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CONTRIBUTION TO THE DESIGN OF INVERTER CONVERTERS FOR HEATING AND WELDING AT HIGHER FREQUENCIES

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The paper shows a significant contribution to analytical calculations of half-bridge and full-bridge inverter parameters, aiming to facilitate the operating process itself while designing systems like these. Attempts have been made within the well-known literature to precisely calculate the waveforms of characteristic currents and voltages of the inverter. Due to its complexity, exact explicit analytical forms have yet to be found, but instead, approximate forms were found. Large formulae for inverter currents and voltages prevented them from being used as an inverter project solution. The paper deals with simple analytical dependences for inverters, with a necessary accuracy from the aspect of engineering practice, that can also be directly implemented into calculations for characteristic inverter components and parameters. To confirm the new analytical expressions and method, the paper presents two interesting inverters that can be applied.

1. INTRODUCTION

The converter and inverter technology theory has been described in references [1–9]. Specific new analytical dependencies are derived in [7–12]. More complete analytical functions with mid- and high-frequency electrothermal applications are investigated in [13–20].

The analyses of half-bridge and full-bridge inverters with energy dosage used in devices for inductive heating and welding of steel tubes are presented. As for the thermal area, these devices can be applied in many other places since there are no limits. The theory presented here and the calculation of new analytical functions are general and, as such, can be applied to other kinds of inverters.

The paper supports already achieved results in the theory and results found in references [21–40] so that through identifying shortcomings, new functions are developed and studied, making the design of both types of inverters easier. Figure 1 shows the half-bridge inverter with energy dosage.

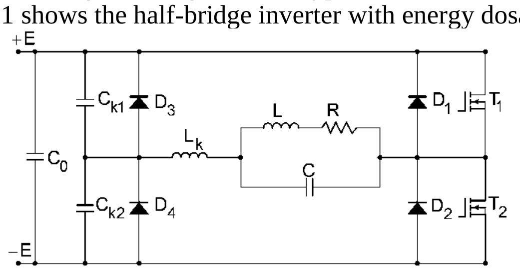

Fig. 1 – Electrical scheme of the half-bridge inverter with energy dosing.

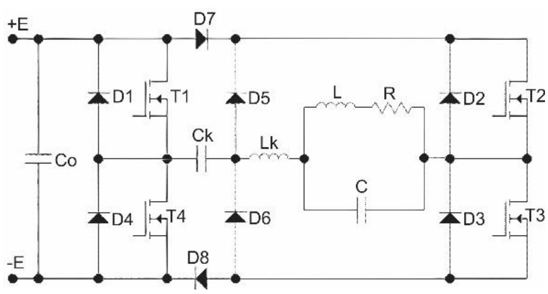

Fig. 2 – Electrical scheme of the full-bridge inverter with energy dosing.

Figure 2 shows the full-bridge inverter with energy dosing. The concept of energy dosing presents the addition of energy via diodes D3, D4 (half-bridge inverter, Fig. 1) and D5, D6 (full-bridge inverter, Fig. 2) after the transistor switch has been switched off. The dosing process lasts up to the end of half a period current through the load when the current value is reduced to zero. We can single out the characteristic circuit from [1–3], shown in Fig. 3.

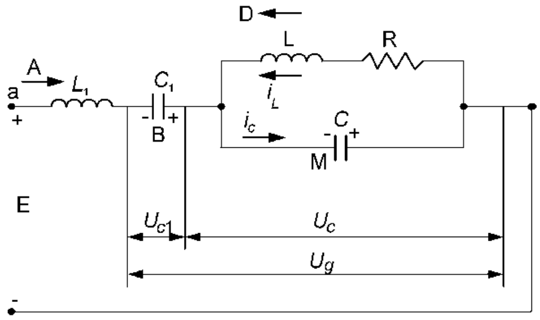

Fig. 3 – Electrical scheme of inverter circuit with characteristic elements.

We can single out the characteristic circuit from [1–3], shown in Fig. 3. The labels A, D, B, and M indicate the energies of those electronic energy components.

Electrodynamical balance equations can be written for the circuit in Fig 3:

$$L_1\frac{\mathrm{d}i}{dt}+\frac{1}{C_1}\int i\mathrm{d}t+\frac{1}{C}\int i_C\mathrm{d}t=E, \tag{1}$$

$$\frac{1}{C}\int i_c dt+Ri_L+L\frac{\mathrm{d}i_L}{\mathrm{d}t}=0, \tag{2}$$

$$i+i_L-i_C=0. \tag{3}$$

Let us introduce from [1–3] the substitutions of the form:

$$u'=\frac{u}{E}, \tag{4}$$

$$i'=\frac{1}{E\omega C}, \tag{5}$$

where the controlling frequency is ω and $\theta = \omega t$. Further,

$$n=\frac{L}{L_1},\ a=\frac{C}{C_1}\ \text{and}\ \cos\phi=\frac{R}{\sqrt{R^2+\omega^2L^2}}. \tag{6}$$

If we substitute the known values, (1), (2), and (3) become:

$$\frac{n}{\xi_0^2}\frac{\mathrm{d}i'}{\mathrm{d}\theta}+a\int i\mathrm{d}\theta+\int i'_c\mathrm{d}\theta=1, \tag{7}$$

$$\frac{1}{\xi_0^2}\frac{\mathrm{d}i'}{\mathrm{d}\theta}+\int i'_c\mathrm{d}\theta+\frac{\cot\phi}{\xi_0^2}i=0, \tag{8}$$

where

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$$\xi_0 = \frac{\omega_0}{\omega} = \frac{1}{\omega\sqrt{LC}}. \quad (9)$$

By identifying the Laplace transformation in (7), (8) and (9), we get

$$\frac{n}{\xi_0^2}[si(s) - A'] + \frac{a}{s}i(s) - \frac{B'}{s} + \frac{i'(s)}{s} - \frac{u'}{s} = \frac{1}{s}, \quad (10)$$

$$\frac{i'(s)}{s} - \frac{M'}{s} + \frac{1}{\xi_0^2}[si'_L(s) - D' + i'_L(s)\cot\phi] = 0, \quad (11)$$

$$i'(s) + i'_L(s) - i'_c(s) = 0, \quad (12)$$

where A' and D' are inductive energies on L_1 and L at commutation ($\theta = 0$),

$$A' = \frac{A}{E\omega C} \text{ and } D' = \frac{D}{E\omega C}. \quad (13)$$

B' and M' refer to the capacitors C_1 and C at commutation we get,

$$B' = \frac{B}{E} \text{ and } M' = \frac{M}{E}. \quad (14)$$

Solving the systems (10), (11), and (12) we get

$$i'(s) = \frac{D'_i}{D}; \quad i'_c(s) = \frac{D_{ic}'}{D}; \quad i_L'(s) = \frac{D_{iL}'}{D}, \quad (15)$$

that is

$$i'(s) = \frac{u_i(s)}{V(s)}; \quad i'_c(s) = \frac{u_{ic}(s)}{V(s)}; \quad i_L(s) = \frac{u_{iL}(s)}{V(s)}, \quad (16)$$

where we get

$$V(s) = s^4 + s^3\cot\phi + s^2\xi_0^2\frac{1+a+n}{n} + s\xi_0^2\cot\phi\frac{1+a}{n} + \frac{a}{n}\xi_0^4 = 0. \quad (17)$$

The authors have foreseen from [7–9] that (17) fulfills the Kantorovich conditions, thus getting

$$i'(\theta) = \sum_{i=1}^{4}\frac{u(s_i)}{V(s_i)}e^{s_i\theta}. \quad (18)$$

where s_i are the roots of the eq. (17). Many examples in practice have proven that zeros of eq. (17) are not real but conjugated and complex so that (18) does not correspond, while the echo is tabular and a combination of the sine and cosine functions.

Newer papers [10–12] deal with new analytical calculations of inverters. Here, we have shown the calculations for both inverters and referred to the conclusions in [7–9], as well as the correct names for currents since combinations of the sine and cosine functions are too difficult for analytical calculations when designing inverters. However, in the inverter design phase, since we have yet to determine the values of components, it is impossible to determine them in such a way. The authors suggest an approximate new analytical calculation of inverter parameters according to the reasons given here.

2. CALCULATION FOR PRACTICAL APPLICATION WITH ANALYSIS AND DISCUSSION

To simplify the calculation of simple analytical values of characteristic sizes of inverters, we will use, as per [7–9], an electrical scheme of the oscillatory circuit given in Fig. 4.

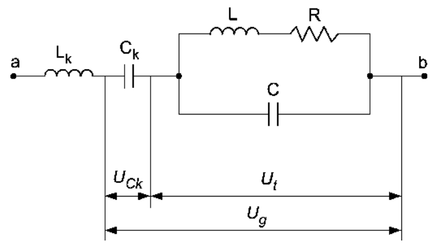

Fig. 4 – Electrical scheme of inverter oscillatory circuit with characteristic voltage parameters.

Half-bridge and full-bridge inverters are realized through MOSFET transistors as switches. Also, some other power semiconductors can be used as switches, but this does not influence calculations.

L_k corresponds to the commutation inductivity, while the capacitor C_k has the key role because it is charged and re-charged from the minimal to the maximal value of the source of supply, and, as a current limitation, it protects the transistors as switches. Components R and L are the load and an inductor in the heating and welding. The compensation capacitor C completes the oscillatory circuit.

Voltages in Fig. 4 describe the condition and working pace of the inverter through a thorough approximation.

2.1. CALCULATION OF THE FULL-BRIDGE INVERTER PARAMETERS

In full-bridge inverters, Fig. 2, the capacitor is charged from $-E$ voltage value to $+E$ voltage value. Thus, a current appears among at the ends of a and b, and we get

$$L_k\frac{\mathrm{d}i}{\mathrm{d}t} + u_g = E. \quad (19)$$

As per [7–9], we get equations for the voltage and current

$$i_\sim(1) = I_m(1)\sin(\theta + \varphi_1), \quad (20)$$

$$u_g = U_{gm}\sin[\theta - (\delta - \varphi_1)], \quad (21)$$

where $\theta = \omega t$, while φ_1 and $(\delta - \varphi_1)$ are phases. If we use (20) and (21) in (19), we get

$$\omega L_k\frac{\mathrm{d}i}{\mathrm{d}\theta} + U_{gm}\sin[\theta - (\delta - \phi_1)] = E. \quad (22)$$

Due to the more complicated and longer calculation of (22) as per [7–9], we are going to use the idea for calculation from [13], and we get the currency form

$$i(\theta) = \frac{E}{\omega L_k}\theta + A - \frac{U_{gm}}{\omega L_k}[\cos(\delta - \phi_1) - \cos(\delta - \phi_1 - \theta)]. \quad (23)$$

The effective solution in [13] is found for the problem of maximal current $i(\theta)$ determined from (23). So, as per [13], if we differentiate (23) concerning θ and equate it with zero, we get

$$\theta = \theta_m = \delta - \phi_1 + \arcsin\frac{E}{U_{gm}}. \quad (24)$$

Suppose we substitute the value in (24) with the switch current (23). In that case, we get the maximal value of the current through a transistor, which is useful for designing circuit elements, especially with the number of transistors in the branch of the bridge, that is, in the whole inverter. The maximum current of this type of inverter is 571 A.

The data for value θ is particularly important when the diode for the energy dosing starts to function, which is often marked as θ_d in literature. The harsh calculation formula for θ_d has been used in [7–9], and a huge error was committed, which caused incorrect current calculations. However, researchers have cited these formulae and filled the tables with the current data, which they read from curves plotted with PSPICE simulation.

The paper's [13] authors have originally calculated the formula for the capacitance C_k. Still, Newton's numerical method for determining value θ_d was applied due to the transcendent equation. A computer has been used for this occasion, and the correct mathematical approach and correct values have been acquired.

Research in this paper aims to get a simple way of determining θ_d, which can be applied in the design and practical realization of the inverter.

Since we have an analytical formulation for the current (23) switch and the point of its maximum, as per (24), we are introducing a new idea in this paper in a way that we are going to assume a new analytical formulation for the switch current, in the form of

$$i(\theta) = I_{mkp} \sin \frac{\pi}{2\theta_m}\theta, \tag{25}$$

where I_{mkp} shows the maximal value from (23) for θ_m as per relation (24).

The analytical formulation of the inverter switch current (25) is good and simple for further analytical calculations. We will calculate and find a new analytical formulation of the voltage for charging and re-charging the capacitor C_k. By integration of (25), we get

$$u_{ck}(\theta) = \frac{1}{\omega C_k}\int i(\theta)\mathrm{d}\theta = \frac{I_{mkp}}{\omega C_k}\int \sin\frac{\pi}{2\theta_m}\theta \mathrm{d}\theta, \tag{26}$$

which, after integration, gives

$$u_{ck}(\theta) = -\frac{I_{mkp}}{\omega C_k}\frac{2\cdot m}{\pi}\cos\theta + C, \tag{27}$$

and we can determine the integration constant value C from the condition

$$u_{ck}(\theta = 0) = -E, \tag{28}$$

which, after substitution, gives

$$C = \frac{2I_{mkp}\theta_m}{\pi\omega C_k} - E. \tag{29}$$

Finally, the formulation for the capacitor charge C_k is

$$u_{ck}(\theta) = \frac{2I_{mkp}\theta_m}{\pi\omega C_k}\left[1 - \cos\frac{\pi}{2\theta_m}\theta\right] - E. \tag{30}$$

The analytical formulation for the capacitor charge (30) will help us to find the value at which the energy dosing diode functioning starts, which is achieved with the condition (31)

$$u_{ck}(\theta = \theta_d) = E. \tag{31}$$

After we substitute (31) into (30) and perform elementary transformations, we get

$$\theta_d = \frac{2\theta_m}{\pi}\arccos\left(1 - \frac{\pi E\omega C_k}{I_{mkp}\theta_m}\right). \tag{32}$$

The value θ_d has been determined in [7–9] in the wrong way, while in [13–16], it has been determined properly by applying the iterative approach, so that the procedure and values determined in this paper due to the correctness of the results and by applying a simple analytical formulation, gives a contribution to research in the field of inverter technology.

The average value of the switch current can be calculated as

$$I_{okp} = \frac{1}{\pi}\int_0^{2\theta_m} I_{mkp}\sin\frac{\pi}{2\theta_m}\theta\mathrm{d}\theta, \tag{33}$$

which later gives a simple relation

$$I_{okp} = \frac{4I_{mkp}\theta_m}{\pi^2}, \tag{34}$$

after simplifying, we get

$$I_{okp} = 0.4 I_{mkp}\theta_m. \tag{35}$$

Knowing that the average value of the current from the source is

$$I_0 = 4E\,f\,C_k\,, \tag{36}$$

we can find an average value of the diode dosing current as

$$I_{odd} = I_{okp} - I_0\,, \tag{37}$$

which can be illustrated practically by examples.

Example 1. The full-bridge inverter's design is required to generate 100 kW of power and 350 kHz frequency for welding steel tubes. Table 1 neatly shows the input data and the values of the key inverter components calculated by applying [7–9].

Table 1

Data and calculated values of the full bridge inverter of the generator for HF inductive steel tube welding

Input parameters					
P [kW]	F [kHz]	E [V]	cosφ	tanδ	C_0 [μF]
100	350	500	0.17	1.6	10000
Calculated value					
C_k [nF]	L_k [nH]	C [μF]	L [μH]	R [mΩ]	U_{tm} [V]
286	419.25	2.65	75.78	28.75	446

To compare the theories mentioned above from [7–9] and the results found in [13–15] and this paper, the values of characteristic inverter parameters are calculated, which are given in Table 2. Based on these results, we may conclude that the results here, besides the new simple analytical values, show a more precise percentage.

Table 2

The comparative characteristic value of full bridge inverter by the method presented in this paper and theory [7–9]

values / type of computation	θ_m [rad]	I_{mkp} [A]	θ_d [rad]	I_{odd} [A]	I_{mdd} [A]
1. Algorithms from [1-3]	0.834	422	1.573	30	260
2. Methods in this paper	1.1587	571	1.54	68	318.3
Relative deviation1-2 [%]	27.25	26	2.14	55.9	18.3

Namely, from [7], using the PSPICE simulation, there are characteristic voltage values and graphical current values. At the same time, in the part that relies on the theory, there are no numerical results derived by applying this theory, but rather some other results that are close to those from the simulation.

By applying the methods, results, and theory in [13] and the contribution shown in this paper by applying approximations, we get good numerical results for the inverter design. At the same time, the mathematical approaches are correctly used. Ranges for achieving the best calculations are identified, giving a great deal of advantage about excessive correct values, out of which it is impossible to determine and calculate the relevant values of the converter and inverter in the design phase.

2.2. CALCULATION 2.2 CALCULATION OF THE HALF-BRIDGE INVERTER PARAMETERS

For the half-bridge inverter, according to the electrical scheme shown in Fig. 1, the equation (19) of the full-bridge inverter becomes

$$L_k \frac{\mathrm{d}i}{\mathrm{d}t} + u_g = \frac{E}{2}, \tag{38}$$

which, after substituting known values, makes the equation of the electrodynamic balance

$$\omega L_k \frac{\mathrm{d}i}{\mathrm{d}\theta} + U_{gm} \sin[\theta - (\delta - \phi_1)] = \frac{E}{2}. \tag{39}$$

Using the idea from [13,14], current feedback in the form

$$i(\theta) = \frac{E}{2\omega L_k}\theta + A - $$
$$- \frac{U_{gm}}{\omega L_k}\left[\cos(\delta - \phi_1) - \cos(\delta - \phi_1 - \theta)\right]. \quad 40)$$

Differentiating the relation for relation for the current (40) with respect to θ and equating it with zero, we get θ for which the maximal currency is

$$\theta = \theta_m = \delta - \phi_1 + \arcsin\frac{E}{2U_{gm}}. \tag{41}$$

Assuming we approximate the current of the half-bridge inverter to be in the form of (25), we can calculate the analytical form of the voltage of capacitor charge C_{k1} and C_{k2}, the value of which is $C_k/2$,

$$u_{ck}(\theta) = \frac{1}{\omega C_k}\int i(\theta)\mathrm{d}\theta = -\frac{I_{mkp}}{\omega C_k}\frac{2\theta_m}{\pi}\cos\theta + C. \tag{42}$$

The constant of integration C from (42) can be determined from the condition

$$u_{ck}(\theta = 0) = 0, \tag{43}$$

which later becomes

$$C = \frac{2I_{mkp}\theta_m}{\pi\omega C_k}. \tag{44}$$

If we substitute (44) into (42) we get

$$u_{ck}(\theta) = \frac{2I_{mkp}\theta_m}{\pi\omega C_k}\left(1 - \cos\frac{\pi}{2\theta_m}\theta\right). \tag{45}$$

The variable θ_d, when the energy dosing diode starts to function, can be determined from the condition

$$u_{ck}(\theta = \theta_d) = E, \tag{46}$$

Which, after replacing in (45), gives

$$\theta_d = \frac{2\theta_m}{\pi}\arccos\left(-\frac{\pi E\omega C_k}{4I_{mkp}\theta_m}\right). \tag{47}$$

An average value of the switch current for this type of inverter is

$$I_{okp} = \frac{1}{2\pi}\int_0^{2\theta_m} I_{mkp}\sin\frac{\pi}{2\theta_m}\theta\mathrm{d}\theta, \tag{48}$$

which, after the integration and change of the limits, gives

$$I_{okp} = \frac{2I_{mkp}\theta_m}{\pi^2}. \tag{49}$$

After simplification, (49) becomes

$$I_{okp} = 0.2I_{mkp}\theta_m, \tag{50}$$

which is very simple and practical for calculations.

The average value of the inverter current from the source is

$$I_0 = EfC_k\,. \tag{51}$$

Based on this, we can find the average value of the energy dose of the diode current,

$$I_{odd} = I_{okp} - I_0. \tag{52}$$

To show the significance of the presented theory, it will be verified through a practical design calculation of the half-bridge inverter.

Example 2. It is necessary to design the half-bridge inverter for the generator that shall be used for the post-weld heating and normalization of the steel tube. Besides, the two-level welding of the steel tube may be carried out by a procedure wherein the first level – an HF inductive generator heats the tube up to 1250 °C. Later in the second level, the MF generator is applied, which heats, *e.g.*, finishes the welding process of the tube up to the necessary temperature.

In this case, the required power is 50 kW, and the frequency is 10 kHz. Table 3 shows the input data and calculated values of the important components of the inverter, determined by applying the known theory [7–9].

Table 3

Input data and calculated values of the half-bridge inverter of the generator for MF heating, normalizing, and tempering steel tubes

Input parameters					
P [kW]	F [kHz]	E [V]	$\cos\varphi$	$\tan\delta$	C_0 [μF]
50	10	500	0.17	1.55	10000
Calculated value					
$C_{k1}/2$ [μF]	L_k [μH]	C [μF]	L [μH]	R [mΩ]	U_{tm} [V]
10	7.31	179.85	1.368	14.82	226

The ensuing algorithm for inverter design, with all previous experience and procedures from [7–9] and [13,14], has led us to calculate the characteristic and important values of the inverter, which are given in Table 4.

Table 4

Comparative characteristic values of the half-bridge inverter by the method presented in this paper and theory [7–9]

values / type of computation	θ_m [rad]	I_{mkp} [A]	θ_d [rad]	I_{odd} [A]	I_{mdd} [A]
1. Algorithms from [1-3]	0.843	413.9	1.576	14	248
2. Methods in this paper	1.149	559.4	1.425	30	290
Relative deviation1-2 [%]	26.6	26	10.60	53.3	14.5

Reviewing the results from Table 4 has shown that the numerical results from applying the theory from [7–9] do not closely correspond to real values. Since the results received through the application of [13,14] and the results acquired in this paper have an insignificant error, we consider them correct compared to results from [7–9]. The maximum current of the half-bridge inverter is 559.4 A.

Results from [13,15–20] and this paper are approximate with an identified range, where the approximation is good and with a minor error. The results are also correct and straightforward, so researchers may use them freely in their fields of interest.

The presented theory for the half-bridge inverter is original and mathematically correct, and the results from the mentioned *Example 2* have been obtained through the correct application of formulae and patterns. The case of a very important technology segment of processing steel tubes has also been presented. The process describes the heating, weld normalization, and transition zone of the steel tube weld to release the voltages resulting from mechanical deformation and heat treatment, as well as the effect of exposing it to the electromagnetic fields of the inductor.

The load on the inverter depends on the product being welded, such as the thickness of the steel strip, the diameter of the pipe, and the production speed. Depending on the impedance of the consumer, the required power will be used. In case of an overshoot, the electronic protection will operate, limiting the current of the inverter. The welding process aims to optimize parameters such as the inductor and the magnetic field concentrator. The steel pipe will be welded with a lower current if there is insufficient power. In exceptional cases, there will be no welding. That is why the necessary protections are foreseen. One innovation introduced by the authors of this work is a pyrometer for non-contact welding temperature measurement. Measuring the welding temperature saves energy and ensures quality welding.

References [31–40] enabled a clearer understanding of this research and the derivation of useful expressions for the practical design of inverters.

3. CONCLUSION

This paper contributes to the analysis and synthesis of half-bridge and full-bridge inverters. Besides the new formulae, which are very simple for analytical calculations, there are some analyses of the theory so far dealing with this field, pointing to the shortcomings, wrong methods, and most adequate application that shall connect the theory and practice at the same time, be crowned with the correct results in applied research.

Implications from [8] of correct analyses when the inverters are designed are approximate. Rather, the analyses are a good approximation in the field of current and voltage, and it is almost impossible to calculate most parameters. However, these parameters can't be used in the procedure of inverter design by the step-by-step system since they require special values of the components for the wave forms of the current and voltage to be calculated.

The authors of this paper, by application of the program package Mathematica, have shown and proven that the zeros are complex conjugate and, in that case, have already presented a development in [7–9] that implies a combination of exponential functions for currents that does not apply. A combination of sine and cosine functions can be done using tables. For the half-bridge and full-bridge inverter, and many other types, echoes for currents and voltages are combinations of the sine and cosine functions.

It must be pointed out that a complete determination of waveforms of the currents and voltages for inverters of the analytical form is possible only when the special values of the inverter elements are determined so that they cannot be used in synthesis when designing. The modeling process, for example, using PSPICE simulation, is useful but only when the inverter is calculated.

Thus, this paper deals with finding out new analytical dependencies, which will be used in the design of inverter parameters, as well as for analyses of inverter behavior, this way enabling easier and more straightforward calculation of inverter elements that many researchers and designers may carry out themselves.

The paper also deals with approximating the description and calculation of the transistor current switches. The values are determined according to the new formula θ_m, where the current has a maximal value. Through analysis, it can be determined and identified that the approximation gives good results in the range of currents (0 to θ_m). Hence, the authors perform all calculations as they transfer everything into this domain.

Although the value θ_d has been correctly determined in [13,15], due to excessive iterative procedure, this paper deals with finding out new formulae by introducing a new relation for the current, which enables the description of the waveform of the capacitor charging and re-charging C_k voltage, which when transferred into the relation (0 to θ_m), enables good calculation of θ_d. However, as per its value, it is beyond the mentioned domain. This has made it possible to calculate the maximal and the average current of the energy dosing diode.

Knowing these simple analytical dependencies makes it possible to use them to calculate the parameters of the inverter components, which is a great advantage. The paper contributes to the analytical calculations of the half-bridge and full-bridge inverters. Moreover, the presented theory can be applied to other types of inverters and converters, and the applied research crowns the results in such a way that two designed inverters of the steel tube manufacturing technology have proven the results from the theoretical contribution to this paper, as well as the results from [13].

The objective of the paper is to figure out the effects and consequences of applied difficult applied difficult and lengthy analytical calculations, the modeling and simulation effects and procedures used by professionals and scientists, approximate methods, and to single out the simplest ones which give good results by identification of good application domains, as well as to find out new analytical procedures for simple and good inverter design, for the sake of engineering practice.

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REFERENCES

1. P. Wood, *Switching Power Converters*, Van Nostrand Reinhold, New York (1981).
2. B.P. Bedford, *Principles of Inverter Circuits*, John Wiley, New York, 1964.

3. B.P. Bedford, R. Hoft, *Teorija avtonomnih invertorov* (Russian edition), Moscow, Energiia, 1969.
4. H.M. Rashid, *Power Electronics: circuits, devices, and applications*, 2nd Ed., Prentice-Hall International, Englewood Cliffs, New Jersey, 1993.
5. T. Brodić, *Power Electronics* (in Bosnian), Svjetlost, Sarajevo, Bosnia & Herzegovina, 1990.
6. C.W. Lander, *Power Electronics*, 2nd Ed., McGraw-Hill, New York, 1987.
7. T. Todorov, D. Aleksiev, N. Madjarov, D. Ivanov, *Autonomous Inverters* (in Bulgarian), Gabrovo, Bulgaria, 1996.
8. I. Senko, T. Todorov, *Devices of Power Electronics* (in Bulgarian), Gabrovo, Bulgaria 1975.
9. T. Todorov, *Development and introduction of methods of analysis and calculations of the characteristics of autonomous inverters in devices for inductive heating* (in Russian), Ph Thesis in Technical Science, Leningrad, Russia, Polytechnics Institute "M.I. Kalinina", 1973.
10. H. Yu, B-M. Song, J-S. Lai, *Design of a novel ZVT soft-switching chopper*, IEEE Trans. on Power Electronics, **17**, *1*, pp. 101–108 (2002).
11. J. Seong-Jeub, C. Gyn-Hyeong, *A zero-voltage and zero-current switching full bridge dc-dc converter with transformer isolation*, IEEE Trans. on Power Electronics, **16**, *5*, pp. 573–580 (2001).
12. M.P. Chen, J.K.u Chen, K. Murata, M. Nakahara, K. Harada, *Surge analysis of induction heating power supply with PLL*, IEEE Trans. on Power Electronics, **16**, *5*, pp. 702–709 (2001).
13. M. Milićević, V. Milićević, *Analysis of the transistor converter of power together with energy dosage for the inductive heating and welding of steel tubes*, European Trans. on Electrical Power, **14**, *2* (2004).
14. T.S. Todorov, P.T. Ivanov, M. Milićević *et al*., *Specialized high-frequency power supplies for induction heating applications*, IHS-2000, Padua, Italy (2000).
15. M. Milicević, V. Milićević, *Impeder for HF inductive welding of steel tubes*, IEE Proceedings, Science, Measurement and Technology, **149**, *3*, pp. 113–116 (2002).
16. M. Milićević, *Contribution to summary of transistor and thyristor converter for electrothermia* (invited paper), Proceedings 41st Int. Oct. Conf. on Mining and Metallurgy (Ed. A. Kostov, M. Ljubojev), Mining Metal. Inst., Kladovo, Serbia, pp. 387–394, 2009.
17. M. Milićević, T.S. Todorov, *Some possibilities for improving the energy indicators and quality of high-frequency induction welding of tubes* (in Bulgarian), IX National Scientific Conf. Electronics ET2000, Sozopol, Bulgaria, 2000.
18. M. Milićević, V. Milićević, *Optimization of energy parameters and quality of HF induction welding of steel seam tubes* (in Serbian: *Optimizacija energetskih parametara i kvaliteta VF induktivnog zavarivanja čeličnih šavnih cevi*), Proc. XI Int. Symposium – Power Electronics Ee-2001 (Ed. V. Katić), Novi Sad, Serbia, Oct.-Nov., pp.188–191, 2001.
19. M. Milićević, V. Milićević, *A contribution to analytical parameter calculation of full-bridge power converter with energy dosing* (in Serbian: *Prilog analitičkom izračunavanju parametara punomostnog pretvarača snage sa doziranjem energije*), Proc. XI Int. Symp. Power Electronics Ee2001, Novi Sad, Serbia, Oct.-Nov. pp. 92–95, 2001.
20. M. Milićević, *Contribution to summary of transistor and thyristor converter for electrothermia* (invited paper), 41th International Conference on Mining and Metallurgy, Kladovo, Serbia, pp. 387–394, 2009.
21. J.S. Lai, *Fundamentals of a new family of auxiliary resonant snubber inverter*, Proc. IECON 97, 23rdInt. Conf. Indus. Elect. Control, Instrum. (Cat. No.97CH36066), IEEE, **2**, pp. 645–650 (1997).
22. B.M. Song, J.S. Lai, D. Qu, H. Yu, H.K. Sung, *A novel soft-switching chopper using auxiliary resonant snubbers for a Maglev* system, VPEC Sem. Proc., 16thAnnual Power Elect. Sem., Blacksburg, VA, pp. 279–284, 1998.
23. S.J. Jeon, G.H. Cho, *Zero-voltage and zero-current switching full bridge dc/dc converter for arc welding machines*, Electron. Lett., **35**, *13*, pp. 1043–1044 (1999).
24. L.R. Barbosa, J.B.Jr. Vieira, L.C. Freitas, V.J. Farias, *An improved boost PWM soft-single-switched converter with low voltage and current stresses*, Proc. IEEE Appl. Power Electron. Conf., **2**, pp. 723–728 (2000).
25. M.P. Chen, L.M. Wu, J.Y. Wu, *Implementation of high frequency electronic welder with resonant switching technology,* Proc. Taiwan Int. Welding Conf. '98 on Technol. Adv. and New Industrial Appl. in Welding, Taipei, Taiwan, pp. 179–186, 1998.
26. M.P. Chen, J.K. Chen, K. Murata, M. Nakahara, K. Harada, *The surge analysis of induction heating power supply with PLL*, Proceedings IEEE PEPS '99, pp. 303–308, 1999.
27. T. Summers, R.E. Betz, *Dead-time issues in predictive current control*, Conf. Rec. IEEE 37th Industry Applications Society Annual Meeting (Cat. No.02CH37344), Pittsburgh, PA, **3**, pp. 2086–2093 (2002).
28. C. Attaianese, G. Tamasso, *Optimized modulation for PWM rectifiers*, IEEE Power Eng. Society Winter Meeting, NY, **2**, pp. 1264–1269 (2002).
29. V.M. Nejković, M.S. Milićević, Z. Radaković, *Temperature distribution in thermal processes,* Welding in the World, 2019.
30. V.M. Nejković, M.S. Milićević, Z. Radaković, *New method of determining of cooling time and preheating temperature in Arcwelding*, Thermal Science, 2019.
31. A. Chebabhi, A.A.M. Al-Dwa, M. Defdaf, A. Kessal, *New modeling and enhanced control strategy for grid-connected four-leg inverter without phase-locked loop and parks transformation*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *2*, pp. 121–126 (2023).
32. M. Touhami, A. Hazzab, *L'amelioration apportee par le controleur pi non lineaire par rapport au pi gain variable*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *2*, pp. 158–163 (2023).
33. D. Benoudjit, S. Rid, N. Nait-Said, M. Saidnait-Said, L. Chrifi-Alaoui, *Electric vehicle propelled by dual-induction motors structure: experimental results*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *2*, pp. 170–175 (2023).
34. D. Ragul, V. Thiyagrajan, *A novel fault-tolerant asymmetrical 21-level inverter topology with reduced components*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *2*, pp. 200–205 (2023).
35. D.-S. Nicolescu, P. Rosca, A. Radulian, C. Predoi, A. Munteanu, *Main electrical components of an assault rifle with adaptive mechanism*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *1*, pp. 36–41 (2023).
36. F. Roubache, S. Chaouch, *Nonlinear fault tolerant control of dual three phase induction machines based electric vehicles*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *1*, pp. 65–70 (2023).
37. I. Dobrin, D. Enache, G. Dumitru, M. Gutu, S. Zamfir, R. Pintea, *Curved dipolar electromagnet, numerical modeling and design*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **67**, *4*, pp. 409–415 (2022).
38. A. Chakrabarti, P.K. Sadhu, P. Pal, *A novel dead-time elimination strategy for voltage source inverters in induction heating systems through fractional-order controllers*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **67**, *2*, pp. 181–185 (2022).
39. C. Tufan, I.V. Nemoianu, M. Maricaru, M. Stanculescu, M.-E.Marin, *Efficient method of harmonic analysis of three-phase circuits with nonlinear controlled switching elements*,, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **67**, *1*, pp. 47–54 (2022).
40. A.M. Morega, M. Petre, Y. Veli, A.A. Dobre, *Flow and heat transfer in an aging heat furnace for aluminum alloy plates*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **67**, *1*, pp. 81–86 (2022).