UDC 621.314

ANALYSIS OF CONVERSION POWER OF SWITCHED-MODE BUCK CONVERTERS WITH TWO POWER SOURCES

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АНАЛІЗ ПЕРЕТВОРЮВАЛЬНОЇ ПОТУЖНОСТІ ІМПУЛЬСНИХ ПЕРЕТВОРЮВАЧІВ ПОНИЖУВАЛЬНОГО ТИПУ З ДВОМА ДЖЕРЕЛАМИ ЖИВЛЕННЯ

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АНАЛИЗ ПРЕОРАЗУЕМОЙ МОЩНОСТИ ИМПУЛЬСНЫХ ПРЕОБРАЗОВАТЕЛЕЙ ПОНИЖАЮЩЕГО ТИПА С ДВУМЯ ИСТОЧНИКАМИ ПИТАНИЯ

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Abstract. The article is devoted to the problem of searching for ways to increase the power density of switched-mode electrical energy converters. The analysis of circuitry solutions is aimed at reducing the conversion power – the power that is converted through magnetic field of inductor that converts the parameters of electrical energy. It is shown that this problem is not well understood and requires further research. This determined the purpose of this article. The analysis of electrical processes of switched-mode buck converters with two power sources with different voltages is performed. Relations are obtained for the transfer characteristic and the converted power of the switched-mode buck converters with two power sources with different voltages. The dependences of the output voltage and the conversion power of the converter are researched. The results of the research show that the schemes considered are a more general case of buck converters and have significant potential for increasing power density. The article also provides examples of the use of buck converters with two power sources: inverter and switched-mode voltage regulator of an industrial grid. The article is intended for a wide range of electronics developers, including for specialists engaged in research of switching electrical energy converters.

Key words: electrical energy, switched-mode converter, buck converter, DC-DC converters, AC-AC converters, inverters, conversion power, inductor.

Анотація. Стаття присвячена актуальній на сьогоднішній день проблемі – пошуку способів підвищення питомої потужності імпульсних перетворювачів електричної енергії. Виконано аналіз схемотехнічних рішень, спрямованих на зменшення перетворювальної потужності – потужності, що проходить через магнітні поля дроселів, які здійснюють перетворення параметрів електричної енергії. Показано, що дана проблема недостатньо вивчена і вимагає подальших досліджень. Це і визначило мету даної роботи. Виконано аналіз електричних процесів в імпульсних перетворювачах понижувального типу, здатних працювати від двох джерел живлення з різними напругами. Отримано співвідношення для передавальної характеристики і перетворювальної потужності імпульсних перетворювачів понижувального типу, здатних працювати від двох джерел живлення з різними напругами. Проведено дослідження залежностей вихідної напруги і перетворювальної потужності перетворювача. Результати проведених досліджень показують, що розглянуті схеми є більш загальним випадком перетворювачів понижувального типу і мають значний потенціал для збільшення питомої потужності. У статті також надано приклади використання понижувальних перетворювачів, що працюють від двох джерел живлення: інвертора й імпульсного стабілізатора напруги промислової мережі. Стаття призначена для широкого кола розробників електроніки, в тому числі і для фахівців, що займаються дослідженнями імпульсних перетворювачів електричної енергії.

Ключові слова: електрична енергія, імпульсний перетворювач, понижувальний перетворювач, перетворювач постійної напруги, перетворювач змінної напруги, інвертор, перетворювальна потужність, дросель.

Аннотация. Статья посвящена актуальной на сегодняшний день проблеме – поиску способов повышения удельной мощности импульсных преобразователей электрической энергии. Выполнен анализ схемотехнических решений, направленных на уменьшение преобразуемой мощности – мощности, проходящей через магнитные поля дросселей, осуществляющих преобразование параметров электрической энергии. Показано, что данная проблема недостаточно изучена и требует дальнейших исследований. Это и определило цель данной работы. Выполнен анализ электрических процессов в импульсных преобразователях понижающего типа, способных работать от двух источников питания с разными напряжениями. Получены соотношения для передаточной характеристики и преобразуемой мощности импульсных преобразователей понижающего типа, способных работать от двух источников питания с разными напряжениями. Проведены исследования зависимостей выходного напряжения и преобразуемой мощности преобразователя. Результаты проведенных исследований показывают, что рассмотренные схемы являются более общим случаем преобразователей понижающего типа и имеют значительный потенциал для увеличения удельной мощности. В статье также даны примеры использования понижающих преобразователей, работающих от двух источников питания: инвертора и импульсного стабилизатора напряжения промышленной сети. Статья предназначена для широкого круга разработчиков электроники, в том числе и для специалистов, занимающихся исследованиями импульсных преобразователей электрической энергии.

Ключевые слова: электрическая энергия, импульсный преобразователь, понижающий преобразователь, преобразователь постоянного напряжения, преобразователь переменного напряжения, инвертор, преобразуемая мощность, дроссель.

Switched-mode power supplies (SMPSs) are the basis of the power systems in modern telecommunication equipment. The dimensions and weight of telecommunication devices depend on parameters of SMPSs. Therefore, reducing the size and weight of SMPSs is a one of the main tasks for developers of telecommunication equipment.

SMPSs have to use components which accumulate energy in electrical or magnetic fields: inductors and capacitors. But the power density of these components, especially inductors, is still low. Thus, the SMPSs have a significant weight and size which sometimes can exceed the weight and size of other system units. Therefore, the search for ways to increase the power density of the SMPSs will be actually continued for the foreseeable future.

Usually SMPSs convert electrical energy with inductors, and inductors are one of the biggest components of SMPS. There are two factors which the parameters of the inductors depend on: the operating frequency and the quantity of conversion power – the power that is converted through magnetic field of inductor. The higher the frequency and the less the conversions power then the more compact and lightweight the inductors can be. However, the operating frequency is limited with losses in the components. Therefore, the only effective way to miniaturize the inductors is to reduce the conversion power.

One of the known methods for reducing the conversion power is connecting the conversion part of the SMPS according to the voltage increasing or decreasing schemes. According to known research results [1, 2], the most famous SMPS schemes (Fig. 1) can be obtained with various connections of the input or output of the conversion part to the input and output of the SMPS. In this case, the flyback converter is actually the conversion part of the SMPS, and the conversion power P_{CONV} depends on the input V_{IN} and output voltage V_{OUT}:

$$P_{CONV} = P_{OUT}\left(1 - \frac{V_{OUT}}{V_{IN}}\right) \text{ – buck converter;}$$

$$P_{CONV} = P_{OUT}\left(1 - \frac{V_{IN}}{V_{OUT}}\right) \text{ – boost converter;} \qquad (1)$$

$$P_{CONV} = P_{OUT} \text{ – buck-boost and flyback converters,}$$

where P_{OUT} is the output power of the converter.

It can be seen from (1) that the conversion power of buck converter is less than its output power ($P_{CONV} < P_{OUT}$) (Fig. 2). Thus, the inductor of the buck converter will be smaller and lighter than the inductor of the flyback converter at the same output power P_{OUT}.

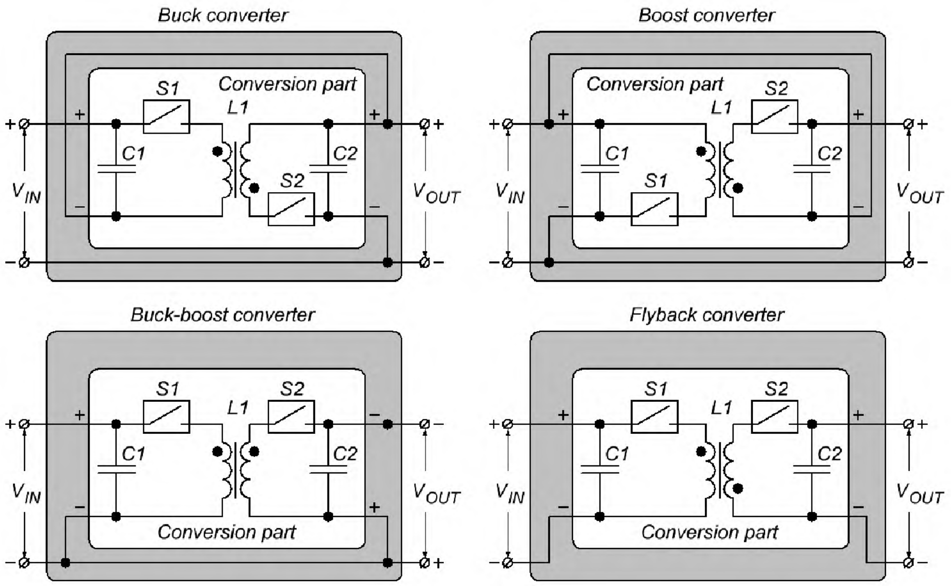

Figure 1 – The most famous SMPSs

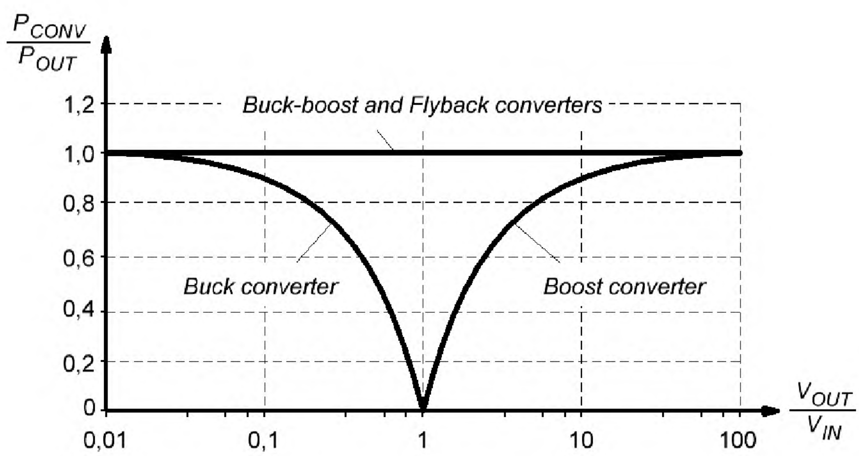

Figure 2 – The dependencies of relative conversion power vs. relative output voltage of most famous SMPSs

But is it possible to further reduce the conversion power P_{CONV} of buck converter? Let's look at the scheme of a traditional buck converter (Fig. 3, *a*). Typically, the buck converter is powered by a single voltage source V_{IN}. But sometimes there are several power supplies with different voltages in the system. In this case, the switches *S1* and *S2* can be connected to sources with voltage V_{IN1} and V_{IN2} to get needed voltage V_{OUT} at the output. However, how much will the conversion power P_{CONV} decrease? The results of research of this issue in the well-known literature are extremely few and they are not systematized.

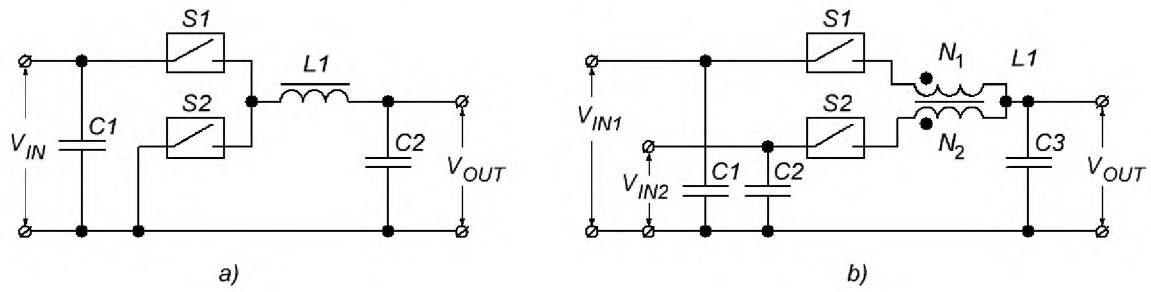

Figure 3 – The traditional buck converter *a)* and buck converter with two voltage sources *b)*

This determined **the purpose of the article**, which consists of researching the processes in a buck converter with two power sources (Fig. 3, *b*) to determine how much the conversion power P_{CONV} can decrease compared to the output power of the converter P_{OUT}.

Let's discover the electrical processes in the buck converter shown in Fig. 3, *b*. The conversion of electrical energy occurs in two stages. At the first stage, the switch *S1* is on, and the switch *S2* is off. At this time, the inductor is connected to the power supply V_{IN1}, the voltage $V_{IN1} - V_{OUT}$ is applied to its active winding with the number of turns N_1 and its current changes by ΔI_1 (Fig. 4):

$$\Delta I_1 = \frac{V_{IN1} - V_{OUT}}{L_1} t_1 , \quad (2)$$

where t_1 is the duration of the first stage of converting; L_1 is the inductance of the active winding with the number of turns N_1.

At the second stage, the switch *S1* is off, and the switch *S2* is on. At this time, the inductor is connected to the power supply V_{IN2}, the voltage $V_{IN2}–V_{OUT}$ is applied to its active winding with the number of turns N_2 and its current changes by ΔI_2:

$$\Delta I_2 = \frac{V_{IN2} - V_{OUT}}{L_2} t_2 , \quad (3)$$

where t_2 is the duration of the second stage of converting; L_2 is the inductance of the active winding with the number of turns N_2.

Let's determine the relationship between the changes of current ΔI_1 and ΔI_2. In a quasi-steady state, the magnetic flux ф(t) in the inductor core should not change during the conversion cycle. It means that the changes of the magnetic flux at the first stage $\Delta\Phi_1$ and at the second stage $\Delta\Phi_2$ must be same:

$$\Delta\Phi_1 = -\Delta\Phi_2 . \quad (4)$$

Based on (4) and the Ampere's circuital law, we can write:

$$\Delta I_1 N_1 = -\Delta I_2 N_2 . \quad (5)$$

Substituting formulas (2) and (3) into formula (5), we obtain the expression for the transfer characteristic of converter:

$$V_{OUT} = \frac{V_{IN1} t_1 N_2 + V_{IN2} t_2 N_1}{t_1 N_2 + t_2 N_1} . \quad (6)$$

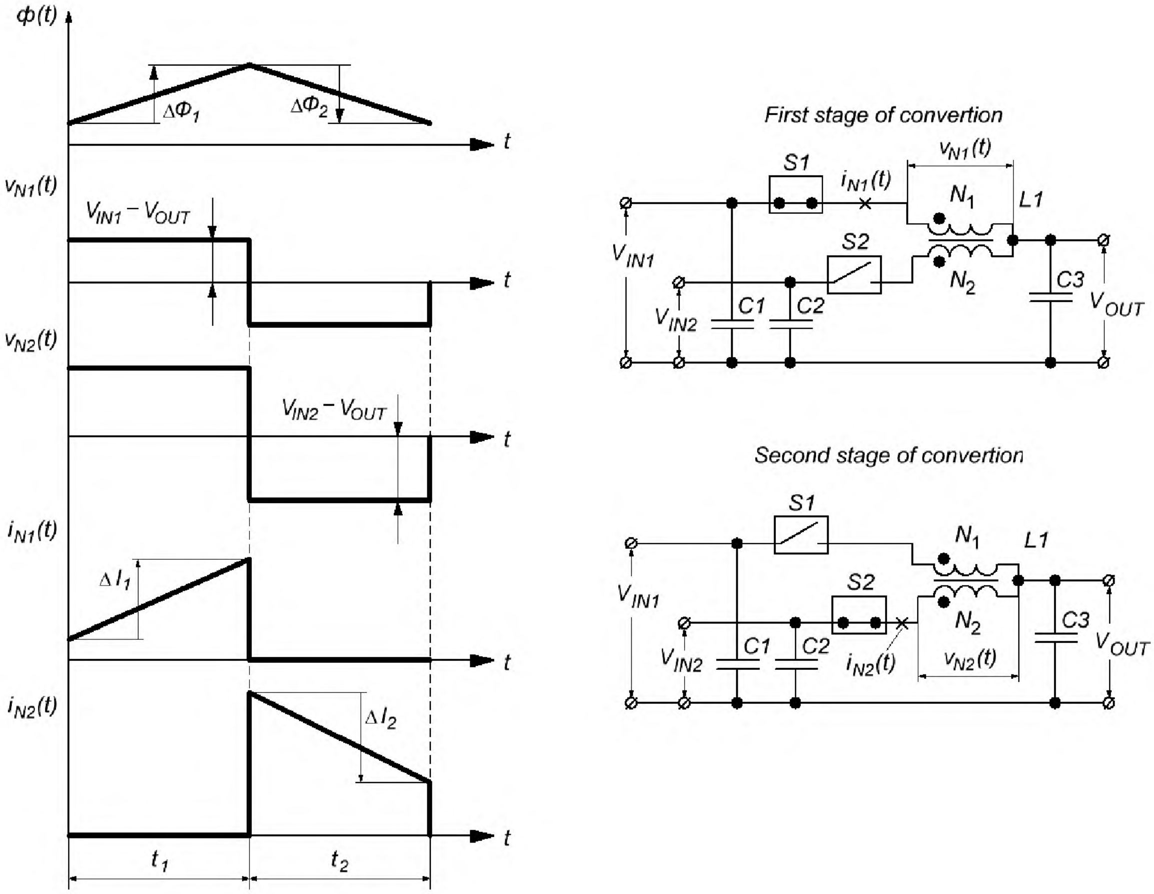

Figure 4 – Electromagnetic processes of the buck converter with two voltage sources

To determine the conversion power, it is necessary to modify the circuit shown in the Fig. 3, *b*. The voltage source V_{IN1} is replaced with a voltage source $V_{IN1} - V_{IN2}$, connected in series with the voltage source V_{IN2} (Fig. 5). It allows us to convert the scheme of Fig. 3, *b* to the traditional buck converter with single power source, shown in Fig. 1, and use the known formula to determine the conversion power (1).

Let's write the formula (1) in the new form:

$$P_{CONV} = P_{OUT\_EKV}\left(1 - \frac{V_{OUT\_EKV}}{V_{IN\_EKV}}\right), \quad (7)$$

where P_{OUT_EKV}, V_{IN_EKV}, V_{OUT_EKV} are the output power, input voltage and output voltage of the equivalent converter, respectively.

The values of P_{OUT_EKV}, V_{IN_EKV} and V_{OUT_EKV} can be determined using Fig. 5:

$$P_{OUT\_EKV} = I_{OUT}(V_{OUT} - V_{IN2});$$
$$V_{IN\_EKV} = V_{IN1} - V_{IN2}; \quad (8)$$
$$V_{OUT\_EKV} = V_{OUT} - V_{IN2},$$

where I_{OUT} is the output current of the converter (load current).

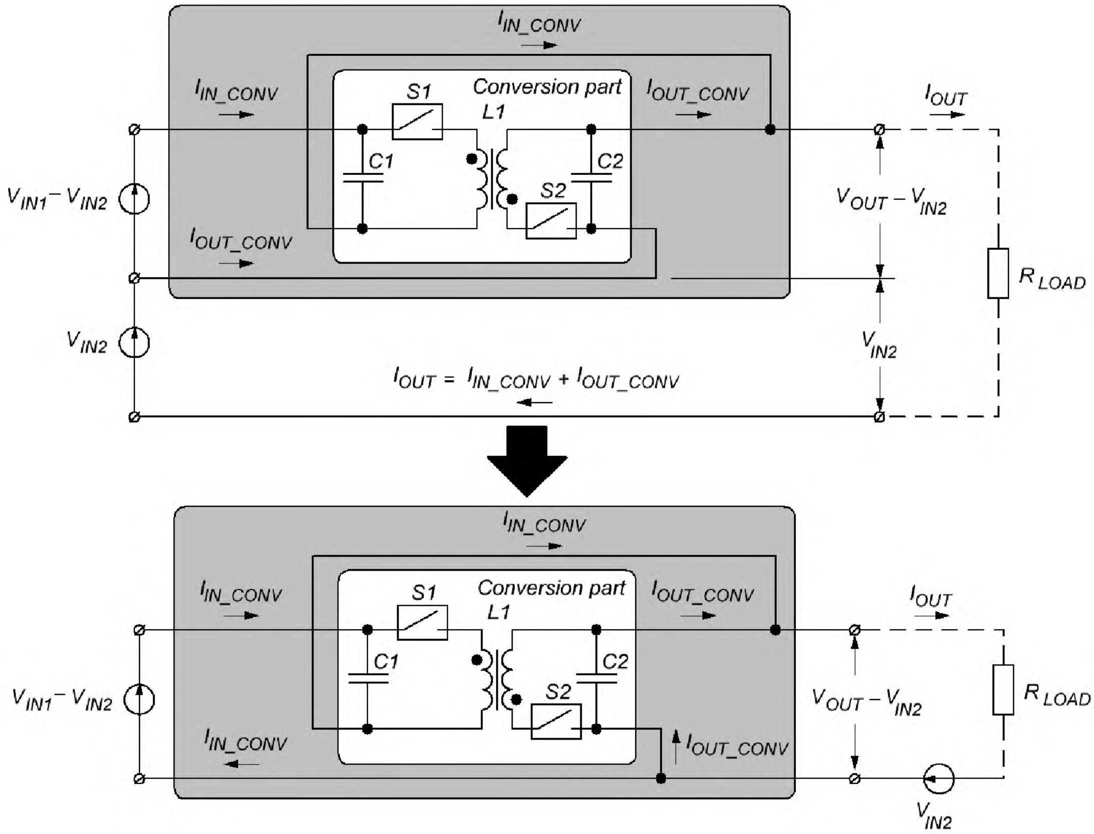

Figure 5 – Modification of the buck converter with two power sources into traditional buck converter with single power source

Substituting (8) in the formula (7), we obtain:

$$P_{CONV} = I_{OUT} \frac{(V_{OUT} - V_{IN2})(V_{IN1} - V_{OUT})}{V_{IN1} - V_{IN2}}. \tag{9}$$

The output power of the converter is equal to:

$$P_{OUT} = V_{OUT} I_{OUT}. \tag{10}$$

Having expressed from (10) the value of the output current I_{OUT}, and substituting it into (9), we obtain:

$$P_{CONV} = P_{OUT} \frac{(V_{OUT} - V_{IN2})(V_{IN1} - V_{OUT})}{V_{OUT}(V_{IN1} - V_{IN2})}. \tag{11}$$

Formula (11) allows us to determine the relationship between the output power of the converter P_{OUT} and its conversion power P_{CONV}, thereby allowing us to determine the required energy capacity of the inductor, and, consequently, its weight and dimensions.

Analysis of the results. From the formula (6) it can be seen that the output voltage V_{OUT} of buck converter with two power sources can only be in the range limited by the voltages $V_{IN1}...V_{IN2}$.When the switch *S1* is constantly on and switch *S2* is constantly off (when $t_1 \to \infty$ and $t_2 \to 0$), the output voltage is equal to the voltage of the first power source ($V_{OUT} = V_{IN1}$).When the switch *S1* is constantly off and switch *S2* is constantly on (when $t_1 \to 0$ and $t_2 \to \infty$), the output voltage is equal to the voltage of the second power source ($V_{OUT} = V_{IN2}$).

Formula (6) can also be represented as:

$$V_{OUT} = \frac{V_{IN1}\left(t_1/t_2\right)n_{21} + V_{IN2}}{\left(t_1/t_2\right)n_{21} + 1}; \quad (12)$$

where $n_{21} = N_2/N_1$ is the inductor turns ratio.

Formula (12) is more convenient for research and allows us to determine how the output voltage of the converter V_{OUT} depends on two key parameters of the converter: the ratio of conversion stages durations (t_1/t_2) and the inductor turns ratio n_{21}. The research results (Fig. 6) show that the inductor turns ratio n_{21} allows us to shift the control characteristic to the region with the best ratio t_1/t_2. It can be useful for developing the converters with a precision output voltage.

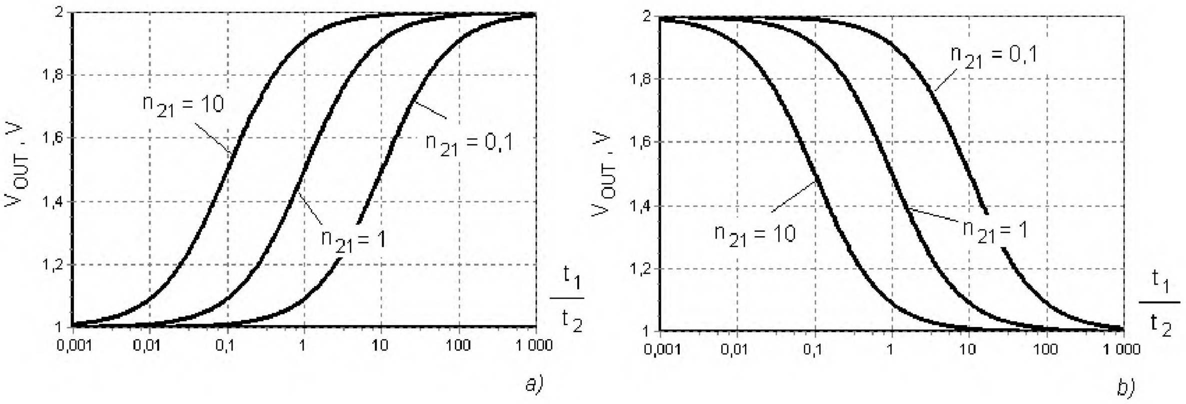

Figure 6 – Dependences of the output voltage V_{OUT} vs. the ratio of conversion stages durations (t_1/t_2) at the input voltages V_{IN1} = 2 V and V_{IN2} = 1 V, *a)* and V_{IN1} = 1 V and V_{IN2} = 2 V, *b)*

An analysis of formula (11) shows that the conversion power P_{CONV} depends on how much the output voltage V_{OUT} differs from the input voltages V_{IN1} and V_{IN2}. In the case when $V_{OUT} = V_{IN1}$ or $V_{OUT} = V_{IN2}$, the converter's output can be connected directly to one of the power sources, therefore, there is no need for energy conversion and the conversion power is zero ($P_{CONV} = 0$). It is obvious that the conversion power reaches its maximum when the output voltage V_{OUT} is as different as possible from the input voltages V_{IN1} and V_{IN2}, that is, when $V_{OUT} = 0{,}5(V_{IN1} + V_{IN2})$.

Substituting this value in (11), we obtain a formula that allows us to determine the maximum value of the conversion power P_{CONV_MAX} for a certain input voltage difference $\Delta V_{IN} = |V_{IN1} - V_{IN2}|$:

$$P_{CONV\_MAX} = 0{,}25 P_{OUT} \frac{\Delta V_{IN}}{V_{OUT}}. \quad (13)$$

From formula (13) it can be seen that the conversion power of the buck converter with two power sources also can be less than its output power. In addition, the smaller the difference between the input voltages ΔV_{IN}, the smaller the conversion power of the P_{CONV}.

It can be seen from formulas (6) and (11) that the traditional buck converter with single power source (Fig. 3, *a*) is a special case of a buck converter with two power sources (Fig. 3, *b*). When the second power source is missing ($V_{IN2} = 0$), these formulas are transformed into known formulas for a traditional buck converter. For example, formula (11) at $V_{IN2} = 0$ transforms into formula (1).

It allows us to obtain the dependences of the conversion power P_{CONV} of both types of converters at single coordinate system (Fig. 7). In this case, the dependence for converter with the missing of a second power source ($V_{IN2}/V_{IN1} = 0$) is equivalent to the dependence of the traditional buck converter shown in Fig. 2.

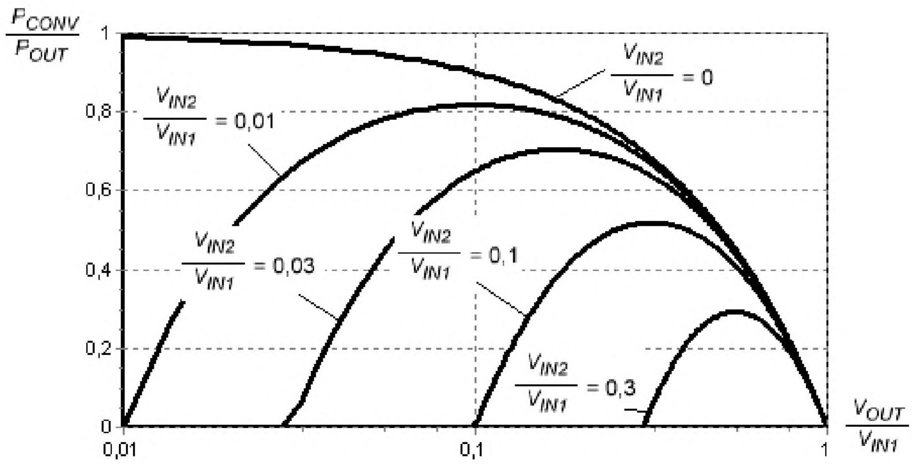

Figure 7 – Dependences of the conversion power P_{CONV} vs. the output voltage of converter V_{OUT}

Examples of using buck converters with two power sources. As can be seen from Fig. 6, the use of two power supplies can further reduce the conversion power P_{CONV} compared to a traditional buck converter with single power supply, and therefore reduce the weight and dimensions of the its inductor. One example of the use of such SMPSs is inverters, some of which operate from bipolar power sources (Fig. 8, *a*).

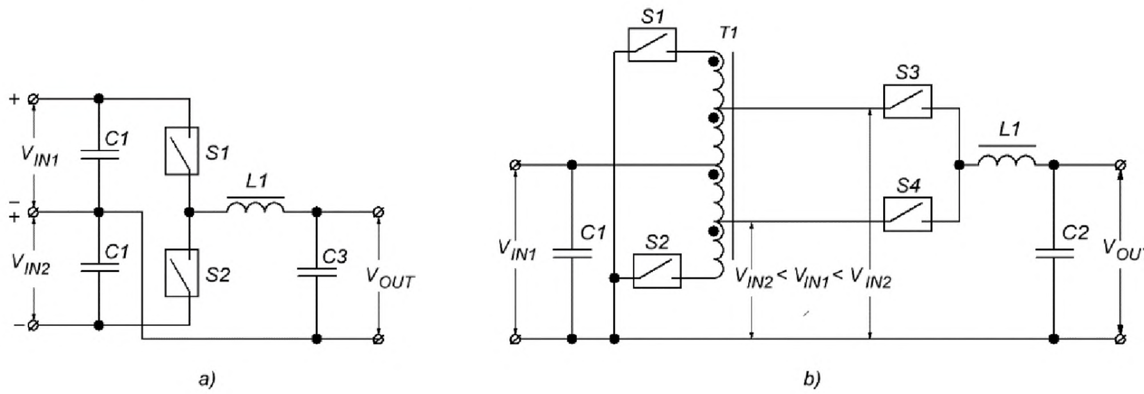

Figure 8 – Examples of using buck converters with two power sources: inverter *a)* and switched-mode voltage regulator for AC power grid *b)*

In addition, a similar conversion method was used in switched-mode voltage regulators for AC power grid (Fig. 8, *b*) [3]. In this case, the primary AC grid voltage was used as the V_{IN1} source, and the increased or decreased AC grid voltage taken from the windings of autotransformer *T1* was used as V_{IN2}. Increasing or decreasing input voltage in the scheme shown on Fig. 8, *b*, is realized by changing the switching algorithms of synchronously controlled switches *S1–S4*. When it is necessary to increase the input voltage, the switches *S1* + *S4* and *S2* + *S3* switch-on synchronously and when it is necessary to decrease the input voltage, the switches *S1* + *S3* and *S2* + *S4* switch-on synchronously. The simultaneous switching-on of the switches *S3* + *S4* (the switches *S1* and *S2* are off at this time) short-circuits the autotransformer *T1*, which is equivalent to connecting the inductor *L1* to the voltage source V_{IN1}.

Conclusions. Buck converters with two power sources are a more common case of buck converters. In some cases they can have less conversion power, and, consequently, they can be lighter, more compact and cheaper than traditional buck converters with single power source.

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DOI: 10.33243/2518-7139-2019-1-2-52-60