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Transistor Converter with Multicell Structure and Combined Control for Micro Resistance Welding Machines

***Abstract**. Micro resistance welding is effective way to reliably join small-scale parts in electronics industry and instrument-making. High quality welded joints are obtained by accurate regulation of welding current with transistor converter module which is one of the most important sub-systems in micro resistance welding machine. Multicell-type transistor converter with combined control, represented in the paper, provides high accuracy of current regulation and high energy efficiency therefore is proposed for use in micro resistance welding.*

***Streszczenie.** Mikro zgrzewanie jest skutecznym sposobem łączenia małych elementów w przemyśle elektronicznym i produkcji oprzyrządowania. Wysokiej jakości połączenia spawane uzyskiwane są przez precyzyjną regulację prądu spawania w przekształtniku tranzystorowym, który jest jednym z najważniejszych podsystemów mikro zgrzewarki. Przedstawiony w artykule wielokomórkowy przekształtnik tranzystorowy o sterowaniu łączonym zapewnia wysoką dokładność regulacji prądu i wysoką sprawność energetyczną, z tego powodu jest zalecany do pracy w układach mikro zgrzewarkach. (**Przekształtnik tranzystorowy o strukturze wielokomórkowej i sterowaniu łączonym dla mikro zgrzewarki oporowej**)*

Keywords: transistor converter, multicell structure, linear and switch modes of transistor operation, micro resistance welding.
Słowa kluczowe: przekształtnik tranzystorowy, struktura wielokomórkowa, sterowanie łączone, mikro zgrzewarka oporowa

Introduction

Transistor converters (TC) are widely used in many different electronic and electro-technical devices and systems. In micro resistance welding machines the transistor converter module regulates welding current and is considered to be one of the most important sub-systems. Micro resistance welding is an effective way to join small-scale parts and is actively used in electronics industry and instrument-making. Joining is performed by squeezing parts between the electrodes and then conducting electrical current through their interface. Generated heat in the welding area rises and reaches the melting temperature, thus creating a welded joint. To obtain high quality weld joints, the electrical current through parts' interface must be accurately adjusted and then precisely controlled in accordance with a predetermined profile [1-3].

It is known that operating TC transistors in their linear region results the most accurate current regulation [4-9]. The main disadvantage of using transistors in linear operation mode is substantial power losses. Losses could amount to kilowatts due to extremely large welding currents typically exceeding hundreds or sometimes thousands of amperes. Operating TC transistors in a switching mode reduces power losses, however does not provide the necessary current regulation accuracy for producing high quality micro resistance welding. Combining both, linear and switch transistor operation modes, provides producing reliable high quality welding while reducing power losses. These two modes could be used simultaneously or sequentially during current regulation process. The overview of known implementations of combined transistor operation modes is represented at [10].

DC transistor converter for micro resistance welding machines which provides improved energy efficiency and high current regulation accuracy due to multicell structure of converter and utilization of combined transistor operation mode is described in the following section.

Converter structure and principle of operation

Block diagram in Fig. 1 represents a welding current pulse generator which includes a multicell transistor converter. Energy Source provides the energy that is required for the welding process. Transistor Converter, which consists of *n* unified cells, regulates welding current in load (welded contact) in accordance with previously specified profile. Control System manages cells' switching and generates control signals U_{CONT1} ... U_{CONTn} that must be tracked by converter cells' currents. Each converter's cell is composed of Power Block and Control Block. Power Block includes two simple converters: converter in linear mode and converter in switch mode. These simple converters of Power Block are built utilizing power transistors which accomplish cell's current regulation. Control Block generates continuous and pulse control signals (U_C and U_P) required by Power Block converters and switches them depending on the phase of current forming. Control System utilizes signals from current sensors in cells and in load for current monitoring.

In some designs of welding pulse generators not only current profile but also profiles of voltage and power in the welding area may be predetermined and controlled [5, 11, 12]. The delivered power is calculated by multiplying signals from current and voltage sensors (Fig. 1).

Fig. 2 illustrates how the multicell converter regulates current. The common welding current i_W in the load is formed as a sum of *n* currents provided by cells. Each of these *n* currents is regulated separately by its cell from 0 to the specified maximum current I_{MAX}. To increase resulting welding current additional cells are gradually activated until the desired current is reached. Algorithm of converter cells' switching is described below.

Initially, from t_1 the current in the load is generated by Cell 1 only. Until the t_2 is reached Cell 1 precisely regulates its current in linear mode in accordance with continuous control signal U_C. When its current reaches the predefined maximum value I_{MAX} (time moment t_2) Cell 1 maintains achieved current value I_{MAX} in switch mode under the effect of pulse control signal U_P until the end of welding. At the moment t_2 Cell 2 joins the welding process and starts generating current to the load.

Cell 2 operates in the linear mode until t_3. After the t_3 mark Cell 2 retains constant current I_{MAX} operating in the switch mode. If additional current is required, next cells join its forming process and repeat the above sequence first operating in the linear mode and then switching to the pulse mode until the desired current is achieved. Fig. 2 demonstrates an example of how the common welding current was generated via six (6) cells activation. Shaded areas on Fig. 2 demonstrate time intervals where current regulation was carried out in linear mode of transistor operation.

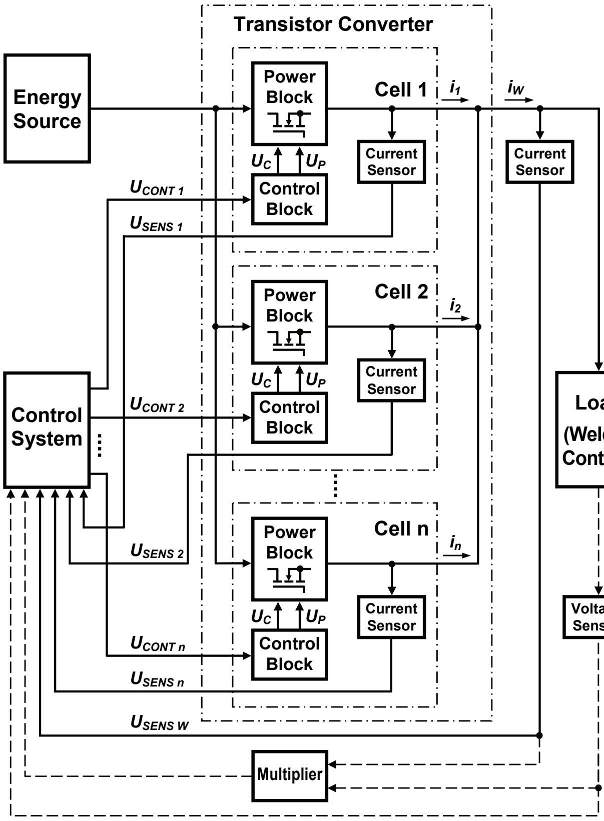

Fig. 1. Welding current pulse generator based on multicell-type transistor converter with combined control

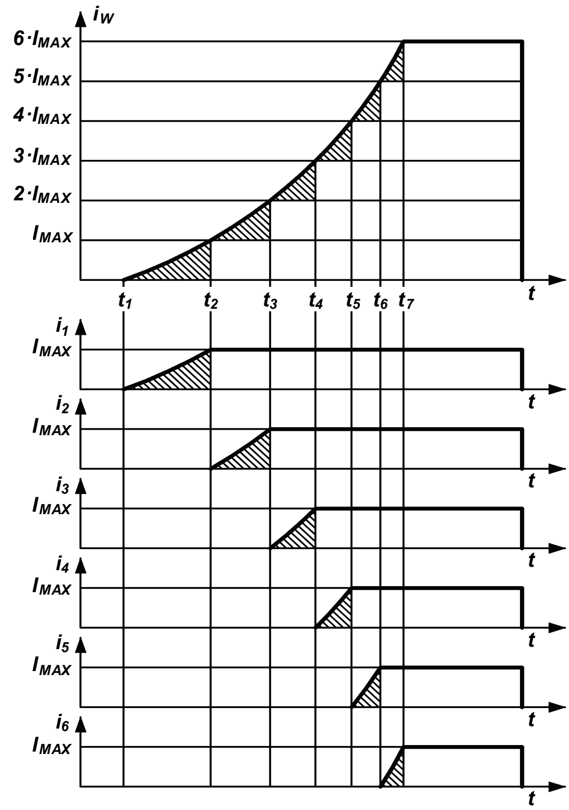

Fig. 2. Welding current diagrams of multicell-type transistor converter with combined control

It is obvious that power losses in the multicell-type converter with combined control are significantly smaller than in converter regulating current in linear mode for the full duration of welding process. Furthermore, the combined control allows for higher accuracy of current profile tracking as it operates in linear region of transistor output during crucial time intervals of current forming.

Fig. 2 illustrates a typical current waveform for micro resistance welding. It includes two stages:

– initial gradual current increase according to specified profile that is determined by strict welding conditions (material and thickness of parts);

– current stabilization at maximum level until the welding process is completed.

Special characteristics of the welding current profile depend on the particulars of the electro-physical processes in the welding contact [1-3, 5]. The initial stage of gradual current increase is the crucial stage in achieving high quality weld joints, therefore welding current changes during that stage must be accurately controlled.

Converter Cell Structure

The converter cell, as it is shown in Fig. 3, is composed of two main blocks: Power Block and Control Block. The Power Block consists of two types of converters adjoined in parallel: Converter in Linear Mode and Converter in Switch Mode. Control Block generates the required control signals for both converters: continuous control signal and pulse control signal. Control signals' switching is performed by Switch Block.

Continuous control signal U_C is generated by Continuous Control Block and is equal to the difference between signal from Control System U_{CONT}, which specifies cell's current waveform, and the signal U_{SENS}, which is proportional to real cell's current value measured by current sensor. The obtained signal corrected by Continuous Regulator and adjusted by Amplifier then enters Converter in Linear Mode.

Pulse control signal U_P is generated by Pulse Control Block. First, the signal of difference between the signal U_{MAX}, which is proportional to specified maximum current value, and the signal U_{SENS}, which is proportional to real cell's current, is formed. The signal U_{SENS} initially passes through Low Pass Filter to reduce its high frequency component. Then Pulse Regulator corrects the obtained

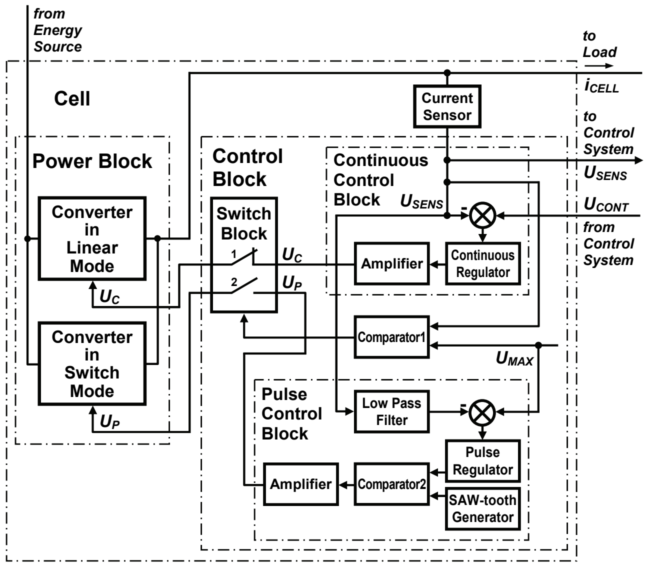

Fig. 3. Converter cell structure

signal of the difference for further comparing it with SAW-tooth Generator signal by Comparator 2. The resulting output signal of Comparator 2 is formed as a sequence of rectangular pulses and is defined as pulse control signal U_P. The amplitude of the earlier obtained differential signal controls the Pulse Width Modulation (PWM).

Comparator 1 compares U_{SENS} with U_{MAX} and registers the moment when cell's current achieves specified maximum level. The output signal of Comparator 1 is used as the control signal for Switch Block. During the initial stage of cell's operation the output signal from Comparator 1 sets Switch Block to allow continuous control signal U_C pass to Converter in Linear Mode. When cell's current achieves specified maximum level, the output signal from Comparator 1 changes and sets Switch Block to allow pulse control signal U_P pass to Converter in Switch Mode.

Control Signal Forming for Converter Cells

Fig. 4 illustrates basic principle of control signal forming for converter cells. The reference signal U_{REF}, which defines the load current profile, is generates by Reference Signal Generator of Control System. The control signal U_{CONT1} for Cell 1 is produced by Subtracting Block 1 as a difference between the reference signal U_{REF} and the feedback signal $U_{SENS\,W}$ from the welding current sensor.

At the start of the welding process the control signal U_{CONT1} is directed to Cell 1. The current sensor in Cell 1 generates the signal U_{SENS1}, which is proportional to the real current. U_{SENS1} is compared with U_{CONT1} by Subtracting Block 2. While the current of Cell 1 is below its maximum value I_{MAX}, both signals (U_{SENS1} and U_{CONT1}) are equal to each other, therefore the output of Subtracting Block 2 is zero. Upon the Cell 1 current reaching its maximum value, the signal U_{SENS1} stabilizes at the value U_{MAX}, which is proportional to I_{MAX}, while U_{CONT1} continues to increase, resulting in a positive differential signal from Subtracting Block 2. The differential signal $U_{CONT1} – U_{MAX}$ is used as the control signal U_{CONT2} for Cell 2. Upon the Cell 2 current reaching I_{MAX}, the signal U_{SENS2} stabilizes at the value U_{MAX}, while U_{CONT2} continues to increase, resulting in a positive differential signal from Subtracting Block 3. The differential signal $U_{CONT2} – U_{MAX}$ is used as the control signal U_{CONT3} for Cell 3. This sequence repeats itself for each successive cell.

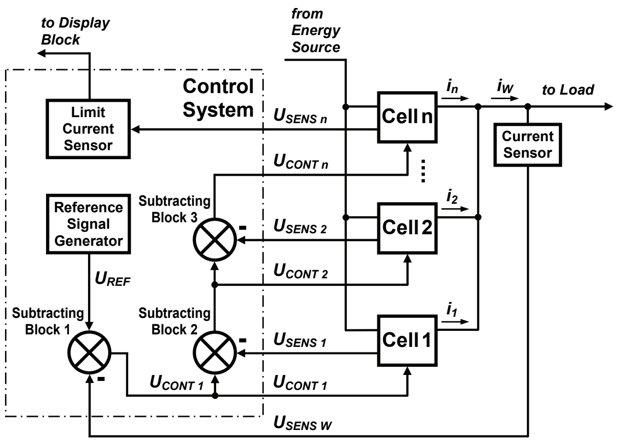

Fig. 4. The forming of control signals for converter cells

The successive formation of control signals $U_{CONT2}…U_{CONTn}$ is described by the formula:

(1) $$U_{CONT\,k} = U_{CONT\,k\text{-}1} – U_{MAX} = U_{CONT1} – (k – 1)\cdot U_{MAX}\ ,$$

where k – the index of converter's cell (from 2 to n).

As soon as the last Cell n begins to operate, the signal $U_{SENS\ n}$ enters Limit Current Sensor which generates a signal for Display Block indicating that possible current level was reached.

When it is required to decrease the load current, cells are sequentially switched off as a result of negative control signal, which is formed when the reference signal is decreasing.

In cases when one or more cells become inoperative the current forming process is not interrupted. The zero signal from a non-operating cell current sensor at one input of subtracting block and the control signal at the other input result in a differential signal which is equal to the control signal, therefore it is used without alteration for the control of the next cell.

Converter Simulation

Converter simulation was carried out to confirm the validity of the above stated current regulation. Fig. 5 illustrates the simulation model designed with MATLAB software. The model includes two cells with each cell consisting of Converter in Linear Mode and Converter in Switch Mode (in Fig. 5 they are labelled as Linear Converter and Switch Converter). Reference Signal Generator generates the signal profile for the load current. The load is imitated by resistance R and inductance L, together they represent the main properties of welding circuit and welded contact.

Simulation parameters:

– maximum cell current:	100 A;
– energy source voltage:	10 V (DC);
– current waveform in the initial stage:	square function;
– load resistance:	3 mOhm;
– load inductance:	300 nH;
– pulse control frequency:	100 kHz.

Fig. 6 illustrates currents obtained from the above simulation. Diagrams (a) and (b) show cells' currents. Diagram (c) shows resulting load current.

Diagrams of currents graphically illustrate the switching process of cells. Initially, Linear Converter 1 is switched on and regulates the load current in accordance with the signal from Reference Signal Generator. When Cell 1 current reaches its maximum value (100 A), Current Detector & Switch 1 switches off Linear Converter 1 and at the same time switches on Switch Converter 1 together with Linear Converter 2. During the switching interval the current of Cell 1 initially sharply falls to "0" and then gradually increases as illustrated in Fig. 6 – diagram (a). The current increase rate depends on smoothing inductance value in Switch Converter 1 (the inductance is inside block Switch Converter). The profile of resulting current in the load is not distorted during the switching of converters, Fig. 6 – diagram (c), as the current gain in Cell 2 compensates current loss in Cell 1 clearly shown in Fig. 6 – diagram (b). Switch Converter 1 keeps the current at 100 A level while Linear Converter 2 coordinates current increase based on the reference signal and compensates the pulsating current of Switch Converter 1.

Upon the current of Cell 2 reaching 100 A, Current Detector & Switch 2 switches off Linear Converter 2 and switches on Switch Converter 2. Both, Switch Converter 1 and Switch Converter 2, continue to supply the resulting current.

Energy efficiency estimation of multicell-type transistor converter with combined control

Energy efficiency estimation of the above represented multicell-type transistor converter with combined control was carried out by calculating the power losses in its transistors and comparing them with the losses in transistors of converter prototype, which operates in linear mode all the time during welding process. The converter prototype architecture and its principles of operation are described in [1].

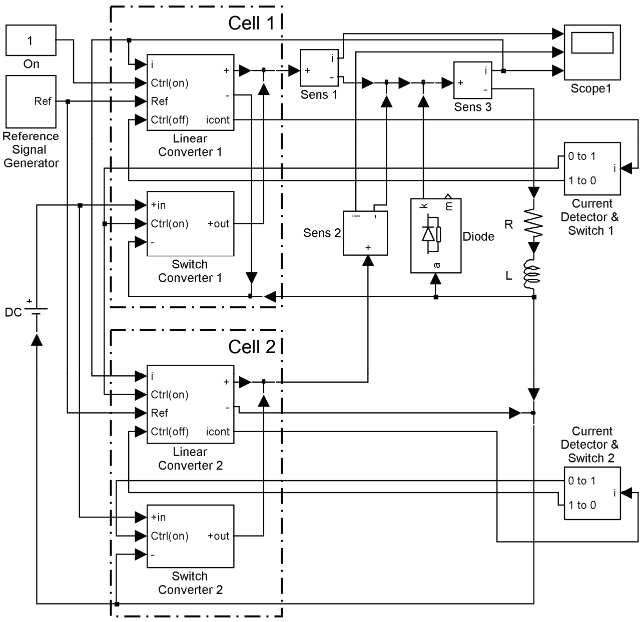

Fig. 5. Simulation model of multicell-type converter with combined control

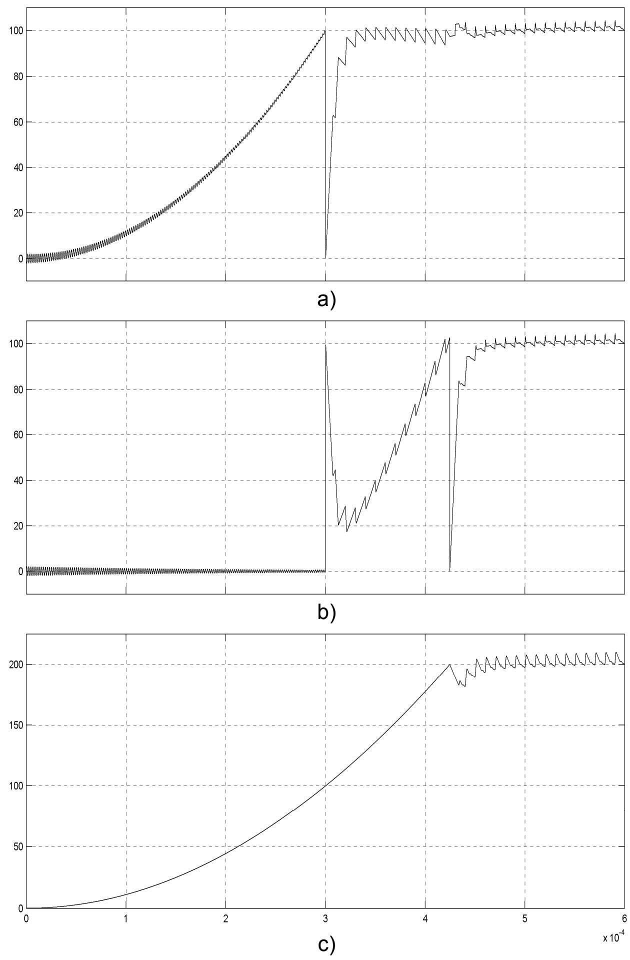

Fig. 6. Diagrams of currents obtained with the simulation of multicell-type converter with combined control

Welding current forming by converter prototype in linear mode is illustrated in Fig. 7 – (a) and the current forming by proposed multicell-type transistor converter with combined control is illustrated in Fig. 7 – (b). The abbreviations for the newly introduced variables are: i_W – welding current through welded contact, $I_{W\,lim}$ – welding current limit value, I_{MAX} – maximum level of converter's cell current.

Shaded areas in Fig. 7 mark the intervals of current regulation in linear mode in order to visually compare power losses.

Due to the fact that initial gradual increase of current is the most important stage in achieving proper welding, energy efficiency was estimated for that stage only.

Averaged power losses in transistors of the converter prototype are represented as:

$$P_{LOSS\,1}=\frac{\int_{t_{start}}^{t_{end}} i_W(t)\cdot\left(U_S(t)-U_W(t)\right)dt}{t_{end}-t_{start}}, \tag{2}$$

where $P_{LOSS\,1}$ – averaged power losses in transistors of converter prototype; $i_W(t)$ – welding current through welded contact; $U_W(t)$ – voltage across welded contact; $U_S(t)$ – energy source voltage; t_{start} – welding start time; t_{end} – end time of initial gradual increase stage.

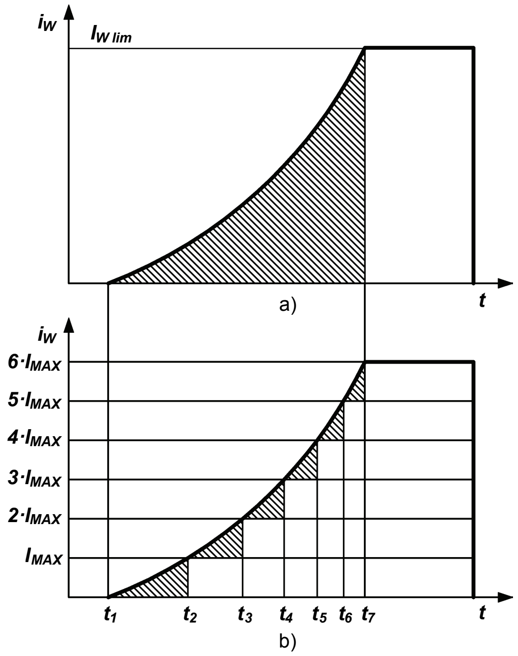

Fig. 7. The diagram of converter prototype current (a) and the diagram of proposed multicell-type converter current (b)

Averaged power losses in transistors of the multicell-type converter with combined control are calculated as:

$$P_{LOSS\,2}=\frac{\sum_{1}^{n}\left(\int_{t_k}^{t_{k+1}}\left(i_W(t)-I_{MAX}(k-1)\right)\left(U_S(t)-U_W(t)\right)dt\right)}{n\cdot\left(t_{end}-t_{start}\right)}, \tag{3}$$

where $P_{LOSS\,2}$ – averaged power losses in transistors of the multicell-type converter with combined control; I_{MAX} – maximum value of converter cell current; n – number of cells in the converter; k – cell index (from 1 to n); t_k – start time when cell k begins to operate; t_{k+1} – stop time when cell k suspends linear mode and cell $k+1$ begins to operate.

The mathematical relationship between power losses in transistors of multicell-type converter with combined control and power losses in transistors of converter prototype may be represented as the relation between welding currents of converters (because of the equality of voltages in the converters) and calculated as:

$$\frac{P_{LOSS\,1}}{P_{LOSS\,2}} = \frac{\left(\int\limits_{t_{start}}^{t_{end}} i_W(t)dt\right)}{\sum\limits_{k=1}^{n}\left(\int\limits_{t_k}^{t_{k+1}}\left(i_W(t) - I_{MAX}(k-1)\right)\right)\Big/ n}, \tag{4}$$

The power losses in switch mode are small comparing to the losses in linear mode, so they were ignored in the formula.

The calculation was carried out with MathCAD software with the following parameters:

– maximum value of cell current: 100 A;
– energy source voltage: 10 V;
– current waveform on the initial stage: square function;
– number of converter cells: 2…20;
– welding current limit: 500 A;
– current initial increase stage ($t_{end} - t_{start}$): 1 ms.

The diagram in Fig. 8 is obtained as a result of calculations by formula (4). It shows the change of relation between power losses depending on the number of converter cells.

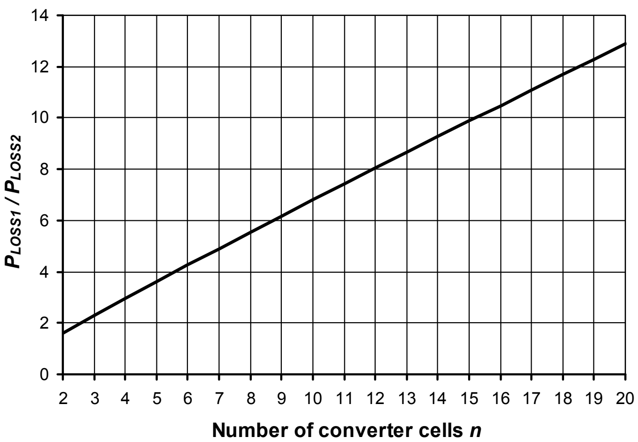

Fig. 8. The diagram that demonstrates the change of relation between power losses depending on the number of converter cells

Conclusion

Carried out simulation and calculation results theoretically confirmed the advantages of the represented multicell-type transistor converter with combined control. The converter allows to obtain high current regulation accuracy and high energy efficiency, so It may be recommended for current regulation in micro resistance welding machines.

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