Compact Transducer for Load Matching and Process Control Enhancement

Nikolay Dimitrov Madzharov
Technical University of Gabrovo
H.Dimitar str. 4
5300 Gabrovo
Bulgaria

ABSTRACT: *The inverter for energy dosing for ultrasonic application has been created in this research. The energy dosage will be used for improved power output. This kind of power supply is most attractive for various ultrasonic applications where the compact transducer can chance the technology progress. We have deployed a network simulation experiment that permitted to explain the parameters range of the current frequencies and study the performance. The experimental results have proved the enhancement in loads matching and process control in a wide range of loads impedances. The study outcome and power network progress and its structure are presented in this paper.*

Keywords: Inverter, Energy Dosing, Ultrasonic, Compact Transducer

Received: 4 October 2022, Revised 15 December 2022, Accepted 28 December 2022

DOI: 10.6025/jnt/2023/14/1/15-21

1. Introduction

It is well known that one of the major requirements to power sources is that they provide the necessary voltage for the CT, as a guarantee for obtaining the specified power and for meeting all requirements to the technological process.

Owing to the variety in geometrical dimensions, configuration, different CTs should be supplied with different voltage and respectively frequency [1, 5, 6, 7, 8, 9, 10].

Not with standing the progress made, the methods used to regulate the output voltage of power sources, are not sufficiently smooth and envisage the use of relatively complex matching transformers. A solution to this problem has been used, based on autonomous invertors with energy dosing, which, in their method of operation, generate, with a specified power, an output voltage corresponding to the particular parameters of the load [3, 4, 9].

2. Resonance Inverters with Energy Dosing

The block diagram of the inverter with energy dosing is presented in the Figure 1. It is shown schematically that between the source of constant voltage (the rectifier) and the autonomous inverter another block is connected - a doser. By means of this block the energy is transmitted to the load in definite portions (doses). It is from the term dose that the name converter with energy dosing derives.

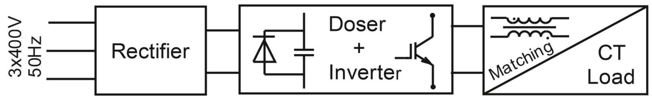

Figure 1. Inverter with energy dosing - block diagram

Figure 2 presents a half-bridge resonant inverters with energy dosing. The number of additional elements here is minimum - two diodes in the half-bridge circuit (VD_3 an VD_4). The time charts in Figures 3 illustrate the method of operation and the order in which the switching devices (the transistors) and the diodes. It can be seen that in the course of one half-period the capacitor C_K in the circuit in Figure 4, which is charged in a stationary mode up to voltage E, is discharged completely, a dose of energy W and power P being formed at that, equal to $W = E^2C_K$, $P = E^2C_K.f$.

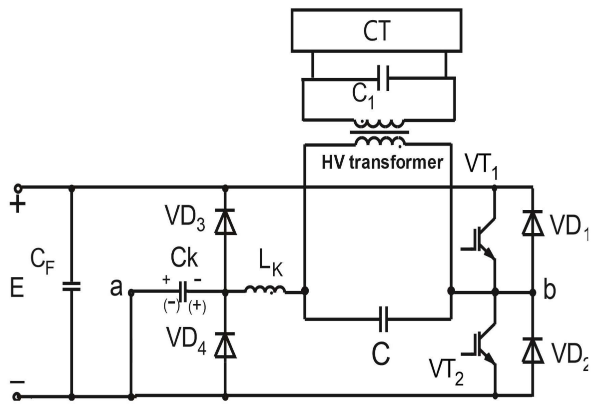

Figure 2. Half-bridge RI with ED

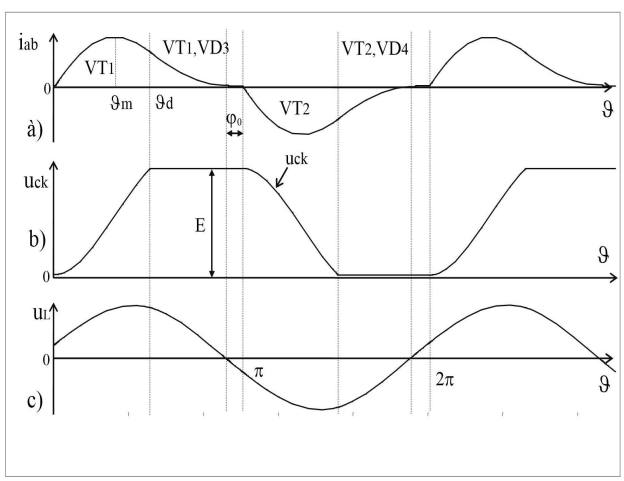

Figure 3. Time charts of RI with ED

It must be noted that in the two inverters the transistors operate with a zero current of switching on and off. The dose of energy W and the power P in the inductor equal, respectively

$$W = kE^2 C_K \tag{1}$$

$$P = kE^2 C_K f = \frac{U_L^2 \cos^2 \varphi_L}{R_L} \tag{2}$$

where C_K is the capacitance of the dosing capacitor;

f - the frequency of switching (operating frequency) of the inverter;

k - a coefficient dependent on the circuit of the doser and the inverter, e.q. k =1, 2, 4;

U_L - effective value of the variable voltage, $\cos\varphi_L$ and R_L - power factor and ohmic resistance of the CT, respectively.

According to (2) when the values of E, C_d and f do not vary, the power P is a constant value independent of the load parameters and the changes in them, regardless of the reason which caused them. In practically, this means that the output voltage of the converter with energy dosing (voltage U_L) changes in strict accordance with the concrete load parameters, i.e. self-harmonization is performed without the necessity of influence by the control system. It is exactly this fact that is new and of major importance, the fact that enables the principle of energy dosing in power supply sources for ultrasonic applications. But it is not the only new thing. Another equally important advantage of the converter with energy dosing is the fact that the extreme operation modes - idle running and short circuitare safe, since they do not cause overvoltages and overcurrents.

By changing the values E, C_d and f it is possible to regulate the output voltage and output power or to fix an assigned level for them.

$$U_L = \left[\frac{E}{\cos\varphi_L} \sqrt{kC_K R_L} \right] \sqrt{f} \tag{3}$$

The equation (3) suggest that the output voltage can be maintained constant if the switching frequency is varied when the load and input voltage are modified [3,4].

3. Practical Realizations and Commercial Introductions

Autonomous inverters with energy dosing for ultrasonic application have been studied well both theoretically and in practice. Mechanical phenomena in the CT circuit may be reflected into an electrical circuit (Figure 4) with the following elements:

C_0 - transducer capacitance (static capacitance);

C - capacitance due to mechanical elasticity of CT;

L - inductance describing CT mass;

R - electrical resistance reflecting mechanical power dissipation in the CT and in treated material.

While capacitance C_0 is almost constant at different loading conditions, values of C, L and especially of R vary with loading. The CT capacitance must be compensated with an inductance, which is usually located inside of the generator. There are two possibilities for compensation – by series or by parallel choke. Also, there are two resonances of CT in the operation frequency range – one series with small equivalent resistance of the device, close to R, and one parallel with high value of R equivalent. Resonance curve of a circuit C – L is very steep (narrow) due to high quality factor. If Co is compensated by Lo at the resonant frequency of C – L, CT is in conditions of series resonance. Parallel resonancoe takes place at higher frequency than series

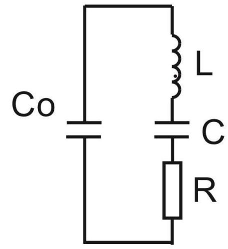

Figure 4. Basic scheme of piezoelectric CT

It must be noted that the self-sustaining of the power, retaining zero current of switching on and switching off of the transistors, is best realized in the case of an active load, or tank circuit adjusted to a resonance. Therefore a PLL control system is envisaged in the converters, by means of which the state of the tank circuit is monitored and if necessary the operation frequency is changed. If the requirement for zero current of switching off is overlooked, which is absolutely permissible, the PLL system is not necessary. In this case the power remains constant, at a constant frequency [5,8].

The goal of experiments was to determine the working characteristics of inverter with energy dosing, the best matching, efficiency and amplitude of CT vibration. The amplitude of CT was measured by Dynamic Vibration Sensor.

The CT parameters:

• Co as measured at 1 kHz, is 20 ± 1 nF. This value increases with temperature and aging. In service conditions at 28 kHz the capacitance is about 20 % higher, but it was not possible to measure it directly.

• C and L with a 200 Hz gap between serial and parallel resonance are 274 pF and 116 mH.

• R varies in a wide range between 5 Ohm in free air and ~250 Ohm under load, depending upon paper and pressure.

Analyzing the “Π” equivalent parameters (Figure 5) it was found that the value of L2 (Z2) was small. Hence, the capacitor C2 must be big and does not influence matching essentially.

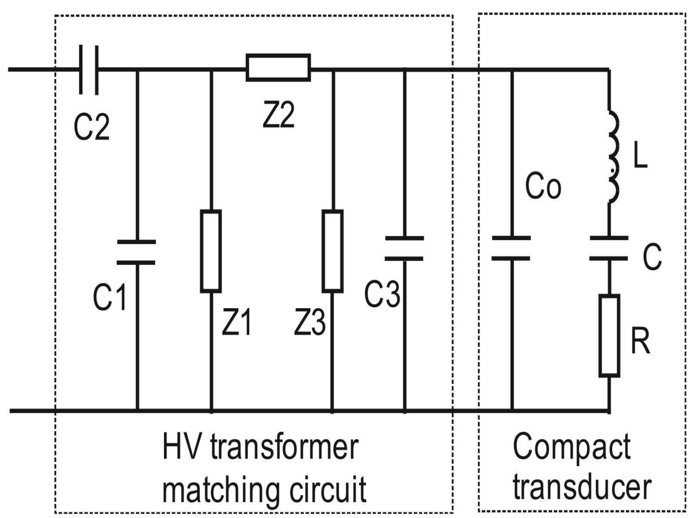

Figure 5. HV transformer, matching capacitors and CT equivalent circuit

Tables 1 and 2 show the CT amplitude and RI with ED power vs C1 value.

Force 4000 N on the CT			
C1, nF	Amplitude idle, mV	Amplitude load, mV	Power RI with ED, W
2,95	1943	1941	2583
3,9	1948	1918	2482
4,9	1942	1872	2405
6,1	1945	1877	2380

Table 1. Amplitudes for idle and loaded CT vs C1 value

C1 = 7,8 nF					
Force N	Amplitude idle, mV	Amplitude load, mV	Gen.Power W	Power load W	Efficiency %
4000	1939	2017	2498	2389	95,6
5500	1933	1977	3663	3466	94,6

Table 2. Amplitude measurement for C1 = 7.8nF

Along with the experimental study of the ultrasonic system, computer simulation of its operation was done using PSPICE. For that purpose, a PSPICE – model was developed on the basis of the Figure 5. The values of the elements corresponded to the measurements of the OS and SC tests and to the calculations of the "Π" equivalent circuit are shown in table 3.

Force %	Z1, Ohm	L1, mH	C1, nF	Z2, Ohm	L2, mH	C2, nF	Z3, Ohm	L3, mH	C3, nF
120	1730	9,8	3,2	152,6	0,86	37,3	326	1,86	17,4 92%
110	1734	9,86	3,3	152,5	0,867	37,3	316	1,8	18.0 95%
100	1802	10,25	3,16	152	0,864	37,4	301	1,71	18,9 100%
90	1835	10,4	3,09	150,38	0,855	37,8	288,87	1,64	19,7 104%
80	1857	10,56	3,06	150,2	0,854	37,8	280,17	1,59	20,3 107%
70	1865	10,6	3,05	150	0,854	37,8	269,9	1,53	21.0 1 11%

Table 3. "Π" parameters of the HV transformer, CT and compensating capacitors vs. force on the CT

Figures 6,7 and 8 show the waveforms of the RE with ED (Ugen and I gen) and CT voltage, current and phase shift vs frequency.

Methodology has been worked out for CT matching and optimization, taking into consideration the non-sinusoid character of the electrical quantities, and it has been verified computter simulations and by experimental investigations. The investigations have been performed with the diferent loads for ultrasonik applications. When the load has the form of a high-resonant CT the operation of the inverter with energy dosing is analogous - the power is the same in the case of an low-resonat CT. This result, as well as the adaptive properties in other loads, and the safe operation of the inverter in extreme modes, are unique.

Two investigations were conducted: the first one with the automatic control system being switched off (Figure 10), and the second one - with the system being switched on (Figure 9). Figure 9 and figure 10 presents a characteristics, taken experimentally of the converter described, as well as of any other converters constructed using the principle of energy dosing. The character-

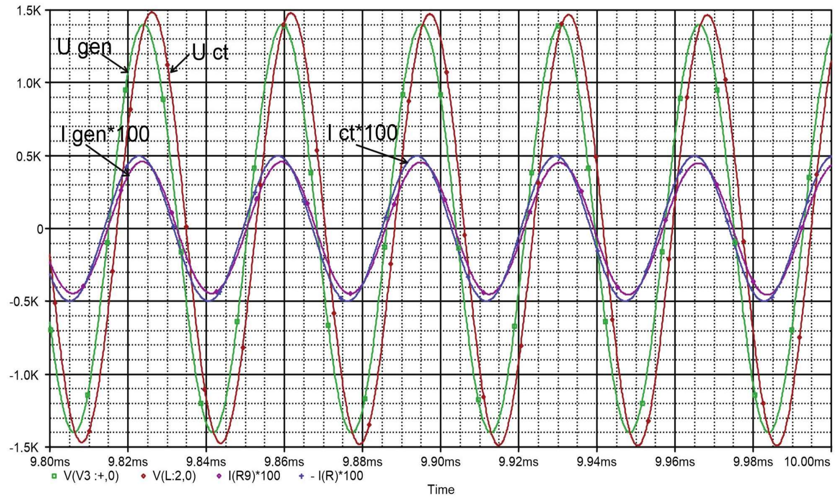

Figure 6. Waveforms of the voltages Ugen, Uct and currents Igen, Ict

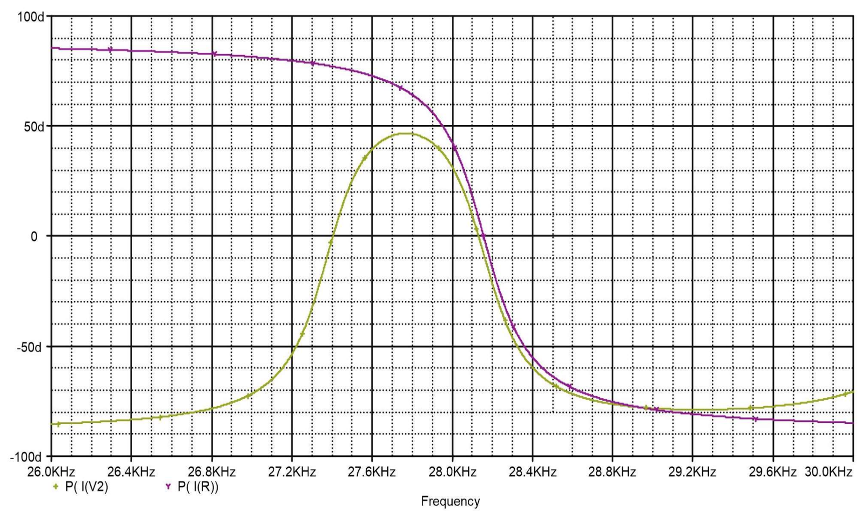

Figure 7. Phase-frequency characteristics of the generator P(I(V2)) and CT currents P(I(R))

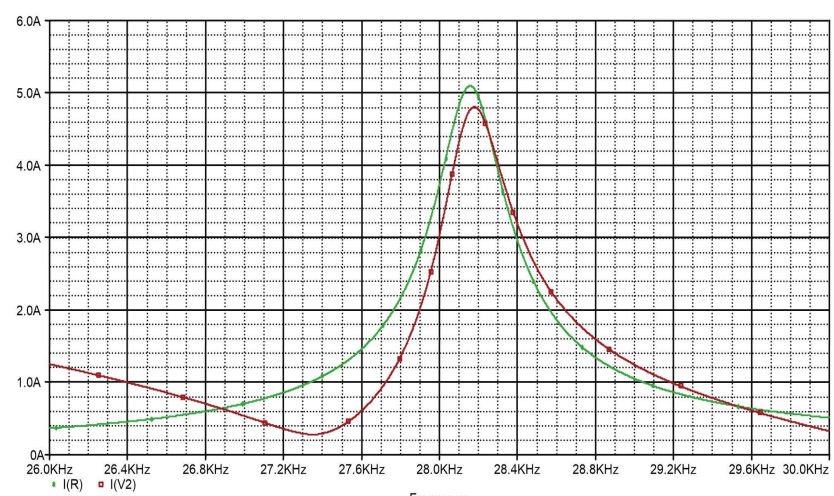

Figure 8. Amplitude-frequency characteristics of the generator I(V2) and CT currents I(R)

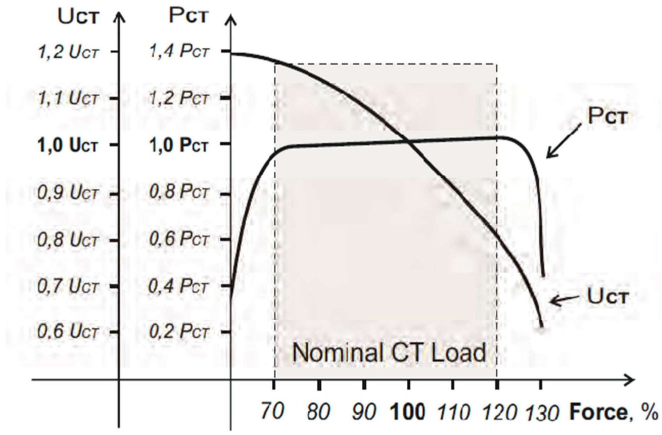

Figure 9. Load characteristics with the control system being switched on

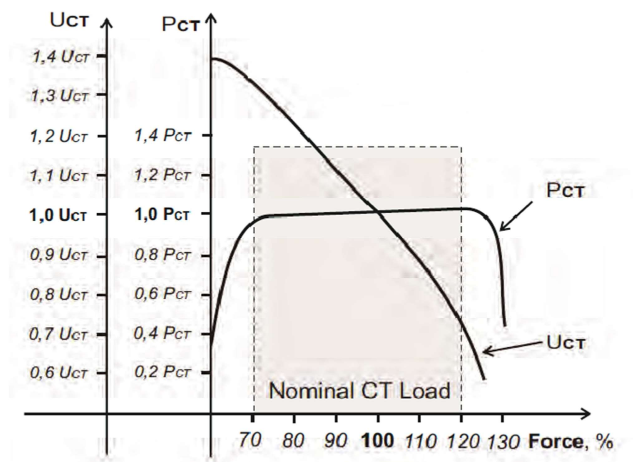

Figure 10. Load characteristics with the control system being switched off

istic manifests the dependence of the output voltage and the power on the load resistance i.e. force on the CT. It can be seen that when the force on the CT increases, the voltage decreases, and what is more, it decrease sufficiently to keep the power constant.

When the load is in a state close to short circuit (force more than 120% of the nominal one) and idle running (force less that 70% of the nominal one) the power naturally drops. The voltage in the case of short circuit also decreases, and in idle running it increases but not as much as with the conventional circuits of autonomous inverters used in installations for ultasonic applications.

4. Conclusions

The investigation has been done on a resonant inverter with energy dosing potentially suitable for use in ultrasonic systems. The experimental tests and measurements of the ultrasonic mock-ups were made including design and construction of the supporting circuitry-matching capacitors and HV transformer.The information up to here although incomplete, allows us to draw the following conclusions:

1. A half-bridge circuit of a resonance inverter with energy dosing has been analysed.

2. It has been found that the autonomous inverter must operate with a load circuit tuned in resonance on the first harmonic of the alternating current. This is in practice the condition for commutation of switching devices in the mode ZCS.

3. The non-sinusoid character of the alternating current has been taken into account and in accordance with this a methodology for design has been created.

4. Computer modelling with PSPICE program and experimental study with real CT have been made. The values of the elements were set correspondingly to the measurements of the OS and SC tests and to the calculations of the "T" and "IT" parameters.

5. The ability of resonance inverters with energy dosing to maintain constant power in the load has been confirmed, for different combinations of the load parameters, when the ZCS of the switching device is maintained.

References

[1] Lin L., F. Lee. *Novel zero-current switching and zero-voltage switching Converters. IEEE* 5/1996.

[2] Thornton C. Simplified simultaneous power supply voltage sequencing. *Power electronics*, 4/2003.

[3] Madzharov N.D., A DC/DC converter with energy dosing , Proceeding PCIM'04, PC, Nurnberg, Germany, 2004.

[4] Madzharov N.D., Resonant Power Supplies with Energy Dosing and PLL Control System, Proceeding PCIM'08, *Power Conversion*, Nurnberg, Germany, 2008.

[5] Kraev G., N. Hinov, L. Okoliyski, "Analysis and Design of Serial ZVS Resonant Inverter", Annual Journal of Electronics, Volume 5, BOOK 1, Technical University of Sofia, Faculty of Electronic Engineering and Technologies, ISSN 1313-1842, pp.169-172, 2011.

[6] Kraev G., N. Hinov, D. Arnaudov, N. Ranguelov and N. Gradinarov, „Multiphase DC-DC Converter with Improved Characteristics for Charging Supercapacitors and Capacitors with Large Capacitance", *Annual Journal of Electronics, Vol. 6, BOOK 1, TU Sofia, Faculty of Electronic Engineering and Technologies*, ISSN 1314-0078, pp.128-131, 2012.

[7] Bankov, N., Tsv. Grigorova. "Series Resonant DC/AC Converters Methods of control – Investigation, Modelling and Applications" – Chapter 4 in book "Advanced Technologies: Research-Development-Applications" Edited by Bojan Lalic. ISBN 3-86611-197-5, plV pro literature Verlag Robert Mayer- Scholz, Mammendorf, Germany, 2006, pp. 57-76.

[8] Bankov, N., Al. Vuchev, G. Terziyski. "Study of LCC Resonant Transistor DC/DC Converter with Capacitive Output Filter" – Chapter 4 in book "Power Quality Harmonics Analysis and Real Measurements Data", Edited by Gregorio Romero Rey and Luisa Martinez Muneta, ISBN 978-953-307- 335-4, INTECH, November 2011, pp. 111-130.

[9] Nedelchev I., I. Nemigenchev. Analysis of the Class E Amplifier with Load Variation. International Scientific Conference on Information, *Communication and Energy Systems and Technologies*, *ICEST, IEEE*, Ohrid, Macedonia, vol. 1, pp. 313-316, 24-27 June, 2007.

[10] Nedelchev, I. (2011). *Power RF Amplifier Class E Using Impedance Matching Transformer*. International Scientific Conference, UNITECH'11 Gabrovo, pp 331 - 336,18-19 November 2011.