Design of RF power amplifiers at 40.68 MHz

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Abstract - Paper describes challenges related to the design of RF power amplifier operating at 40.68MHz with high efficiency. The amplifier is aimed to drive a welding actuator in a blood separator device. Therefore the paper begins with brief description of dielectric welding theory and proceeds with explanation of RF generator role in the process. Then the requirements related to welding plastic tubes used for blood separation are defined. The essential part of the paper discusses a design process of RF generator. The main request was to obtain the most efficient solution based on using MOS transistors. Accordingly a design of Class E power amplifier is considered. Finally, simulations and parametric analyses verified a design that provides more than 50W on 50Ω load with efficiency of over 80%.

I. INTRODUCTION

Bodily fluids usually are stored in sealed plastic bags. The bags are filled trough plastic tubes. Therefore it is sufficient to seal the tubes. Special equipment provides reliable watertight closing by welding plastic tubes. These devices utilises the elementary welding theory. The tube has to be heated until begin to melt. Then it has to be exposed to a pressure for a certain amount of time sufficient to seal walls of tube together. As the tubes are made of a dielectric material, plastic, the most efficient way to heat it is to utilize dielectric loses caused by high frequency RF signals. In general this technique is often used in industry when fast and reliable sealing is needed. Depending on particular purpose the power needed for the welding process range from a few tens to several hundred watts [1]. This paper considers an RF generator that should provide output power of at least 50W on 50Ω load. The presented results are extension of previously published paper by the same author [2].

The paper is organized in five sections. The following section describes basic theory of RF sealing. The third section presents a brief description of the main blocks of the device for welding plastic tubes. The central part of the paper describes the design of the crucial part of the welding device – the output amplifier of the RF generator. The chosen solutions are verified by simulations and appropriate analysis in the fifth section. The obtained results proved that the designed solution of Class E amplifier delivers required power of at least 50W to the load with efficiency better than 80 %.

II. RF WELDING THEORY

Temperature is the crucial parameter responsible for melting of any material. At some temperature level interconnecting bonds between particles (atoms, molecules) get lose so that one material turns from solid to liquid phase.

If two pieces of melted material are pressured, they easily can be mixed making a joint after cooling and returning into solid phase. Besides temperature and pressure the third parameter that controls the welding is time.

The heating phenomenon initiates friction between moving particles. The greater the friction the higher the temperature. Therefore one needs to cause particles movement in order to obtain heat. The moving can be elicited by exposing material to an alternating electrical field. Often change of polarity provoke dipoles to turn from one to another direction causing friction.

According to the AC signal frequency different types of heating are recognized: induction heating, RF or HF heating, microwave heating, infra-red heating. Fig. 1 illustrates the frequency range for each of these types of heating [1].

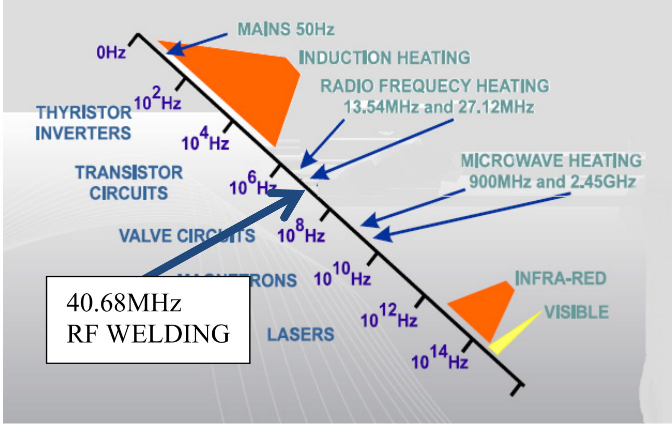

Fig. 1. Frequency ranges that are used for different types of heating materials, reprinted from [1]

Each range has advantages and drawbacks for different applications. The most appropriate frequencies for heating insulators (and poor conductor materials) are RF signals ranged from 1MHz to 200MHz. In order to avoid interfering and disrupting radio communication International Telecommunication Union (ITU) in article 1.15 of Radio Regulations [3] defined ISM RF band for “Operation of equipment or appliances designed to generate and use locally radio frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications”. In RF band the allowed ISM frequencies are 13.56MHz, 27.12MHz and 40.68MHz. Besides, there are reserved ISM frequencies in microwave band 915MHz, 2450MHz, 5800MHz, and 24.125GHz [3].

In RF electric field dipoles of a dielectric start to alternate direction and due to the friction of molecules within the material it start to heat. It is quite expected that the heating power will be proportional to the frequency. Besides it will be affected by electric field as external factor but also with the

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property of the material like dielectric constant and the loses according to the following formula:

$$P = 0.555 * f * E^2 * \varepsilon * (\tan\delta * 10^{-6}). \qquad (1)$$

P - heat generated per unit of volume [W/cm^3]
f - frequency of electromagnetic field [MHz]
E – electric field [V/m]
ε - dielectric constant of material [F/m]
tanδ - tangent of the angle of losses [4].

Obviously, the material with higher dielectric constant and higher losses, will heat more. The RF heating can be utilised for welding if the amount of generated heat is sufficient to cause melting of the material. The welding depends on time and pressure, as well. Therefore it is crucial to put the melted material under sufficient pressure for appropriate time to ensure that the melting heat stays in the material until reaching proper sealing.

RF welding technique is commonly used in medicine for sealing plastic materials that keep liquids because it heats containers locally without affecting its valuable contents. Explicitly most of liquids required in hospitals are kept in plastic bags (blood, blood derivate, infusion...). The bags are filled in or out through plastic tubes that should be sealed to preserve a sample of fluid. It is desirable to finish the sealing process for as quickly as possible with minimal impact on its contents.

The following section describes a device for plastic tube sealing that is used in blood donation.

III. PLASTIC TUBE WELDING DEVICE

In general RF welding device consists of:

- Actuator (the welding unit)
- RF generator
- Control logic
- Power supply

Fig. 2 depicts how each of the blocks are interconnected with other.

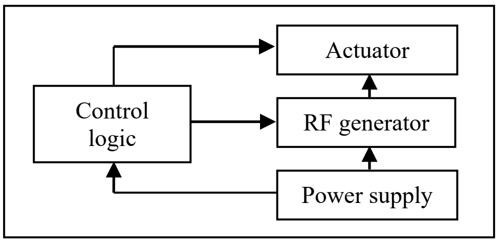

Fig. 1. Block diagram of RF welding device

The welding device that is subject of this paper follows the same structure but has some specifics related to its implementation particular applications.

Actuator is the part where the welding process occurs. The welding material is plastic tube. Therefore it should be settled between two electrodes that provides RF electric field. Practically electrodes with dielectric in between form a capacitor. One electrode is fixed while the other is movable so it can be released and pressed. At the beginning it is released and allows tube to be placed. Then electromagnet presses the movable electrode and RF signal is applied. If the electric field is sufficient, the plastic starts to heat until melting point. As being pressed, it is welded, sealing the tube.

The appropriate electric field is caused by high voltage on the electrodes. The easiest way to produce high voltage on a capacitor is to use serial resonant (LC) that operate at resonant frequency. Therefore an inductor connected in series with the capacitor has to be an integral part of the actuator. Shape of electrodes affects efficiency but this part has solved mechanical engineers. Electrical engineers have to resolve other three blocks.

RF generator provides 40.68 MHz signal that delivers 50W to the actuator. The control logic block manages the process of welding. The RF generator and control logic are powered from DC power supply.

The most challenging part was RF generator and the rest of the paper describes its design.

IV. RF GENERATOR

RF generator has the task to provide signal capable to stimulate the actuator with adequate output power. As previously mentioned the signal should have frequency of 40.68MHz that provides power greater than 50W at 50Ω load. This can not be made in a single stage. Firstly it is necessary to generate 40.68MHz signal in oscillator stage. Then an amplifier is needed to gain amplitude until sufficient electric field is obtained in the actuator. The amplifier is divided in two sections: preamplifier and power amplifier. Preamplifier increases signal from oscillator giving the sufficient strength to excite the power amplifier. Additional requirement is to design output stage as efficient as possible. This constraint comes from the need to supply the device from an external battery.

The load is serial resonant circuit and output is optimised for resonant frequency. Consequently the linearity is not the issue so that class C, D or E amplifiers seem to be good solutions. The design started from the class C power amplifier presented in Fig. 3.

It consists of a pair of transistors Q1 and Q2 connected in push-pull configuration. Both are the same polarity type (npn) transistors and need to be excited with opposite phase signals that come from transformer T1. Transistors are loaded with parallel resonant circuit configured by L1 and C4 in parallel to output capacitance of transistors. Values of L1 and C4 are tuned to the resonant frequency of 40.68MHz. Capacitors C5 and C6 decouples balun transformer T2, made of six composite coils. It balances the differential output impedance of the amplifier to the single ended impedance of the actuator. Serial resonant circuit LA-CA represents actuator model. As capacitor CA form welding electrodes with plastic tube in between, its capacitance is predefined with physical dimensions of electrodes, size of plastic tube and properties of the plastics. Therefore inductance LA is tuned to fit the resonance frequency of 40.68 MHz with capacitance of electrodes CA. Additional matching between output impedance of the transformer and the actuator utilizes Π filter that consists of L2, C7 and C8.

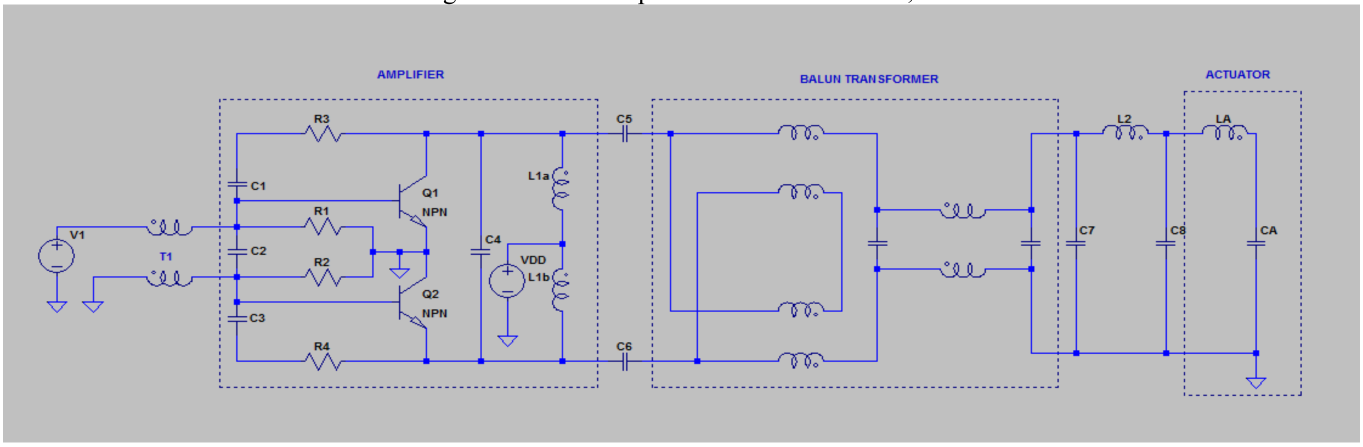

Fig. 3. Electrical scheme of output stage of RF generator

The amplifier in Fig. 3 delivers 50W at 50Ω load but operates with efficiency of less than 70 % when supplied from 15V DC.

Aiming to get better efficiency we decided to design RF generator with output stage operating in class E. The following section describes attempts and realizations achieved.

V. CLASS E RF POWER AMPLIFIER DESIGN

The main source of power dissipation on a transistor is situation when transistor drives considerable current simultaneously with large voltage drop across. Oppositely, when transistor operates as switch dissipation is minimal. Namely, when transistor is turned-off (switch opened) no current flew while the voltage across the switch is maximal – consequently the dissipated power is zero. When the switch is closed (transistor turn-on) it conducts maximal current but voltage drop across is almost zero so the dissipation tends to zero. This theory is built in all energy efficient solutions. Class E amplifiers are one of them [5]-[8]. In an ideal case, efficiency of class E amplifiers is 100%. In practice it can reach up to 96%. Fig. 4 illustrates basic schematics of a class E amplifier realized with an nMOS transistor operating as a switch.

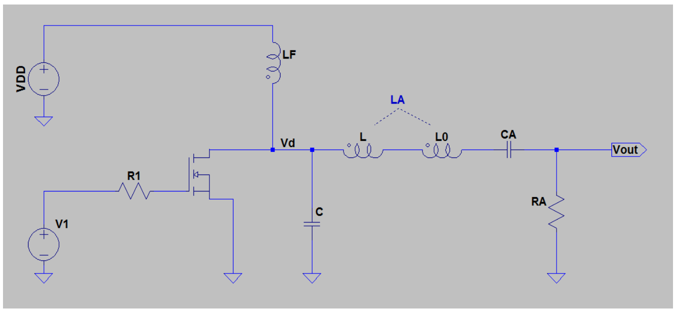

Fig. 4. Class E amplifier

In the switching mode drain voltage changes between VDD and zero trough inductor LF. The drain is loaded with a capacitance C in parallel with serial resonance circuit of the actuator: LA and CA with serial resistivity RA. Practically LA consists of L and L0 (LA=L+L0). During the switching the circuit changes configuration alternating two equivalent circuits for each half of the cycle. When the transistor is on, C is shorted and only LA in series with CA exists. When transistor is off C (togather with parasitic output capacitance of transistor, C_{DS}) is connected to LA and CA. The inductance L has role to match the optimum operating regime. Details about class E amplifiers one can find in [5, 6].

Class E amplifiers are invented and are used to provide the highest possible efficiency (η) by reducing dissipation on transistor. The efficiency represents the ratio of the useful power at the load and the invested power from DC supply. The load power is defined as:

$$P_{OUT} = \frac{1}{2} \cdot \frac{{V_{OUT}}^2}{R_A}, \tag{2}$$

where V_{OUT} denotes amplitude (peak) of the load voltage. The supplied DC power is:

$$P_{DD} = V_{DD} \cdot I_{DD}, \tag{3}$$

where V_{DD} and I_{DD} stands for DC (average) voltage and current, respectively. Consequently, the efficiency is:

$$\eta = \frac{P_{OUT}}{P_{DD}} \cdot 100\%. \tag{4}$$

The difference between useful power at the output and the supplied power is mainly dissipated on transistor. The wasted power depends on the switching speed of transistor and its resistivity while conducting.

On the other hand, the output power depends on RA. However, the values of CA and RA are predefined with the actuator geometry and the properties of plastic tubes that should be sealed. From (1) it is known that the thermal power will be better for higher frequency, higher field and greater loses. As the frequency is restricted by ITU regulations, and properties of the tube material are predefined, the possibilities of trading for efficiency are very limited. They reflect in selecting fast transistor and in tuning L and C values. In order to meet the design specifications we chose transistor LK701 as active device [9].

Fig. 5 depicts simulation results when the circuit in Fig. 4 is supplied with V_{DD} = 24V and exited from the pulse generator V1 with amplitude of 10V at 40.68MHz. The picture shows waveforms of the output voltage V(Vout) and the drain voltage V(Vd). During simulation the battery provides average (DC) current of 450mA. Consequently, the implementation of equations (2), (3), and (4) responded with the output power P_{OUT} = 9W, the DC supplied power P_{DD} = 10.8W, and efficiency of η = 83%.

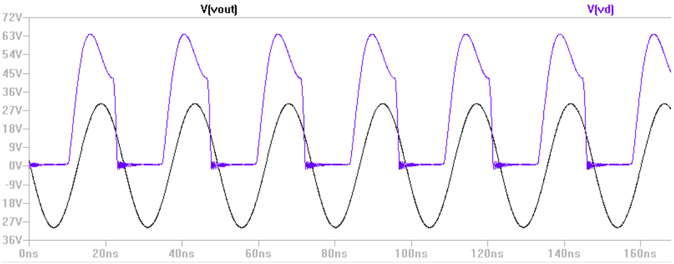

Fig. 5. Simulation results of class E amplifier

Although the efficiency looks acceptable, the main request for the load power is far below the desired specifications. One of possibilities to increase the output voltage (electrostatic field E) is increasing level of power supply. However due to voltage pick caused on LF, when the transistor is turning off, treats to overdrive V_{DS} voltage on drain. Therefore a transformer (L1, L2) is implemented as Fig. 6 illustrates. The transformer firstly the transformer should increase the output voltage. Therefore it has transmission ratio is 1:3. Besides, it helps in matching the impedances of the actuator and the output impedance of transistors. Simulation results of the modified class E amplifier are shown in Fig. 7.

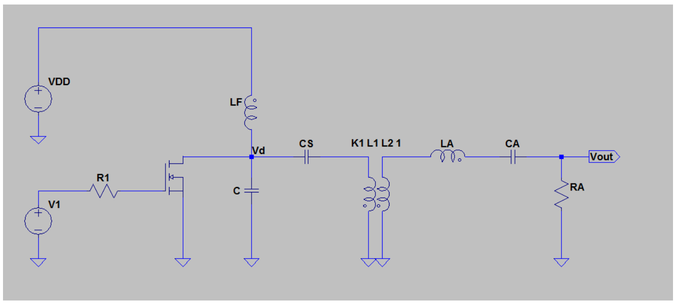

Fig. 6. Modified class E amplifier

This modification increased the output power to P_{OUT} = 45W but DC power raised even more, to P_{OUT} = 45W. Accordingly the efficiency has declined to η = 73%. Actually, the finite transistor output resistance in combination with the parasitic capacitances restrict the transition time when transistor tends to turn on. In order to provide more current to the output, two transistors in parallel were implemented as Fig. 8 illustrates. This modification requires more complex output transformer that consists of L3, L4, L5 and L6. However, L3 and L5 took the role of LF so that the complete circuit complexity is optimized.

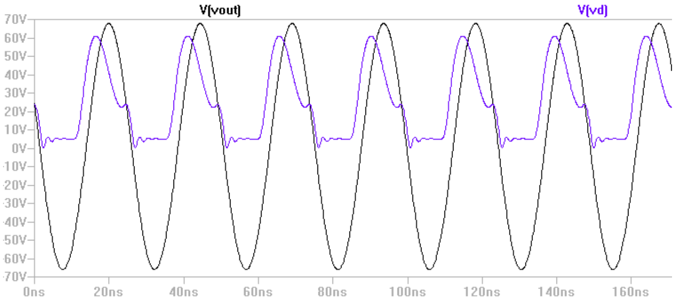

Fig. 7. Simulation results of modified class E amplifier from Fig. 6

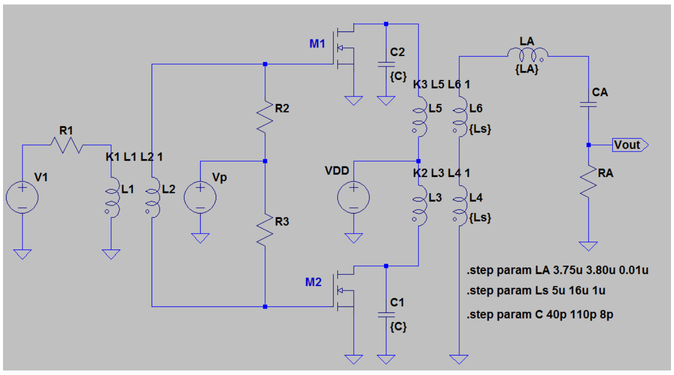

Fig. 8. Class E amplifier after second modification

The transistors operate in anti-phase mode. When one is turned on the other is off and vice versa. This mode provides excitation by transformer (L1, L2). DC voltage threshold voltage was optimized to V_p=4V in order to bias MOS transistors through resistors R2 and R3. The amplifier supply was retained to V_{DD} = 24 V.

The output transformers (L3, L4) and T3 (L5, L6) are designed to sum at the secondary. Therefore they have independent cores with winding direction as shown in Fig. 8. As mentioned above, the values of RA, CA and the frequency of the stimulus V1 are predefined. Consequently, only parameters that could be adjusted for the highest output power are LA, C1, C2 and transmission ratio of the transformer. However, same parameters impact the supplied current so that the higher output power mean better efficiency.

In order to find optimal solution several parametric analyses has been done. For each value we computed output voltage (V_{OUT}), current through the source (I_{DD}), output power, DC supply power (P_{DD}), and the efficiency.

Firstly we considered the effects of capacitances C1 and C2 (denoted as {C}). These capacitances are consisting parts of power amplifier that operates in class E. Their value was swept in range from 40pF to 110pF. The results of the analysis are shown in Table 1. The starting capacitance of 40pF was slightly increased and it can be seen that at some point output voltage starts to decrease which implies decreasing of output power. From Table 1, it is obvious that acceptable values are between 48pF and 56pF, because only in that range the output power is greater than 50W, which was the starting condition for realization of RF generator. As the higher efficiency (80.43%) was obtained for 56pF, this value was adopted for further analysis.

TABLE I
EFFICIENCY REGARDING C

C [pF]	V_{OUT} [V]	I_{DD} [A]	P_{OUT} [W]	P_{DD} [W]	η [%]
40	70.4	2.71	49.56	65.04	76.20
48	71.0	2.64	50.41	61.36	79.56
56	**70.7**	**2.59**	**50.00**	**62.16**	**80.43**
64	70.5	2.57	49.71	61.68	80.60
72	70.0	2.55	49.00	61.20	80.06
80	69	2.53	47.61	60.72	78.41
88	68	2.52	46.24	60.60	76.30
96	67	2.52	44.89	60.60	74.22
104	66	2.51	43.56	60.48	72.16

The second parameter to adjust is transmission ratio of transformers (L3, L4) and (L5, L6). In LTspice this can be done by parametric change of inductances on secondary coil (denoted as {Ls} in Fig. 8). Ls was swept from 5μH to 15μH. Like in the previous analyse, output voltage (V_{OUT}), current through the source (I_{DD}), output power, DC supply power (P_{DD}), and the efficiency were computed for each value of secondary inductance. The results of the analysis are shown in Table 2.

TABLE II
EFFICIENCY REGARDING LS

Ls [uH]	V_{OUT} [V]	I_{DD} [A]	P_{OUT} [W]	P_{DD} [W]	η [%]
5	52	1.55	27.04	37.20	72.68
8	63	2.14	39.69	51.36	77.27
9	67	2.36	44.89	56.64	79.25
10	**71**	**2.59**	**50.41**	**62.16**	**81.09**
11	73	2.83	53.29	67.92	78.45
12	76	3.05	57.76	73.20	78.30
15	78	3.70	60.84	88.80	68.51

It can be seen that the rising of transmission ratio increases both the output power (P_{out}) and the current through the power supply (I_{DD}). Design objective of Pout>50W meet all Ls>10μH. However, the maximal efficiency of 81.09% provides Ls=10μH. Consequently this value was adopted for further analysis. It corresponds to transformation ratio of 1:1.41 because the inductance of primary is 5μH.

The third parametric analysis is used to match inductance of LA. Practically there is not much room for it because LA needs to be matched with capacitance of electrodes (CA), in order to make serial resonant circuit. Therefore LA was swept in narrow range from 3.75μH to 3.80μH. Table 3 shows the output voltage (V_{OUT}), current through the power supply (I_{DD}), output power (P_{OUT}), DC supply power (P_{DD}), and the efficiency (η) for each value of LA.

TABLE III
EFFICIENCY REGARDING LA

LA [H]	V_{OUT} [V]	I_{DD} [A]	P_{OUT} [W]	P_{DD} [W]	η [%]
3.75μ	73.0	2.87	53.29	68.88	77.00
3.76μ	72.5	2.80	52.56	67.20	78.20
3.77μ	72.0	2.74	51.84	65.76	78.80
3.78μ	71.5	2.66	51.12	63.84	80.07
3.79μ	**71.0**	**2.58**	**50.41**	**61.92**	**81.41**
3.80μ	70.0	2.51	49.00	60.24	81.30

As we can see, output power (P_{OUT}= 53.29W) is the highest for LA=3.75μH. However, it is obvious that better efficiency can be obtained for lower but still sufficient output power. Using LA=3.79μH provides maximum efficiency of 81.41 % with P_{OUT}=50.41W which is just above the specified minimum of 50W. The efficiency is lower than theoretical because the predefined impedance of actuator and the operating frequency do not make room for better optimisation.

With the adopted vales for C, Ls and LA it should be checked how sensitive the design is to parameter tolerances. Therefore three Monte Carlo analyses have been performed.

The first was for C1=C2=56pH, L3=L5=5uH (L4=2L3, L6=2L5) with 10% tolerances. It exhibited almost no effect on output voltage. Precisely, its magnitude varied between 69V and 71V.

The second took into account both output transformers. All four inductances have been adopted with 10% tolerances independently. This means that transformation ratio have been included as well as mismatching effects on output loads for M1 and M2. Fig. 9 presents the obtained results.

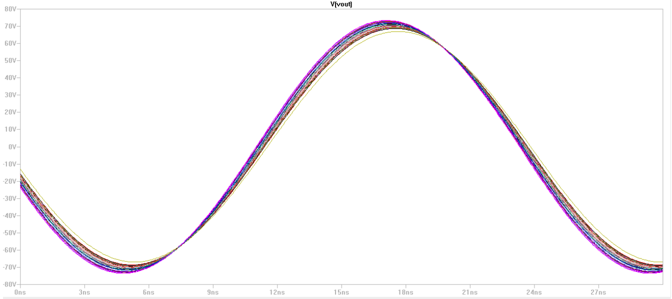

Fig. 9. Results of Monte Carlo analysis obtained for L_3=5μH ±10%, L_4=10μH ±10%, L_5=5μH ±10%, L_6=10μH ±10%

Obviously both the transformer rations and their mismatch affect the decrease of output voltage for less than 10% (the worst case magnitude was >65V).

The third Monte Carlo analysis has been repeated when LA and CA changes with tolerances 10%. The results are illustrated in Fig. 10. They indicate that 10% tolerances of the resonant circuit (LA and CA) parameters significantly affect the output. This was expected due to the high selectivity of serial resonant circuit. Consequently, in order to optimise circuit performance it is very important to match LA and CA for the resonant frequency. It is good to know that during the welding process CA changes the value as the plates of the actuators comes closely when plastics begin to melt. Therefore it is important to provide LA that fits to resonance frequency with the initial value of CA at the beginning of the process.

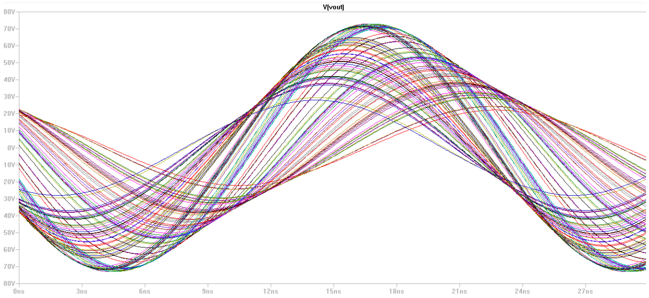

Fig.10. Results of Monte Carlo analysis obtained for C_A and L_A with 10% tolerances.

VI. CONCLUSION

This paper represents an extension of previously published paper explaining power RF generator design [2]. Practically the generator is aimed to provide sufficient power needed for RF welding of plastic tubes that are used in medicine. Namely bodily liquids are stored in plastic bags that end with plastic tubes. The RF welding is needed to seal the tubes quickly and reliably and to keep the liquid from contamination and leakage. The design is constrained with quantified requests enforced by physical phenomena during the welding process. Therefore, the required output power is 50W at 50Ω load. Besides, standards that regulate usage of radio frequency bands allow operating frequency of 40.68 MHz for medical appliances. The generator is loaded with an actuator that performs the welding by applying high electrical RF field on plastic material settled between two metal plates. Due to the friction between particles within the plastics it starts to heat until reaches melting temperature. Therefore the required power should be generated on an imperfect capacitor with loses. The most efficient way to increase the field is to connect the capacitor in series with an inductor and to fit for resonance frequency. Therefore the output stage of RF generator is loaded with serial resonance circuit.

Addition design requirement was high efficiency. Therefore RF power amplifiers that operate in Class E were considered for the output stage. Firstly, the simplest single transistor configuration has been considered. It provided very good efficiency of 83 %, but the output power has been less than 10W that is below the required 50W.

The output power has been increased utilizing a transformer with 1:3 transformation ratio. This has raised the output power to 45W but decreased efficiency to 73%.

The further improvement in trading power for efficiency provided solution with two transistors operating in push-pull configuration. The results obtained with the manually calculated circuit parameters provided output power of 50,46W with efficiency of 81,09%. The power increase is the result of adding the signal at the output transformer.

In order to find the maximum efficiency, parametric analyses have been performed on:

- capacitances C1=C2,
- inductances L4 = L6 that define the transformation ratio of output transformers (L3, L4) and (L5, L6), and
- inductance LA.

These resulted with slightly improvement of efficiency to 81,41% with small decrease of output power to 50.41W.

Finally, it is important to stress that operating at given resonance frequency using capacitor with predefined dimensions and dielectric properties give very limited space for parameter fitting. Moreover, Monte Carlo analyses showed that circuit is very sensitive to circuit parameters in output serial resonant circuit. It is expected that RF generator be practically implemented and therefore it should be upgraded and optimized for robustness in the future.

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REFERENCES

[1] R. James, “Radio Frequency for Rapid, Energy Efficient Heating of Polymers and Composites”, *C-Tech Innovation*, Oct. 2014.

[2] Dušan Petrović, „Challenges in the design of RF power amplifiers for 40.68MHz,” 8th student projects conference IEEESTEC, Niš, Nov. 2015, pp. 43-46.

[3] “Radio Regulations Articles”, *International Telecommunication Union (ITU)*, Edition 2012. Also available on http://www.itu.int/dms_pub/itu-s/oth/02/02/S02020000244501PDFE.PDF (accessed on 20th December 2015)

[4] M. Isgrigg, “RF Sealing Theory”, *Thermex-Thermatron.*

[5] D. Krstić, “Radiotehnika, radiokomunikaciona elektronika i sistemi”, Niš, izdavačka jedinica Univerziteta, 1999.

[6] Al-Shahrani, S. M., Design of Class-E Radio Frequency Power Amplifier, PhD thesis, 2000., URN: etd-07152001-172453 http://scholar.lib.vt.edu/theses/available/etd-07152001-172453/ (September 2015)

[7] Hebert L. Krauss at all, “Solid State Radioengineering”, John Wiley &Sons, 1976.

[8] Sokal, A.D. Sokal: “Class E a New Class of High Efficiency Tuned Single-ended Switching Power Amplifier”, EIII Journal of Solid-State Circuit, vol. SC-10, pp. 168-176. 1975.

[9] http://www.polyfet.com/dsheet/lk701.pdf