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NEW PROJECTING TRANSISTOR HALF BRIDGE INVERTER FOR WELDING

Miroslav S. MILIĆEVIĆ [1], Valentina M. NEJKOVIĆ [2]

[1] University of Belgrade, High Technical School
[2] University of Niš, Faculty of Electronic Engineering
Corresponding author: Miroslav S. MILIĆEVIĆ, E-mail: milicevic.miroslav@mts.rs

Abstract. For purposes of technological processes, the power supply is needed. Within thermically processes, entering features are defined, such as production speed for a specific range of products. All mentioned actions demand calculation of power needed for power supply. The type of voltage is determined. The application of alternating and direct voltage is possible. For specific power and type of power supply, a converter is designed. Welding demands alternating voltage at a particular frequency. Such power supplies are realized through transistor inverters which will work at a specific frequency. This paper analyses existing solutions. The main objective of this paper is the representation of the original calculation with more accurate values of inverter components.

***Keywords**:* converter, thermic, inverter, transistor, process.

1. INTRODUCTION

This paper is developed through theory and implemented research over a more extended time. Its base was referenced from work [1–40]. Half-bridge transistor inverter is designed due to simplicity and costs of development. This converter is calculated for the welding of steel pipes at high frequencies.

Most used inverter in practice has a specific type of power that tends to follow technology demands. Unlike this, this paper calculates a converter that will be adaptive to the technological demands of production.

The concrete example will provide a calculation of elements according to existing theory [1–13], which has already been applied in welding. After that, according to identified deficiencies in the procedure, new analytical calculations in this paper are introduced. In this way, more accurate values with fewer deviations are provided regarding existing solutions.

2. METHODS FOR ANALYSIS AND PROJECTING OF TRANSISTOR INVERTERS

Figure 1 presents the electrical scheme of the half-bridge inverter. The inverter is realized using a MOSFET transistor because it should work to the frequency value of 500 kHz. Besides transistors in inverters, capacitors, inductors, resistors, and diodes are used. Control electric controls work of the inverter. The mentioned figure presented the energy part of the inverter, which is the main task of research in this paper.

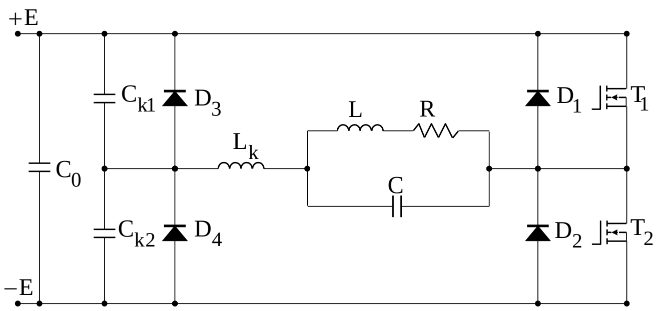

Fig. 1 – Electrical scheme of the transistor inverter.

The three-phase ac voltage is connected to thyristor bridges. Thyristors are controlled electronically to continuously change output dc voltage from 0 to 500 V dc. Electronic regulation using thyristors is not a subject of further analysis in this paper. Authors of this paper in this area also contributed by the publishing of papers, patents, and practical development and installation in the industry.

Behind filter capacitor C_0, there are connected electrolyte capacitors C_{k1} and C_{k2} as separators of dc voltage. Commutation inductivity L_k is connected through capacitors C_{k1} and C_{k2} to the consumer, which presents the circuit with inductivity L and resistance R. The consumer is the inductor that provides energy to the steel tape which transfers into the pipe via the welding process. This highly important circuit of the inverter is presented in Fig. 2, which includes components and specific voltages.

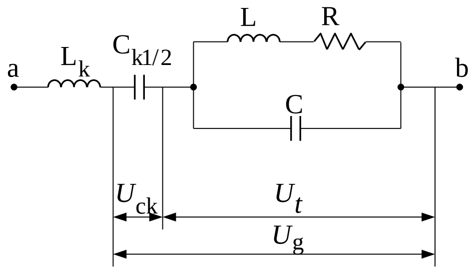

Fig. 2 – Electrical circuit with characteristic components.

The voltage drop on the circuit in Fig. 2 is provided by

$$L_k \frac{\mathrm{d}i}{\mathrm{d}t} + u_g = \frac{E}{2} . \tag{1}$$

According to the literature [1–8], the equations for voltage and current are

$$i_{\sim}(1) = I_m(1)\sin(\theta + \varphi_1) \quad \text{and} \tag{2}$$

and

$$u_g = U_{gm}\sin\left[\theta - (\delta - \varphi_1)\right], \tag{3}$$

where φ_1 and $(\delta - \varphi_1)$ are phases and $\theta = \omega t$.

Using the elementary transformations (1), (2), and (3) yields

$$\omega L_k \frac{\mathrm{d}i}{\mathrm{d}\theta} + U_{gm}\sin\left[\theta - (\delta - \varphi_1)\right] = \frac{E}{2} . \tag{4}$$

Since this paper is devoted to implemented research, there is an example for designing inverters.

Example 1. Design of half-bridge inverter for generator of welding of steel pipes. Input data are the following: P = 50 kW, f = 200 kHz, and E = 500 V. Technology demands through the application [39–40] defined these input data, which the converter must provide.

2.1. Calculation of half-bridge inverter using known methods

This part will be aimed at calculating the inverter using [1–12]. For this type of inverter, there are $\cos\varphi = 0.17$ and $t_0 = 0.1\pi$.

Also,

$$\frac{\omega_{ck}}{\omega} = 1.3 \tag{5}$$

and

$$\mathrm{tg}\,\delta = 1.5 \div 1.6 \tag{6}$$

are adopted, including

$$\mathrm{tg}\,\delta = 1.55\,. \tag{7}$$

The factor Q is calculated using

$$0.5\frac{\omega^2}{\omega_{ck}^2}\left(\mathrm{tg}\,\delta + \sqrt{\mathrm{tg}^2\delta - \frac{\omega_{ck}^2}{\omega^2}}\right) = 0.708\,. \tag{8}$$

The value of the capacity of the capacitor is calculated with

$$C_k = \frac{P}{E^2 f} = 1\,\mu\mathrm{F}\,. \tag{9}$$

Since the value for C_k is divided into two identical capacitors, there will be

$$C_{k1} = C_{k2} = \frac{C_k}{2} = 0.5\,\mu\mathrm{F}\,. \tag{10}$$

Furthermore

$$R_e = \frac{1}{\omega C_k \mathrm{tg}\,\delta} = 0.513\,\Omega\,, \tag{11}$$

$$\varsigma_0^2 = 1 + \mathrm{ctg}^2\varphi = 1.0297; \quad \varsigma_0 = 1.0147\,, \tag{12}$$

$$R_e' = \frac{\mathrm{ctg}\,\varphi\,\varsigma_0^2}{\mathrm{ctg}^2\varphi + \mathrm{pom}} = 5.8076 \quad \left(\mathrm{pom} = (\varsigma_0^2 - 1)^2\right), \tag{13}$$

$$C = \frac{R_e'}{\omega R_e} = 9\,\mu\mathrm{F}\,, \tag{14}$$

and

$$L = \frac{1}{\omega^2 C\,\varsigma_0^2} = 68.33\,\mathrm{nH}\,. \tag{15}$$

The value of the resistance R is obtained from

$$R = \mathrm{ctg}\,\varphi\,\omega L = 14.81\,\mathrm{m}\Omega\,. \tag{16}$$

The voltage drop U_{tm} is calculated using

$$U_{tm} = \frac{\sqrt{2PR}}{\cos\varphi} = 226.4\ \mathrm{V}\,. \tag{17}$$

The phase θ_d is determined by the expression

$$\theta_d = \frac{\pi\omega}{\omega_{ck}} - \frac{\omega}{\omega_{ck}}\mathrm{arctg}\left(2Q\frac{\omega_{ck}}{\omega}\right) = 1.59\ \mathrm{rad}\,. \tag{18}$$

The inductivity of coil L_k is determined with

$$L_k = \frac{QR_e}{\omega} = 289\ \mathrm{nH}\,. \tag{19}$$

Finally, the voltage drop U_{ckm} is provided by

$$U_{ckm} = U_{gm}\sin\delta = \frac{0.5E}{\cos 0.5(\pi - \delta_0)} = 350\ \mathrm{V} \tag{20}$$

and

$$U_{gm} = \frac{U_{ckm}}{\sin\delta} = 416\ \text{V}\,. \tag{21}$$

The maximum current I_{mkp} through the transistor switch is

$$I_{mkp} = E\left[\exp\left(-\frac{\delta_m}{2Q}\right)\sin\frac{\omega_{ck}}{\omega}\delta_m\right]\Big/(\omega_{ck}L_k)\,. \tag{22}$$

where

$$\delta_m = \frac{\omega}{\omega_{ck}}\operatorname{arctg}\frac{2Q\,\omega_{ck}}{\omega} = 0.825\ \text{rad}\,. \tag{23}$$

Replacing the values for δ_m from (23) to (22) provides the current I_{mkp}

$$I_{mkp} = 415\ \text{A}\,. \tag{24}$$

The current I_{0kp} is then

$$I_{0kp} = EfC_k\left[\left(1+\frac{\exp[(t_0-\pi)]}{2QJ}\right)\right] = 113.5\ \text{A} \tag{25}$$

and the current I_0

$$I_0 = EfC_k = 100\,\text{A}\,. \tag{26}$$

The maximum current through the diode is

$$I_{mdd} = i(\theta_d = 1.59) = 266\,\text{A} \tag{27}$$

and

$$I_{0dd} = EfC_k\exp\left(-\frac{\lambda}{2Q}\right) = I_{0kp} - I_0 = 13.5\,\text{A}\,. \tag{28}$$

For a more accurate calculation of values for L_k, there is a correction with

$$\varphi_1 = 2.12\left(1-\frac{\omega}{\omega_{ck}}\right) = 0.489\,\text{rad} \tag{29}$$

and

$$\Delta L_k = tg(\varphi_1 - t_0)/\omega = 72.18\,\text{nH}\,. \tag{30}$$

Finally, the value for the inductivity L_k is

$$L_k = L_k + \Delta L_k = 361\,\text{nH}. \tag{31}$$

Comparison of critical values of invertor with values obtained by PSPICE simulation and in practice, there is a visible deviation. Therefore, this paper identifies the source of mistakes.

2.2. Development of new analytical dependencies of the half-bridge inverter

Analysis in this paper and applied research confirmed that the solution of eq. (4) is not equal to equation (22). Equation (4) will be solved in a simplified manner using experience from works [39–40]. Therefore, eq. (4) will be arranged to move to the "*s*" domain. The solution will be easily defined after finding of inverse Laplace transform

$$i(\theta) = \frac{E}{2\omega L_k}\theta + A - \frac{U_{gm}}{\omega L_k}\left[\cos(\delta-\varphi_1) - \cos(\delta-\varphi_1-\theta)\right]. \tag{32}$$

This equation is present in works and books from the literature [1–8]. To find the maximum, the relation (23) is used. It represents the maximum expression for the current of the transistor (22).

Mathematically, it is incorrect and provides a bad example to researchers who need to design and realize such converters.

The authors of this paper have not noticed the solution in the literature related to the maximum expression for the current (32). Therefore, we will find the first differentiation of the expression (32) in form of

$$\frac{\mathrm{d}i(\theta)}{\mathrm{d}\theta} = \frac{E}{2\omega L_k} + \frac{U_{gm}}{\omega L_k}\sin(\delta - \varphi_1 - \theta) = 0\,. \tag{33}$$

The maximum of function (32) can be obtained if the first differentiation (33) gets equalized with zero. When we find θ such an expression, it represents the value for which the current (32) has reached the maximum value

$$\theta = \theta_m = \delta - \varphi_1 + \arcsin\frac{E}{2U_{gm}}\,, \tag{34}$$

and by exchange of known elements, the numerical value is obtained.

$$\theta_m = 1.143\,\mathrm{rad}\,. \tag{35}$$

Solving eq. (32), and placing that $A=0$ so that there is θ_m from (35), we get

$$I_{mkp} = 567\,\mathrm{A}\,. \tag{36}$$

The voltage drops on the capacitors C_{k1} and C_{k2} can be provided if the expression for current and (θ) integers are within limits $(0, \theta)$

$$u_{ck}(\theta) = \frac{1}{\omega^2 L_k C_k}\left\{E\frac{\theta^2}{4} - U_{gm}\cdot\left[\cos(\delta-\varphi_1)\theta + \sin(\delta-\varphi_1-\theta) - \sin(\delta-\varphi_1)\right]\right\}. \tag{37}$$

Since the voltage in the capacitor is changing from zero to E value, now when the E value is reached, then the $\theta=\theta_d$ transistor gets blocked, and the transfer of the diode starts. The procedure is repeated with the second capacitor also. The relation (37) becomes

$$f(\theta) = \left(\frac{1}{\omega^2 L_k C_k}\right)\left\{E\frac{\theta^2}{4} - U_{gm}\cdot\left[\cos(\delta-\varphi_1)\theta + \sin(\delta-\varphi_1-\theta) - \sin(\delta-\varphi_1)\right]\right\} - E\,. \tag{38}$$

Equation (38) is transcendent, so θ_d can be found by an iterative procedure using Newton's method

$$\theta_{i+1} = \theta_i - \frac{f(\theta_i)}{f'(\theta_i)},\quad i = 0,1,2,\ldots, \tag{39}$$

in which "i" represents the number of iterations. If $i=0$ it can be placed that $\theta=\theta_m$. To complete the procedure, we will find the first differentiation of (38) in the form of

$$f'(\theta) = \frac{1}{\omega^2 L_k C_k}\left\{\frac{E}{2}\theta - U_{gm}\cdot\left[\cos(\delta-\varphi_1) - \cos(\delta-\varphi_1-\theta)\right]\right\}. \tag{40}$$

For calculations using an iterative procedure, the program in software C was developed, and it is available at https://github.com/valentinanejkovic/milicevic/blob/main/sourcecodeC

The use of this program provides

$$\theta_d = 1.5\,\mathrm{rad}\,. \tag{41}$$

To calculate the value of $\theta=\theta_d$, we introduce the procedure by representing the transistor current with

$$i(\theta) = I_{mkp} \sin\frac{\pi}{2\theta_m}\theta . \tag{42}$$

If the capacitor C_k is charged with current(42), the voltage waveform obtained by integration will be obtained

$$u_{ck}(\theta) = -\frac{I_{mkp}}{\omega C_k}\frac{2\theta_m}{\pi}\cos\frac{\pi}{2\theta_m}\theta + C . \tag{43}$$

When the voltage $u_{ck}(\theta)$ reaches the value E, then $\theta = \theta_d$ is obtained,

$$u_{ck}(\theta = \theta_d) = 500\,\mathrm{V} . \tag{44}$$

Arranging and substituting (44) into (43) gives

$$\theta_d = \frac{2\theta_m}{\pi}\arccos\left(-\frac{250\pi\omega C_k}{2\theta_m I_{mkp}}\right) . \tag{45}$$

By changing the known in (45) for the designed inverter, we get

$$\theta_d = 1.425\,\mathrm{rad} . \tag{46}$$

Value deviations for $\theta = \theta_d$ according to equations (41) and (46) are about 5%, which is acceptable for engineering practice.

The current of the inverter diode can be calculated

$$I_{dd} = 245\,\mathrm{A} . \tag{47}$$

When we calculate the value of the current of the inverter transistor

$$I_{0kp} = \frac{1}{2\pi}\int_0^{\pi} i(\theta)\,\mathrm{d}\theta = \frac{1}{2\omega L_k}\left\{E\frac{\pi}{4} - U_{gm}\left[\cos(\delta-\varphi_1) - \frac{2}{\pi}\sin(\delta-\varphi_1)\right]\right\} , \tag{48}$$

after replacement, we get $I_{0kp} = 162$ A. This can be more accurate using the following procedure

$$I_{0kp} = 2\frac{1}{2\pi}\int_0^{\theta_m} i(\theta)\,\mathrm{d}\theta , \tag{49}$$

which, after integration and resolution, provides

$$I_{0kp} = \frac{1}{\pi\omega L_k}\left\{E\frac{\theta_m^2}{4} - U_{gm}\left[\theta_m\cos(\delta-\varphi_1) + \sin(\delta-\varphi_1-\theta_m) - \sin(\delta-\varphi_1)\right]\right\} . \tag{50}$$

The substitution of known elements in (50) gives

$$I_{0kp} = 132\,\mathrm{A} . \tag{51}$$

Since it is already calculated that I_0 = 100 A, the current of the diode will be

$$I_{0dd} = I_{0kp} - I_0 = 32\,\mathrm{A} . \tag{52}$$

The new procedure of calculation θ_m and θ_d is used for the calculation of the maximum current of transistors which is very important for the selection of semiconductors because of cooling. Besides that, analytic dependencies are calculated for discharging and charging capacitors and other new dependencies.

3. RESULTS AND DISCUSSION

After applying known methods from [1–8] using one practical example of designing inverters for HF welding of steel pipes, concrete numerical results are obtained. According to research over more years [13–20], lacks were identified regarding more significant deviations in values for current and voltages, which are specific for this type of inverter.

Therefore, it is suggested to introduce a new algorithm for calculating inverter components. The new expression for the current of the inverter is introduced. The value θ is calculated, and its exchange for current provides the maximum current of the inverter. This current is the current of the transistor, according to which the selection of the transistor is defined regarding current, voltage, and dissipation for cooling.

There is a new expression for the voltage of the capacitor. It helps to calculate θ_d where the capacitor should be charged to the value of E from the regulated converter. The maximum value from the converter is 500 Vdc. Due to the equation, which is transcendent, there is an iterative procedure for which the program software C is provided at: https://github.com/valentinanejkovic/milicevic/blob/main/sourcecodeC.

According to new formulas, other relevant parameters of the inverter can be calculated.

There is a new approximative model for the inverter current, simplifying the calculation of inverter components. To analyze obtained values of methods [1–8] and the new procedure, there will be a table of values for currents in the function of the independent variable θ. This is presented in table T_1.

Table 1

Values for currents in [A] and error of approximation in u [%]

Phase[rad]	*Current transistor according to this paper* I_r [A]	*Current transistor according to the old method* I_s [A]	*Relative error* [%]
0.2	183	189	3.3
0.4	337	317	5.9
0.6	443	389	12.2
0.8	518	414	20
1.0	558	401	28
1.2	567	361	36
1.4	546	304	44
1.6	503	237	53
1.8	444	169	62
2.0	374	105	72
2.2	301	49	84
2.4	232	3,3	98.6
2.6	176	-32	118
2.8	187	-	
3.0	122	-	
3.2	136	-	

Figure 3 presents the graph for the two currents. According to this figure, the current graph via the old method – the lower curve significantly deviates from the new relation for the current. This current will be analyzed for accuracy by comparison with the graph obtained by PSPICE simulation.

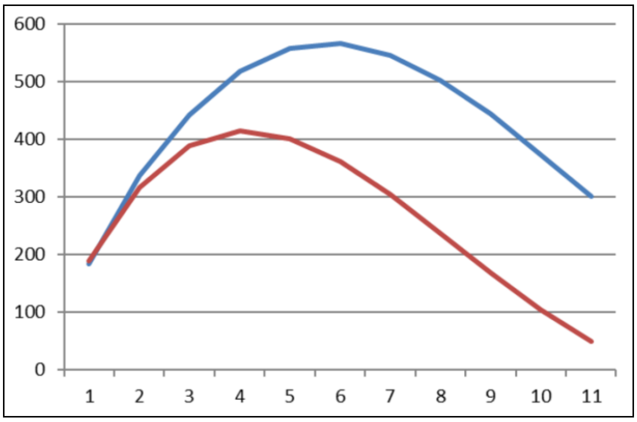

Fig. 3 – Graphical dependency of inverter currents (axes abscise is θ [rad], $\theta = 0.2\,i$, $i = 1,\ldots,11$ and axes ordinate current i_r in [A]).

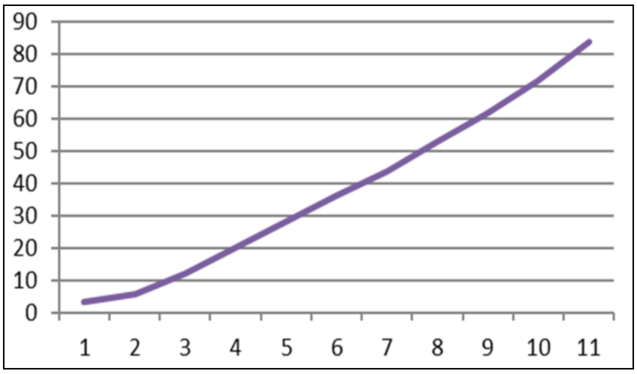

Fig. 4 – Graphical dependency of relative error (axes abscise is θ [rad], $\theta = 0.2\,i$, $i = 1,\ldots,11$ and axes ordinate relative error in [%]).

The last column in table T_1 provides values for the relative error of current deviations. The conclusion is that the expression for currencies by [1–8] develops significant errors. For illustration, there is a graph of relative error for the applied range of variables in Fig. 4.

Figure 4 confirms larger current deviations, which can create significant problems exploiting such inverters.

To estimate the accuracy for the current (32), there will be a simulation on calculated values of the inverter using the software package PSPICE for simulation. The graph for the current of inverters and voltage of capacitors charging is provided in Fig. 5.

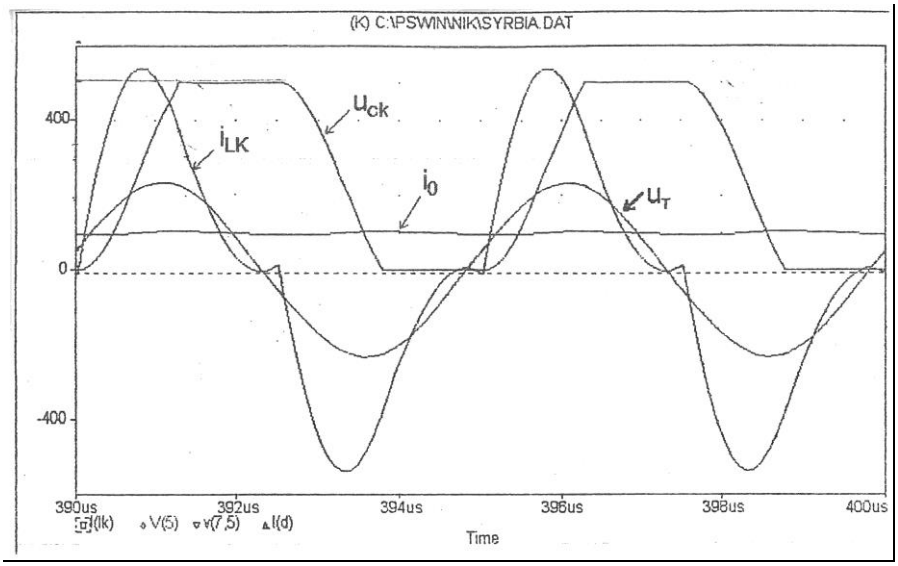

Fig. 5 – Presentation of results of simulation using PSPICE program.

Figure 5 shows that the current is almost the same as the current obtained by (32). The value of currents when they reach the maximum value θ_m is the same. The maximum current is 535 A in simulation. If this value is compared with the value from (36) of 567 A, it is concluded that it is a bit higher. Let's calculate the deviation error

$$\varepsilon = \frac{567 - 535}{567} 100 = 5.6\%\,. \tag{53}$$

An error of 5% for engineering practice is acceptable in the industry. The analysis defined this deviation because while calculating with relation (2), we started only with the first harmonic. As it is known, these systems include higher harmonics, so the error of deviation can be acceptable. As in the practice and conclusions of this paper, it is recommended that the current obtained by (32) decreases by 5 %.

Application of results and suggestions for calculation of inverters, there are conditions for using previously adopted technologies of welding for calculation of all elements of one optimal inverter. This is not possible to calculate using PSPICE simulation. Simulation can be used for fine settings.

4. CONCLUSION

The authors of this paper spent years of research using numerous literature and papers. During that period, they have defined some methods of calculating which provide a rough approximation of elements of inverters. Identifying part of the theory which makes mistakes, there is a new procedure for the exact calculation of values of components of energy electronics.

According to technology demands for welding, such as dimensions of steel pipes, which include diameter and thickness, and desired welding speed. According to the authors' results of this paper, the amount of needed heat is defined. This value is used for the calculation of the power of the generator for welding. The speed of welding is mostly production speed.

When the defined power of the inverter is in the function of the type of material for welding, there is a calculation procedure presented in this work. This paper shows that it is possible to calculate and realize the inverter by simple calculation without applying various software packages.

Regulation of power is feasible by regulating voltage in the thyristor bridge in value from 0 to 500 V. For better accuracy, it is suggested to use a pyrometer for measuring weld temperature. Measuring weld temperature created conditions for automatic regulation of temperature. This application has been practically applied by the authors of this paper.

To get results in this paper, after defining lacks, the authors applied critical analysis. And it was possible to innovate this area by introducing new formulas using iterative methods of numeric mathematics via program software C. Besides that, to estimate the accuracy of new relations, there is the application of the PSPICE package for the simulation of inverters which is finally confirmed by the results of this paper. The paper opens possibilities for engineers and researchers to use the results of this paper and to research the area of inverters and technology of energy electronics which are increasingly applied in practice.

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