений при различных токах нагрузки от 15 до 250 мА на положительном и отрицательном полюсах летающего конденсатора, на выходе из системы накачки заряда и в последнем случае также на выходе микросхемы. На основе полученной информации впервые показано, как при малых токах нагрузки примерно до 100 мА система накачки заряда работает в режиме пачек импульсов, а при бóльших токах – в режиме накачки заряда с постоянной частотой.

Ключевые слова: микросхема, *DC-DC* преобразователь, накачка заряда, инвертор, летающий конденсатор, *LDO*, режим пачки импульсов, режим постоянной частоты.

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