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Determination of Efficiency in a Single-Switch Class E ZVS-1S Quasi-Resonant Inverter in Application for Induction Heating

Abstract. *The paper is an attempt of discussion and presentation of the concept of a method for determining efficiency of high frequency inverter systems used in electroheat processes. Based on the example of a constructed model of a single – switch Class E ZVS-1S quasi-resonant inverter and the obtained results of its measurements, an effort of assessment of the inverter performance and its efficiency has been made.*
The paper presents a brief analysis of the operation and basic relationships in the inverter, the concept of control, conceptual design, difficulties during its implementation and it also identifies sources of power losses in the inverter and determines its efficiency for various load parameters.

Streszczenie. *Artykuł jest próbą dyskusji i przedstawieniem koncepcji metody wyznaczania sprawności układów falowników wysokoczęstotliwosciowych wykorzystywanych w grzejnictwie elektrycznym. Na przykładzie wykonanego modelu układu jednołącznikowego falownika napięciowego ZVS–1S klasy E i wyników zrealizowanych pomiarów podjęto próbę oszacowania jego sprawności.*
W referacie przedstawiono pokrótce analizę pracy oraz podstawowe zależności występujące w falowniku, koncepcję jego sterowania, założenia projektowe, trudności wykonawcze oraz określono źródła strat mocy w falowniku i wyznaczono jego sprawność dla różnych parametrów obciążenia.
(Wyznaczanie sprawności układu jednołącznikowego quasi-rezonansowego falownika napięciowego ZVS-1S klasy E w zastosowaniu do nagrzewania indukcyjnego właściwości)

Keywords: single-switch topology, ZVS, class E inverters, induction heating
Słowa kluczowe: falowniki jednołącznikowe, załączanie przy zerowym napięciu, falowniki klasy E, nagrzewanie indukcyjne

Introduction

Several topologies of single-switch inverters are used, among others, to carry out induction heating. One of them, shown in Figure 1, is the subject of the paper. This class E ZVS inverter is presented in literature [1-3], especially in connection with its application in induction cookers operating usually in the range of 20 ÷ 50 kHz.

The article is an attempt of discussion and presentation of the concept of a method to determine the efficiency of the high frequency inverter systems used in electric heating. Based on a built model of a single-switch Class E ZVS inverter and the results of the executed measurements, an attempt has been made to assess its efficiency.

The paper presents a brief analysis of the work and the basic relationships in the inverter, the concept of its control, conceptual design, implementation difficulties, identifies sources of power losses in the inverter and designates by some measurements its efficiency for various load parameters.

Principle of operation

The inverter (Fig. 1) is supplied from a DC voltage source U_d. Resistance R_0 and inductance L_0 represent the inductor-charge system. The power electronic switch S can conduct current in both directions.

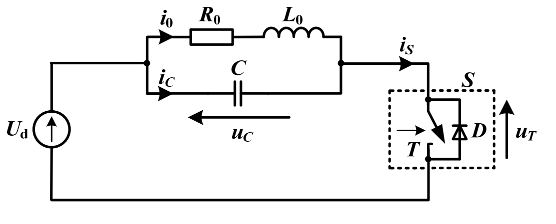


Fig. 1. Circuit diagram of the single-switch inverter

It is advantageous, that the inverter operates in a way assuring switching the transistor at zero voltage (ZVS). In each switching cycle, the inverter operates in two modes and its equivalent circuits for each mode are shown in Figure 2:

- In mode I switch S conducts electric current. The voltage u_C across C and R_0L_0 is practically constant and equal to U_d and load current i_0, equal to switch current i_S, rises exponentially.
- In mode II switch S is off. An oscillation occurs in the R_0L_0C circuit, which lasts until u_C reaches the supply voltage U_d.

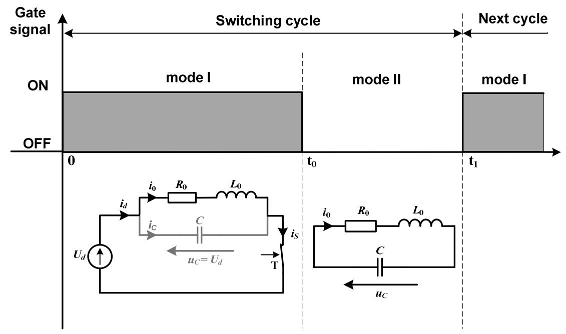


Fig.2. Equivalent circuits of the inverter in modes I and II

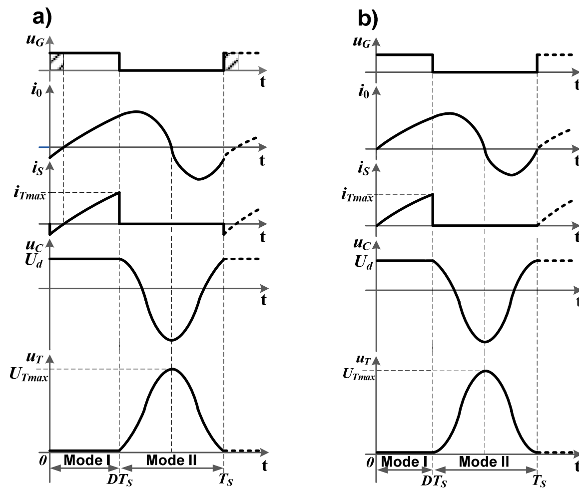


Fig. 3. Current and voltage waveforms in the inverter under ZVS operation: a) suboptimum operation; b) optimum operation; u_G – gate signal, i_0 – load current, i_S – switch current, u_C – voltage across the capacitor, u_T – voltage across the switch

Two cases of ZVS operation of the inverter are distinguished in Figure 3:

- In the first case – suboptimum operation - voltage u_c reaches the value of supply voltage U_d, while current i_0 is negative (Fig.3a). Freewheeling diode D starts conducting, which determines the end of mode II and the beginning of mode I of the next switching cycle. At time interval between the beginning of diode conduction and the instant when current i_0 reaches zero (the shaded area of gate signal u_G in Figure 3a), the gate signal should be applied to the transistor, so that it can take over the diode current.
- The other case - optimum operation - occurs if voltage u_c reaches U_d at the same time when current i_0 reaches zero (Fig. 3b). The transistor should be turned on at this moment, which initiates mode I of the next cycle. The transistor is turned on at zero voltage and zero current; therefore the turn-on losses in the transistor are zero.

The inverter can also be operated at hard switching. If the transistor conduction time is too short or damping of the resonant circuit is too big, voltage u_C will never reach the supply voltage in mode II. As a consequence, it will be necessary to turn the transistor on at non-zero voltage (NZVS), which generates turn-on losses in it. Therefore, this kind of the inverter operation should be avoided.

Concept of the inverter control system

The concept of the inverter control system (Fig. 4) is based on the use of four functional systems: the detector of zero of load current, transistor's current limiter, capacitor's voltage regulator and pulse generator for transistor control with adjustable pulse width control.

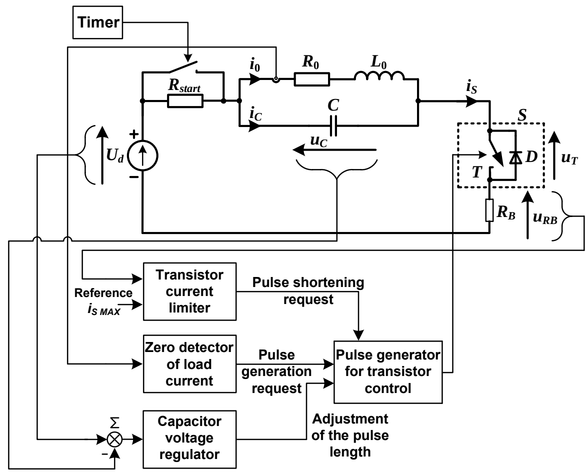


Fig.4. Block diagram of the inverter control system

Detection of zero (from negative values) of load current i_0, marks the point to turn on the switch S (modulation of transistor T). Thus, the transistor begins to conduct the current and the energy is stored in the inductance of the inductor.

The length of control pulse of transistor is initially minimal (e.g.: 10% of the switching cycle, that is, D = 0.1). Consequently there is an oscillation in the resonant circuit, and a measure of energy, related to the conduction time of the transistor is the maximum voltage across the capacitor. The signal which is the difference of the measured maximum positive voltage u_C (after the resonant process the voltage across the capacitor should be equal to the supply voltage) and voltage U_d is applied to the input of the capacitor voltage regulator.

The output signal of the regulator determines the length of the transistor conduction time (increase or decrease of the current value of the D-factor), and also determines the amount of energy supplied to the resonant circuit. As a result, the regulator reduces the error of control to zero and the transistor tends to be switched on at zero voltage (optimum operation). The adjustment of voltage u_C will be executed in many control periods, but with an accuracy of a few millivolts.

If the output of transistor's current limiter (voltage measurement on the shunt R_B), does not block switching on the transistor, it will conduct the current during time interval corresponding to the value of the D-factor determined by the regulator. If the current exceeds the limit value of i_S, resulting from the parameters of the transistor, the conduction time will be reduced accordingly.

The inverter contains a starting system, which is necessary due to the structure of the inverter circuit. The system is implemented with an additional start-up resistor limiting a peak of current loading the capacitor of the resonant circuit. After start-up the resistor is short-circuited. This can be realized using a simple timer circuit (for example NE555) with an adjustable time delay.

Some tests have been performed to check the proper operation of the presented control system. A 10-wire inductor was loaded with a steel rod. Figure 5 shows some registered waveforms. Load current is nearly a sine wave. At turn-off of the transistor a significant peak can be seen in the waveform of the voltage u_T across the transistor, which is a result of the presence of parasitic inductances in the circuit. It increases the turn-off losses in the transistor and worsens the inverter efficiency. This drawback can be minimized by changing the layout of the inverter.

In case of load variation the inverter returned, after transient state, to optimum operation with new control parameters (transistor conduction time and switching frequency).

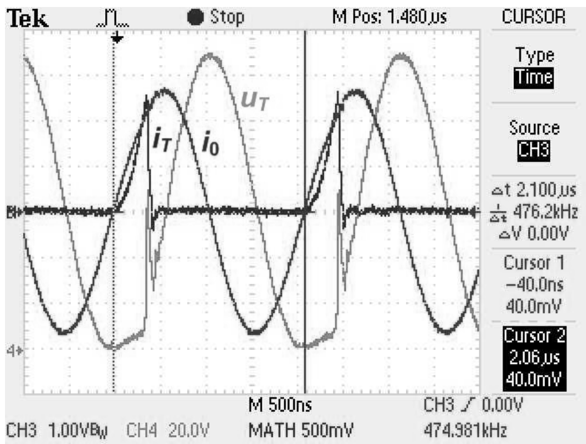


Fig.5. Waveforms of the load current i_0 (25 A/div), the transistor voltage u_T (20V/div) and transistor current i_T (25 A/div) in a model of the inverter with steel load inside the inductor: U_d = 59 V, C = 0.329 µF

Estimating power and efficiency of the inverter

In order to estimate the quality of the executed model (Fig. 6) the efficiency of the system and of the heating process implemented by it was adopted as the assessing criterion.

As each process of the conversion of the energy is inherent with generation of energy losses by the processing circuit, the inverter circuit has been divided into two main tracks in which there are the energy conversions as follows:

- power circuit electrical conversion path - which changes the electrical parameters of the energy supplied from the power source to the heating head (inductor with load),
- heating head electrical conversion path - which converts the electrical energy supplied to the heating head (inductor with load) into the heat energy dissipated in the load.

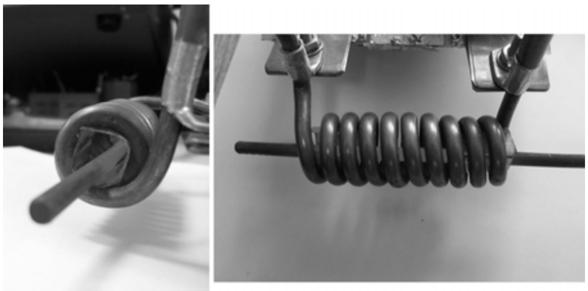


Fig. 6. The inductor with a sample load (steel rod Ø4 mm) during the heating process

On the basis of a general definition of efficiency, the following notation has been introduced:

- ✓ P_e – electric power from the power source to supply the inverter,
- ✓ P_{se} – electric power losses in the main electromagnetic circuit (power loss in the transistor - the main, though not the only one source of losses in this circuit, but it might be reliably estimated and it is also the measure of the control system quality),
- ✓ P_g – electric power which supplies the electro-thermal transducer (inductor with load) and is converted into heat in it,
- ✓ P_u – output power generated in the charge.

Dependencies which define the individual values and the relationships between them:

(1) $$P_e = U_d I_d = U_d I_T$$

Electric power P_e has been determined as a product of the DC input voltage U_d and mean value I_d of the input current.

(2) $$P_g = P_e - P_{se}$$

Electric power loss P_{se} in the system was determined based on the registered waveforms (from an oscilloscope) of current and voltage on the transistor, by integrating their product over the time. Hence, the energy conversion efficiency in the electric circuit is determined by ***the electric efficiency of the high current circuit in the inverter***:

(3) $$\eta_e = \frac{P_g}{P_e} = \frac{P_e - P_{se}}{P_e}$$

The efficiency of the energy conversion in the charge and the inductor is determined by ***the electric efficiency of the inductor-charge system:***

(4) $$\eta_t = \frac{P_u}{P_g} = \frac{I_0^2 \cdot R_{wsad}}{I_0^2 \cdot \left(R_{obw\_rez} + R_{wsad}\right)} = \frac{R_{wsad}}{R_{obw\_rez} + R_{wsad}}$$

where R_{obw_rez} is the resistance of the oscillatory circuit comprising: an inductor, capacitor and the connection between them, in which there are free reloads. R_{wsad} is the resistance contributed by the load to the impedance of the inductor-charge system.

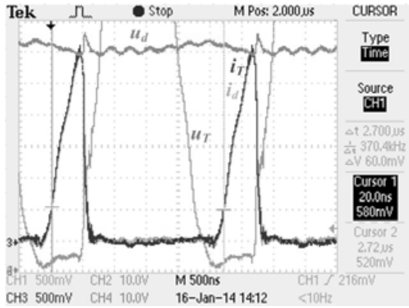
Finally, the energy conversion efficiency throughout the inverter system, is determined by ***the total electric efficiency*** of the inverter:

(5) $$\eta_{et} = \eta_e \cdot \eta_t$$

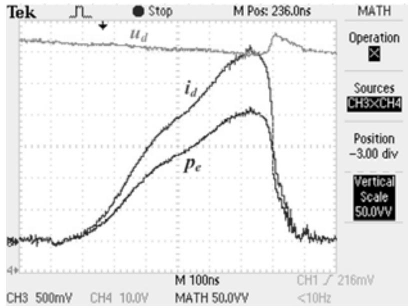
To determine the dependence of efficiency on: the type of load (damping level in the output oscillatory circuit) and output capacitance C, the following recorded oscilloscope waveforms were used (and some of them were next integrated over the time):

- the power supply (Fig. 7b),
- power electrical losses in the transistor (Fig. 7c)
- inverter frequency depending on the load (more exactly: the load diameter),
- installed capacitor C in the output oscillatory circuit.

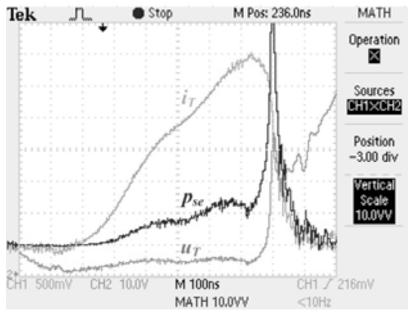
The results of the calculations are shown in diagrams (Fig. 8 and 9).



a)



b)



c)

Fig.7. Examples of supply current waveforms i_d, voltage waveforms U_d, the current in transistor i_T, voltage on transistor u_T, input power p_e and power losses on transistor p_{se} in system with example load: ferromagnetic steel rod Ø3 mm, with capacitor C = 329 nF, at a supply voltage U_d = 70.6 V:

a) general view of waveforms at f = 370.4 kHz
b) electric power on the supply side: P_e = 785.46 W
c) power loss in the transistor: P_{se} = 77.68 W

The graphs in Figure 8 indicate that with increase of capacity C in the oscillating circuit of the inverter, the electrical efficiency of the inductor-charge system also increases. This is caused by the structure of capacitance C, built as a parallel connection of 47 µF capacitors. Thus the resistance R_{obw_rez}, depending also on capacitor ESRs, decreased with an increase of C. Therefore, relatively more energy was generated in the resistance R_{wsad} (4), which represents the charge being heated.

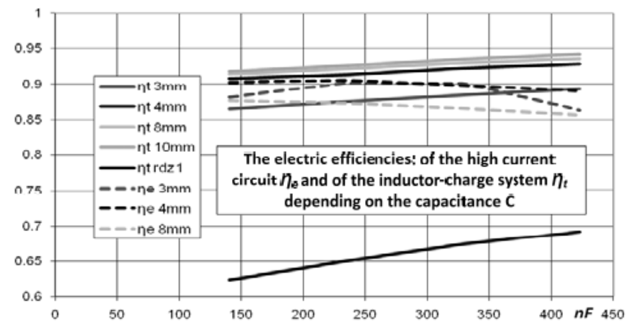


Fig. 8. The graph presents the dependence of the electric efficiencies of: electrical power circuit (η_e) and heating system (η_t) of the inverter model on the capacity *C* installed in the output oscillatory circuit

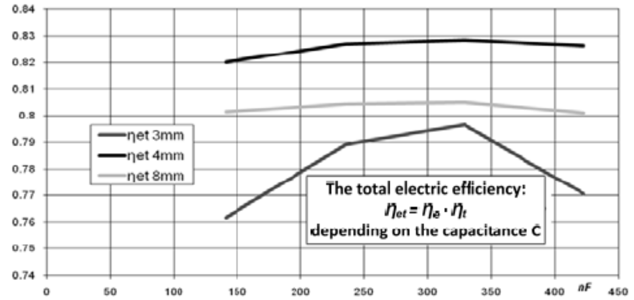


Fig. 9. The graph presents the dependence of the total electric efficiency of the inverter model on the capacity *C* installed in the output oscillatory circuit

The curves for the electric efficiency of the high current circuit show that lowering of efficiency is connected with the increase of the capacity C. This is caused by an increase of the source current I_d, which compensates the energy converted into heat in each switching cycle. This translates into an increase of electric power losses in the main electromagnetic circuit, and hence lowering the electric efficiency of the high current circuit in the inverter. An additional factor is the structure of capacitance C, namely the connections between capacitors forming the capacitor bank. With the increase in their volume, the overall dimensions of the entire battery increase as well as the length of the links between them. Therefore, this causes additional parasitic oscillations in the capacitor circuit reducing the efficiency.

As a result, by overlapping these factors, the maxima for total electrical efficiency of the system were obtained (Fig. 9) for seven installed capacitors. However, a very high total efficiency should be pointed out. In particular, the electrical efficiency of the inverter - which, in literature, is given by authors as a criterion for the assessment of the made structures - slightly more than 90% at the operating frequency of 565 kHz for the load diameter of Ø4 mm. The authors [1] indicate the efficiency of their unit as being near 83% (they do not precise a method of measurement) at the frequency of 20 to 50 kHz, which corresponds to the operating frequency: 11 ÷ 28 times lower than the control frequency of the inverter analyzed in this paper.

Conclusions

The advantage of this inverter is using only one power electronics valve and a disadvantage - high voltage on the switch.

The inverter analyzed in the paper, can operate optimally in class E, provided that the quality factor of the series circuit R_0L_0C is large enough.

An alternative to this operating mode is to move away from the optimal operation by a corresponding increase of the transistor conduction time resulting in an increased output power of the inverter while maintaining a ZVS operation.

Based on a general definition of the efficiency of energy conversion, two electrical conversion paths in the inverter circuit were determined and the powers at various stages in the system were defined. Registration of the curves of the currents and voltages across the transistor, and at the input and output of the inverter, allowed to estimate the power balance in the system and determine the efficiency: electrical efficiency of the power circuit of the inverter, electrical efficiency of the heating head system and the total electrical efficiency of the equipment. The high values of the efficiencies finally confirmed the good performance of the inverter and the validity of the adopted and implemented concept of its control system.

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