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ZVS CLASS-DE FULL-BRIDGE RESONANT INVERTER FOR INDUCTION HEATING

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Abstract: *The paper discusses class-DE series resonance half-bridge inverter with control of the output power for induction heating applications. The inverter control is based on an adaptive frequency control and PWM modified technology with ZVS soft switching. The inverter operations equivalent circuits are treated in detail. Harmonic and piecewise analysis of the inverter is made in established operation mode. Computer simulation and verification of the 3 kVA and 110 kHz, MOSFET inverter have been performed.*

Key Words: ***ZVS, Class-DE Inverter, Quasi-resonant, Induction Heating, Induction Soldering***

1. INTRODUCTION

There has been a tendency in induction heating over the last few years to replace valve generators operating in the R.F. range by semiconductor ones. Due to the commutation losses in transistors the use of these inverters is restricted at high operating frequencies. To avoid this restriction, there has been an increasing use of "soft" switching of transistors voltage and/or current – ZVS and ZCS.

Class-DE topology will obviously lead to high-efficiency operation, similar to the class-E and to a high coefficient of using the switching elements-line in class - D [1].

The purpose of the present paper is to present the application of class-DE quasi-resonant full-bridge inverters in the R.F. range of induction heating.

Fig.1 shows the possible principle circuit of a voltage-fed full-bridge class-DE resonant inverter for induction soldering application with each switch having a resonance capacitance *Cr* and possible oscillations tanks.

The capacitive switching losses presented in classic Class-D operation can be reduced by simply operating the inverter above the resonant frequency of the tuned circuit and reducing the conduction angle of the switches i.e. reducing the duty cycle below 50%[2]. If the switching frequency of the inverter is above the resonant frequency of the LCR network, the load will look inductive and hence the load current will be lagging the midpoint voltage.

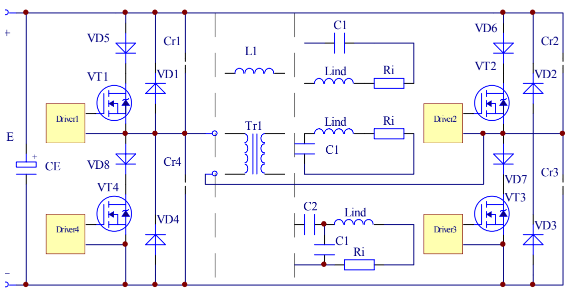

Fig.1. *Principal circuit of a voltage-fed full-bridge class-DE resonant inverter for induction heating with different oscillation tank.*

Hence *zero-voltage and zero-load-current* turn-on is achieved [1,3,4]. This will give Class-E switching conditions in a traditional Class-D topology and thus this method of operation has been termed Class-DE [4].

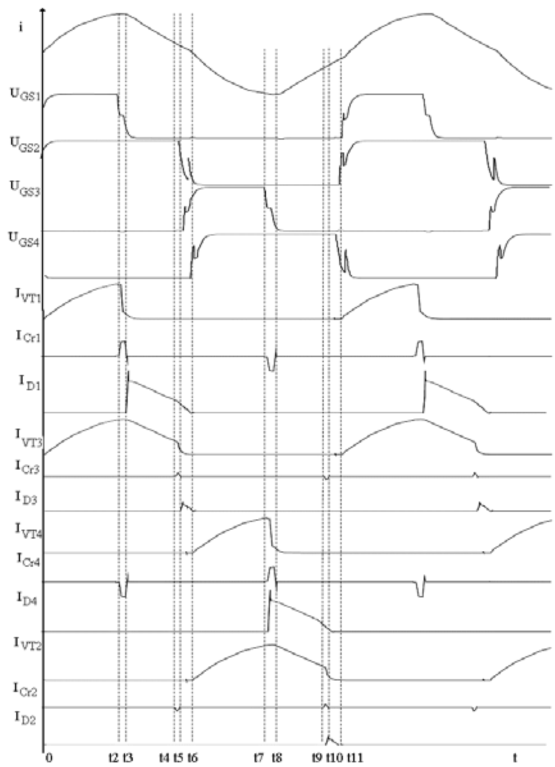

Fig. 2. *Operational waveforms of a class-DE inverter.*

The energy stored in the output capacitances is simply oscillated from one to the other with no power dissipation occurring. These effects can be seen in the waveforms of Figure 2 [3].

2. ANALYSIS

The analysis of class DE inverters could be quite complicated. Often within single period different equivalent circuits, some of which quite elaborated, are to be used. One of the most elaborated circuit is the series-parallel LC-LCR - Fig. 1, where the capacitive increase of the voltage load could not be used. Therefore, in the analysis of class DE invertors, precise and approximate methods should be involved. An example of such approach is the combination of the method of harmonical analysis used in simplifying complicated equivalent circuits and the piece-wise method for the analysis of electromagnetic processes occurring while changing transistors' state.

Simplification by the method of the harmonical analysis involves application of equivalent serial circuits, where the voltage over the equivalent capacitor C_E and the consequent equivalent resistance R_E are assumed to be sinusoidal [2].

The oscillating tank in the AC part of the inverter could be simplified to equivalent R_e and C_e, in series, i.e. to a complex resistance

$$Ze_{a,b} = R_e + jX_e \quad (1)$$

The most complicated equivalent circuit of the inverter, with a switched-on transistor, for the period $0 \le t \le t_1$, is presented on Fig. 3.

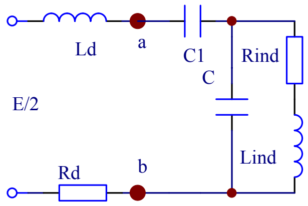

Fig. 3. *Equivalent circuit of voltage-fed full-bridge class-DE resonant inverter for induction heating at $0<t<\lambda$.*

It is transformed to a serial circuit as follows:

$$R_e = \frac{1}{\omega.C}.\frac{\xi_0^2.ctg\varphi}{\left(1-\xi_0^2\right)^2 + ctg^2\varphi} \quad (2)$$

$$tg\psi = tg\varphi.\frac{\frac{1}{\sin^2\varphi} - \xi_0^2}{\xi_0^2} \quad (3)$$

$$tg\delta = \frac{K}{R'} + tg\psi \text{, where:} \quad (4)$$

$$\xi_0^2 = \frac{1}{\omega^2.L_{ind}.C},\ tg\varphi = \frac{\omega.L_{ind}}{R_i},\ R_{el} = R_e + R_d,$$

$$L_d = L_{el}$$

$$R' = \frac{\xi_0^2.ctg\varphi}{\left(1-\xi_0^2\right)^2 + ctg^2\varphi} \quad (5)$$

$$\omega_1 = \sqrt{\frac{1}{L_d.C_{el}} - \left(\frac{R_{el}}{2.L_{el}}\right)^2}, \quad (6)$$

ω_1- resonant frequency

Equivalent capacitor $C_{el} = \dfrac{1}{\omega.R_e.tg\delta}$ (7)

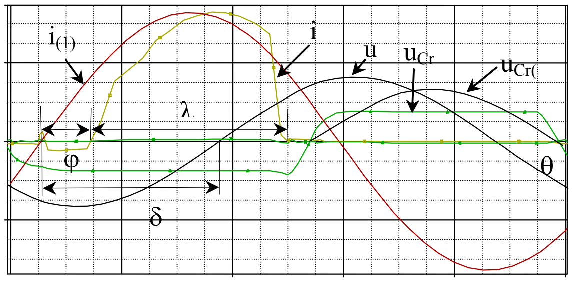

Fig. 4. *The main* phase angles *between the current and the voltage in equivalent circuit*

The current and the voltage for the circuit on Fig. 3, as well as their main phase angles are presented on Fig. 4, where

- $\theta = \omega.t$ - time in circular units;
- δ - current-voltage angle in the circuit;
- φ_1 – the angle between the current and its first harmonic;
- λ - angle of conductance.

For switched-off transistor, the equivalent circuit for the period $t_1 \le t \le t_2$, is presented by Fig. 5.

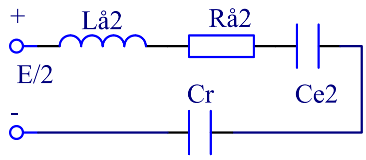

Fig. 5. *Serial equivalent circuit of voltage-fed full-bridge class-DE resonant inverter for induction heating for $\lambda<t<t2$.*

Then:

$$R_{e2} = \frac{1}{\omega.C}.\frac{\xi_0^2.ctg\varphi}{\left(1-\xi_0^2\right)^2 + ctg^2\varphi} \quad (8)$$

$$tg\delta = \frac{K}{R_{e2}'} + tg\varphi \quad (9)$$

With $K = \dfrac{C}{Cs}, Cs = \dfrac{C_1 + C_r}{C_1.C_r}, R' = \dfrac{\xi_0^2.ctg\varphi}{\left(1-\xi_0^2\right)^2 + ctg^2\varphi},$

$$\xi_0^2 = \frac{1}{\omega^2.L_{ind}.C}$$

$$tg\varphi = \frac{\omega.L_{ind}}{R_{ind}} \quad (10)$$

$$\omega_2 = \sqrt{\frac{1}{L_d.C_{el}} - \left(\frac{R_{el}}{2.L_{el}}\right)^2} \quad (11)$$

$$C_{e2} = \frac{1}{\omega.R_e.tg\delta} \quad (12)$$

To analyze the inverter circuit, it is necessary to transfer the tank circuit parameters to the transformer primary side, which is connected in the diagonal of the full-bridge circuit – Fig.1. These are the values of the inductance and the resistance of the inductor coil and the values of the compensation capacitor – $L=L_{ind}/n^2$, $R=R_{ind}/n^2$, $C=C_1 .C_2*n^2/(C_1+C_2)$, where n-transformation coefficient.

The methods reduce to analysis of process in serial oscillation tank.

The equivalent circuit at switch-on condition for different circuits reduces to the circuit, shown on Fig.6.

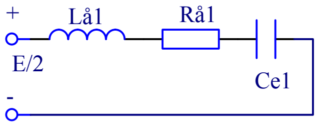

Fig. 6. *Serial equivalent circuit of voltage-fed full-bridge class-DE resonant inverter for induction* heating for 0<t<λ

Where:

- R_{e1} and C_{e1} are respectively the equivalent active resistance and the equivalent capacitance in the oscillating tank of the AC part of the inverter, operated at over resonance work frequency;
- L_{e1} is the commutative inductance, which ensures the inductive character of the current in the switch.

The analysis of the electromagnetic process in a definite mode of a class-DE inverter is performed in three intervals, depending on the state of the switching elements.

2.1. First interval - period $t_0 \div t_1$. Conduction state of VT1.

Equivalent circuit is showing on a Fig.3.

Let us assume that the inverter always operates at approximately cosφ = 1, i.e. the control system always supports the operating frequency equal to the resonant frequency. We can write down:

$$u_{C1} = \begin{pmatrix} -(E+U_3).\cos\omega_1 t + \\ \frac{\delta}{\omega_1}(E+U_3).\sin\omega_1 t \end{pmatrix} e^{-\delta t} + E \qquad (13)$$

$$i_1 = C.e^{-\delta t}\begin{Bmatrix} \frac{\delta}{\omega}(E+U_3)(-\delta.\sin\omega_1 t+\omega_1.\cos\omega_1 t) - \\ (E+U_3)(-\delta.\cos\omega_1 t-\omega_1.\sin\omega_1 t) \end{Bmatrix} \qquad (14)$$

2.2. Second interval - period $t_1 \div t_2$. The transistor's zero voltage switch-off.

Equivalent circuit is showing on a Fig.5.

The solutions, using the superposition method for the currents of each resonant capacitor, are:

$$u_{C2} = \begin{Bmatrix} \frac{C_r}{C+C_r}.(U_1-E).\cos\omega t' \\ +\left[\frac{\delta}{\omega_2}.\frac{C_r}{C+C_r}.(U_1-E)+\frac{1}{\omega_2 C}.I_1\right].\sin\omega_2 t' \end{Bmatrix} e^{-\delta t'} + \\ +\frac{C_r}{C+C_r}.E+\frac{C}{C+C_r}.U_1 \qquad (15)$$

$$i_2 = 2.C.e^{-\delta t'}\begin{bmatrix} \frac{\delta}{\omega_2}.\frac{C_r}{C+C_r}.(U_1-E)(-\delta.\sin\omega_2 t')+ \\ \frac{1}{\omega_2 C}.I_1.(-\delta.\sin\omega_2 t'+\omega_2\cos\omega_2 t')+ \\ +\frac{C_r}{C+C_r}.(U_1-E)(-\omega_2.\sin\omega_2 t') \end{bmatrix} \qquad (16)$$

$$u_{Cr} = \frac{C}{Cr}\begin{Bmatrix} \frac{C_r}{C+C_r}.(U_1-E).\cos\omega_2 t' + \\ \left[\frac{\delta}{\omega_2}.\frac{C_r}{C+C_r}.(U_1-E)+\frac{1}{\omega_2 C}.I_{off}\right].\sin\omega_2 t' \end{Bmatrix}.e^{-\delta t'} + \\ +\frac{C}{C+C_r}.(E-U_1) \qquad (17)$$

Where: $t' = t + t_2 - \chi\frac{T}{2}$, $\omega_2 = \sqrt{\omega_{02}^2 - \delta^2}$, $\omega_{02} = \frac{1}{\sqrt{LC_1}}$

$\delta = \frac{R}{2L}$ and $C_1 = \frac{C.C_r}{C+C_r}$

On the other hand, the time of voltage build-up across transistor - t_2, can be determined by assuming that $u_{Cr}(t_2)=0$. Substituting in (17) we get:

$$0 = \frac{C}{Cr}\begin{Bmatrix} \frac{C_r}{C+C_r}.(U_1-E).\cos\omega_2 t_2 + \\ \left[\frac{\delta}{\omega_2}.\frac{C_r}{C+C_r}.(U_1-E)+\frac{1}{\omega_2 C}.I_1\right].\sin\omega_2 t_2 \end{Bmatrix}.e^{-\delta t_k} + \\ +\frac{C}{C+C_r}.(E-U_1) \qquad (18)$$

2.3. Third interval - period $t_2 \div t_3$. Conduction state of opposite reverse diode.

During this period the reverse diode has been on. If we assume that the initial conditions for current and voltage are:

$i(t_2) = I_2$, $u_C(t_2) = U_2$

$$u_{C3} = \begin{pmatrix} (E-U_2).\cos\omega_1 t + \{\frac{\delta}{.\omega_3} \\ .(E-U_2)+\frac{I_2}{\omega_3.C}\}.\sin\omega_1 t \end{pmatrix} e^{-\delta t} + E \qquad (19)$$

$$i_3 = C.e^{-\delta t}\begin{Bmatrix} \{\frac{\delta}{.\omega_3}.(E-U_2)+\frac{I_2}{\omega_3.C}\}.(-\delta.\sin\omega_1 t+\omega_1.\cos\omega_1 t)+ \\ (E-U_2)(-\delta.\cos\omega_1 t-\omega_1.\sin\omega_1 t) \end{Bmatrix} \qquad (20)$$

Where

$\omega_3 = \sqrt{\omega_{03}^2 - \delta^2}$, $\omega_{03} = \frac{1}{\sqrt{LC}}$, $\delta = \frac{R}{2L}$ $t'' = \frac{T}{2} - (\frac{T}{2}.\chi + \tau_2)$

As the conduction angle λ is varied from 180 ° to zero, the power output will be reduced from its maximum value down to zero. This should be useful in such applications as induction hardening and melting.

For given working frequency, the values of the elements in the equivalent circuits, can be derived from (2), (8), (12).

The stationary solutions for the current and the voltages are obtained for certain working intervals within one period (equivalent circuit) - see 2.1, 2.2 and 2.3. According to expressions (13)÷(20), there are possible for given the pulse-width coefficient χ and initial conditions.

Following this approach, analysis of vol??tage-fed full-bridge class-DE resonant inverter for induction soldering - Fig. 10 has been made in MAPLE 6 with program package for analysis at different time intervals. Graphical representations of the results, obtained for the following current and voltage initial values,

U_1=80 V; I_1=18 A;

U_2=90 V; I_2=10 A;

U_3=90 V; I_3=0 A;

λ=165 °; φ=58.5 °;

t1=600 nS; t2=680 nS, are shown on Fig. 7-9.

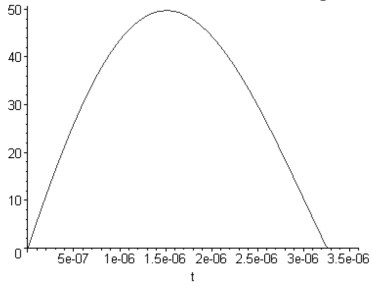

Fig. 7. *Transistor current waveform I_{Dmax} of voltage-fed full-bridge class-DE resonant inverter for induction heating for interval $0<t<t_1$.*

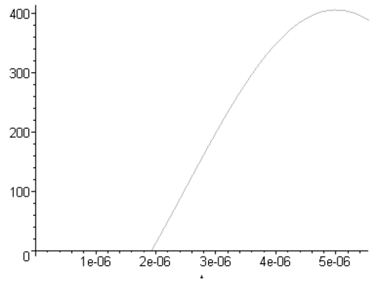

Fig. 8. *Voltage waveform Uds_{max}, of voltage-fed full-bridge class-DE resonant inverter for induction heating for interval $t_1<t<t_2$.*

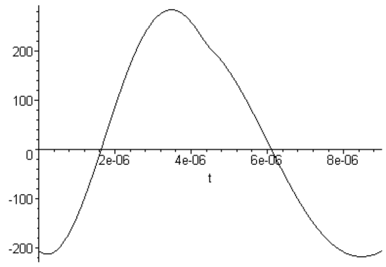

Fig. 9. *Tank capacitor voltage of voltage-fed full-bridge class-DE resonant inverter for induction heating for fill period.*

3. COMPUTER SIMULATION

The inverter has been designed to function in an induction heating installation, for induction soldering of steel/stainless steel details - Fig.10. The size of the details is up to 70 mm and weight up to 0.3 kg. The consumer requirement for the technological time of soldering is up to 40 s.

Application parameters are as follows:

-Input Voltage E = 310 V, DC;

- Input power P_{out} = 3000 VA;

- Output Power = 2600 W

- Working frequency $f_0 \approx$ 110 kHz.

- The soldering is achieved by silver loaded solder at melting temperatures of 650°C.

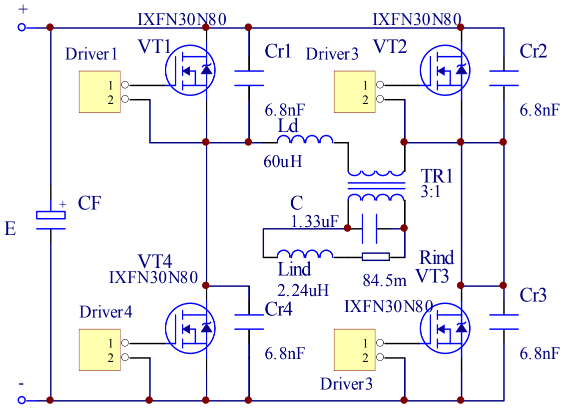

Fig. 10. *Practicalcircuit of voltage-fed full-bridge class-DE resonant inverter for induction soldering.*

For verification on Fig.7, 8, 9, computer simulations with PSPICE have been performed. The passive elements and transistors for the full-bridge class-DE resonant inverter, have been selected on the basis of preliminary calculations.

Fig.11 present the simulated time charts of regulation transistor VT4 operation *for $\lambda\approx 165°$*. Fig. 12 shows the transistor operation voltage and current for nonregulation transistor VT2.

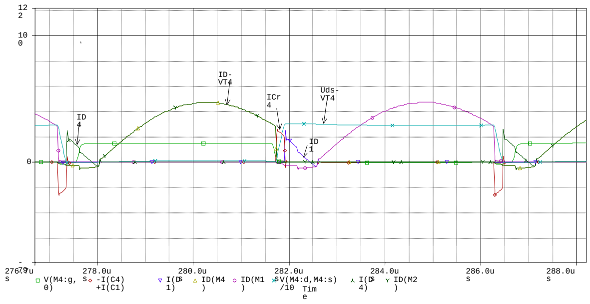

Fig. 11. *P-SPICE waveform for U_{DS} and U_{GS} voltage over transistor VT4 and current I_D, current in resonance capacitor C_{r4} and anti-parallel diode VD4*

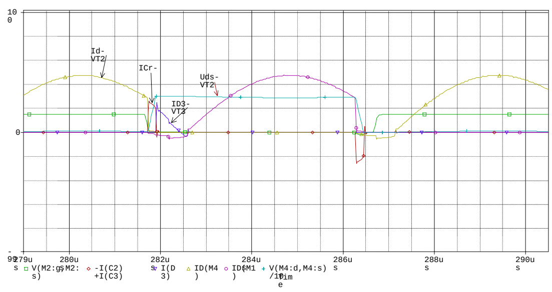

Fig. 12. *P-SPICE waveform for U_{DS} and U_{GS} voltage over transistor VT2 and current I_D, current in resonance capacitor C_{r4} and anti-parallel diode VD4*

Fig.13 present the simulated waveform for current and voltage over load inductor and output power for $\lambda\approx$165°.

Fig. 14 shows regulating characteristic of output power.

Fig. 15 shows inverter efficiency of e class-DE resonant inverter.

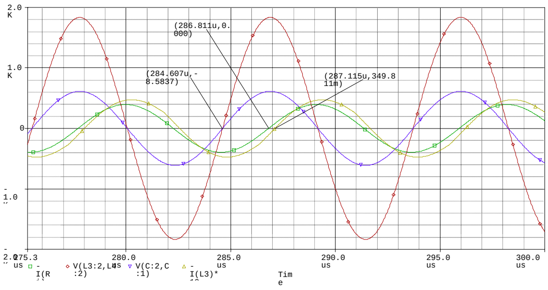

Fig.13. *P-SPICE waveform for* I_{Rind} *and* $U_{inductor}$ *voltage over load inductor and output power*

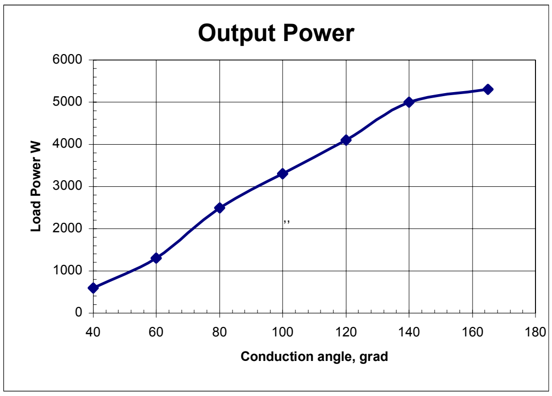

Fig. 14. *Regulating characteristic of voltage-fed full-bridge class-DE resonant inverter for induction soldering.*

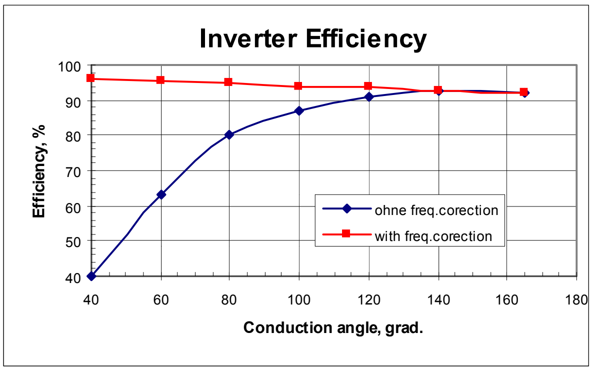

Fig. 15. *Inverter efficiency of voltage-fed full-bridge class-DE resonant inverter.*

4. CONCLUSION

1. A class-DE analysis of an induction technologies inverter and having a complex oscillation tank configuration using the harmonic analysis methods simplyfying the equivalent scheme and the piece-wice forming a solutin during the comutation.
2. A coincidence exists between the results due to the calculations and computer simulation. The offered analysis method can be used in the engineer work applications.
3. A total method can be composed for designing a class-DE invertor based on the offered analysis, having different induction technologies using different loads and oscilation tanks.

5. REFERENCES

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