OPTIMIZATION OF MAGNETIC PULSE FORMING INSTALLATIONS BASED ON PSPICE MODEL OF EQUIVALENT ELECTRICAL CIRCUIT

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Abstract: The obtaining of electrical equivalent scheme with concentrated parameters for magnetic pulse forming devices is difficult because of very complex phenomena that are produced within coil – workpiece assembly. The main disadvantage of such approaches is that they cannot be easily applied to more complicated coil geometries, which are often used in industrial applications. In this paper, magnetic pulse forming is modeled by a theoretical model of an magnetic pulse forming installation takes into account the induction effects with in conductors, the induction effects of work piece motion, and the dynamic behavior of workpiece material. We present the numerical simulation of transients in a magnetic pulse forming installation of cylindrical conductors using PSPICE software and for comparison numerical simulation in ANSYS Multiphysics. Genetic algorithm can be used together with PSPICE simulation program to dynamically implement some optimization problems that can use fitness function derived from a simulation process.

Keywords: magnetic pulse forming, equivalent electrical circuit, PSPICE model, optimal design, genetic algorithms

1. INTRODUCTION

Magnetic pulse forming is an unconventional technology of metal working by plastic deformation at room temperature.

The principle consists in the deformation of thin metallic pieces by intense impulsive forces acting on the conductor placed in a rapidly varying magnetic field.

A rigorous analysis of the system must take into account the non-uniform distribution of the current density within conductors - transient skin effect. In addition, the movement of the workpiece determines induction effects in conductors, modifies the magnetic field distribution, resulting a strong coupling between magnetic and mechanical phenomena.

An exact study require the solution of the equations of mediums in motion coupled with the equations of motion supplied by the mechanics of continuous media, process very difficult to modeling it.

2. ELECTRICAL EQUIVALENT SCHEME

The elements of the magnetic pulse forming scheme are the following: the rectifier, which ensures the charging of capacitor bank at initial voltage U_0, an switch that allows the discharging of the stored energy through the forming coil, intense impulsive electromagnetic forces that appear producing the workpiece deformation (Fig.1).

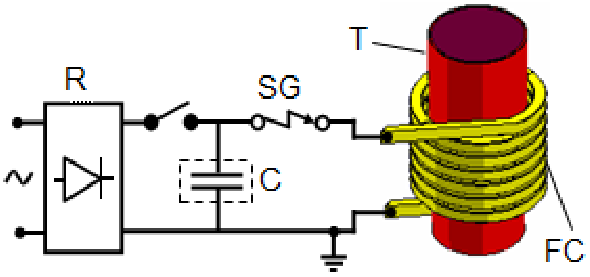


Fig.1. The main components of magnetic pulse forming installation: R - rectifier; C - capacitor bank; SG - spark gap; FC - forming coil; T – thin wall metallic tube

The obtaining of electrical equivalent scheme with concentrated parameters for magnetic pulse forming devices is difficult because of very complex phenomena that are produced within coil – workpiece assembly.

The frequency of damping oscillating current that appear after the starting of capacitor bank discharge, usually, is around tens kHz. Then, the effect of non-uniform distribution of current in massive conductors (transient skin effect) is non negligible and will be taken into account in equivalent electrical scheme.

The displacement of the workpiece during the deformation is considered by the occurrence of an electromotive force induced by the motion. The expression of this e.m.f. is function of equation of workpiece movement, which assumes the solving of mechanical equations of forming, with a high degree of difficulty.

Another phenomenon difficult to be analyzed is the "end-effect", that means the non-uniform distribution of electromagnetic field at the ends of the forming coil.

Finally, the currents that flow through conductors determine the heating of these conductors by Joule losses and as a consequence the variation of material (electrical, magnetic and mechanical) parameters and circuit parameters within equivalent scheme.

The analysis of magnetic pulse forming device is performed using equivalent electrical circuit. If we neglect the skin effect and the movement of the workpiece, we can obtain a first variant of equivalent scheme, shown in Figure 2, where the forming coil – workpiece assembly is equivalent as a transformer.

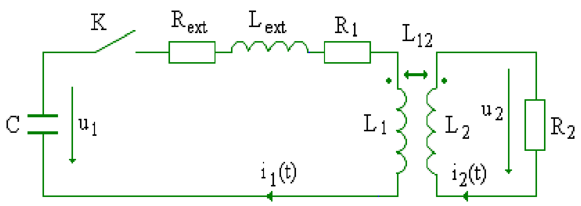


Fig.2. Simplified electrical equivalent circuit of magnetic pulse forming installation

The switch is replaced with an ideal circuit breaker and the resistivity and inductance of feeding conductors are included in R_{ext}, respectively L_{ext}. Forming coil is modeled by R_1 and L_1 components, workpiece by R_2 and L_2 and coupling by mutual inductance L_{12}.

Circuit parameters are considered constant in time that it's not happens in real situation, when these values are modified by geometry and material properties changes (that are modified by heating and deformation of the workpiece).

Electrical equivalent circuit for cylindrical configuration shown in Figure 3 is possible to be improved including the skin effect and effect of moving, as is presented in [1].

The electrical equivalent scheme with concentrated parameters for magnetic pulse forming devices obtaining in [1] is presented, with modifications, in Figure 4. The variation of geometry dimensions of the workpiece is reflected through the variation of mutual inductance between primary and secondary circuit.

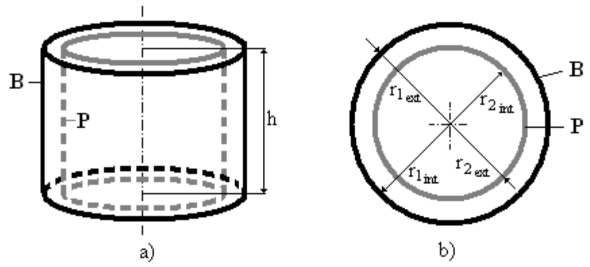


Fig.3. Geometry and dimensions of forming coil and workpiece, for the case of crimping thin wall metallic tubes: a) lateral view; b) upper view

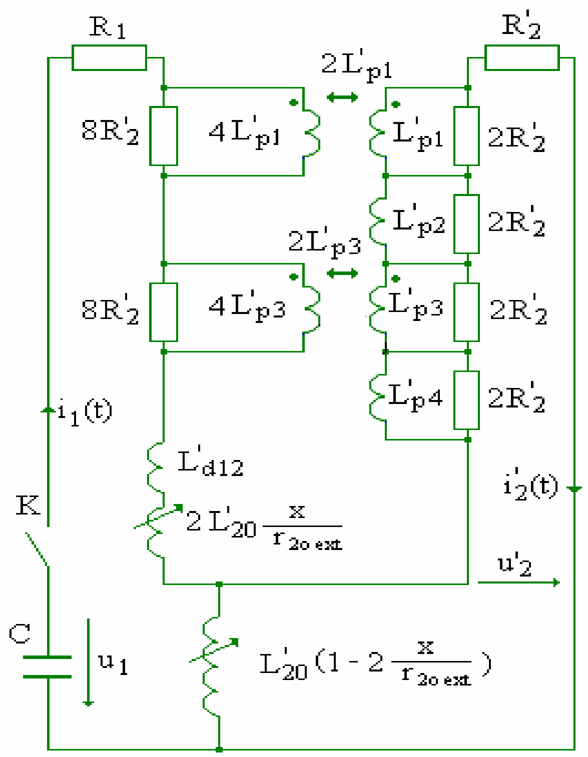


Fig.4. Equivalent circuit diagram for compression of thin wall tubes

The relation between the strength σ and deformation ε is obtained using a visco-plastic model:

$$\sigma = \sigma_0 + \lambda \cdot \varepsilon + \eta \cdot \dot{\varepsilon}^{\delta}$$
$$\varepsilon = \frac{x}{r_{20ext}} \tag{1}$$

where: λ is consolidation coefficient, η is viscosity coefficient and δ rate sensivity coefficient.

The equations of motion may be written:

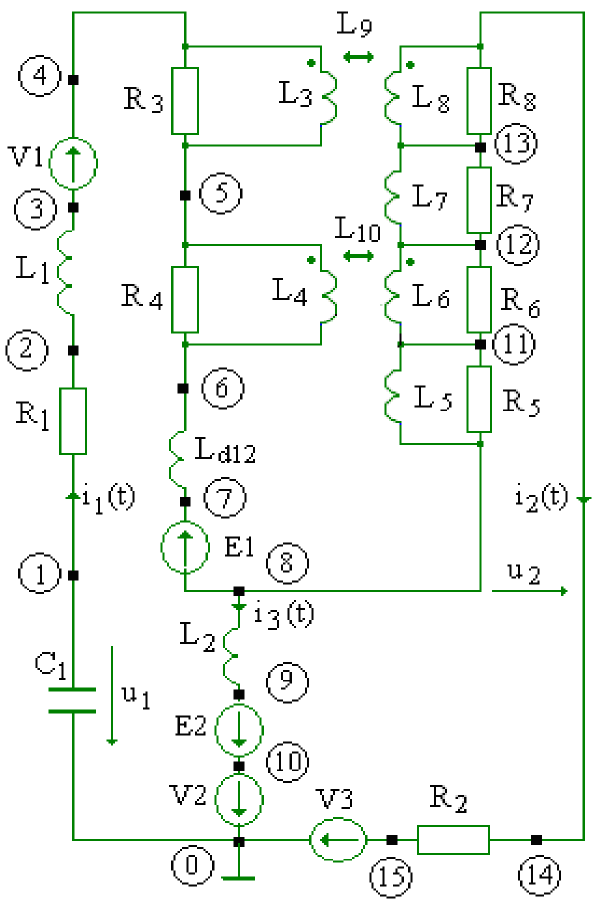
$$\frac{dx}{dt} = v$$

$$\frac{dv}{dt} = \frac{1}{\gamma \cdot d} \cdot p_{em} - \frac{\sigma_0}{\gamma \cdot r_{20ext}} - \frac{\lambda}{\gamma \cdot r_{20ext}^{2}} \cdot x - \frac{\eta}{\gamma \cdot r_{20ext}^{(1+\delta)}} \cdot v^{\delta} \qquad (2)$$

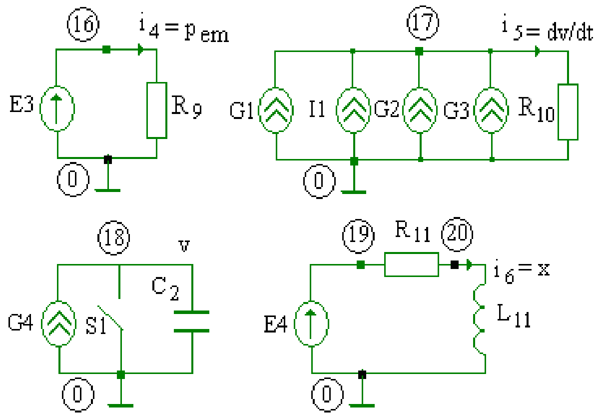
in witch x is the radial deformation, p_{em} is the electromagnetic pressure and γ is the material density.

3. ANALYSIS OF EQUIVALENT CIRCUIT USING PSPICE

We use voltage and current controlled source for taking into account the coupling between mechanical and electromagnetic phenomena. Start from the equivalent circuit from Figure 4 and using (1) and (2) we obtain the PSPICE implementation witch is shown in Figure 5.



a)



b)

Fig.5. Implementation in PSPICE: a) equivalent circuit of electromagnetic phenomenon; b) calculus of electromagnetic pressure p_{em}, acceleration a, strain rate v and deformation x.

The values of circuit components are [3]:

$R_2 = N^2 \cdot r_2$; $\quad R_3 = 8 \cdot N^2 \cdot r_2$;

$R_4 = 8 \cdot N^2 \cdot r_2$; $\quad R_5 = 2 \cdot N^2 \cdot r_2 \cdot \psi_N$;

$R_6 = 2 \cdot N^2 \cdot r_2$; $\quad R_7 = 2 \cdot N^2 \cdot r_2$;

$R_8 = 2 \cdot N^2 \cdot r_2$; $\quad R_9 = \dfrac{2 \cdot h_1}{\mu_0 \cdot N^2}$;

$R_{10} = 1m\Omega$; $\quad C_1 = 200\mu F$; $\quad C_2 = 1mF$;

$$L_1 = \frac{2 \cdot r_2 \cdot \mu_0 \cdot \sigma_2 \cdot (r_{20iext} - r_{20int})^2}{\pi^2} = \frac{2 \cdot r_2 \cdot \tau_p}{\pi^2};$$

$$L_{220} = \frac{\pi \cdot \mu_0 \cdot (r_{20int} + r_{20ext})^2}{4 \cdot h_2};$$

$L_2 = N^2 \cdot L_{220}$;

$$L_{d12} = L_{220} \cdot \left(\frac{r_{1ext}^2}{r_{20ext}^2} - 1\right) \cdot N^2;$$

$L_3 = 4N^2 \cdot L_1$; $\quad L_4 = 4N^2 \cdot \dfrac{L_1}{9}$;

$L_5 = N^2 \cdot L_1 \dfrac{\psi_N}{\alpha_N}$; $\quad L_6 = N^2 \cdot \dfrac{L_1}{9}$;

$L_7 = N^2 \cdot \dfrac{L_1}{4}$; $\quad L_8 = N^2 \cdot L_1$;

$L_9 = 2N^2 \cdot L_1$; $\quad L_{10} = 2N^2 \cdot \dfrac{L_1}{4}$;

$$\alpha_N = \frac{\frac{\pi^2}{8} - (1 + \frac{1}{9} + \frac{1}{25})}{\frac{\pi^4}{96} - (1 + \frac{1}{81} + \frac{1}{625})};$$

$$\psi_N = \alpha_N \cdot [\frac{\pi^2}{8} - (1 + \frac{1}{9} + \frac{1}{25})];$$

$$E1 = \frac{2N^2 \cdot L_{220}}{r_{20ext}} \cdot v \cdot i_3;$$

$$E2 = \frac{2N^2 \cdot L_{220}}{r_{20ext}} \cdot v \cdot i_1;$$

$$E3 = i_2 \cdot (2 \cdot i_1 - i_2) \qquad E4 = v = V(15);$$

$$G1 = \frac{1}{\gamma \cdot (r_{20ext} - r_{20int})} . i_4 \quad ;$$

$$G2 = -\frac{\lambda}{\gamma \cdot r_{20ext}^2} \cdot x;$$

$$G3 = -\frac{\lambda}{\gamma \cdot r_{20ext}^{(1+\delta)}} \cdot v^{\delta}; \qquad I1 = -\frac{\lambda}{\gamma \cdot r_{20ex}};$$

$$F1 = \frac{dv}{dt} = i_5. \qquad (3)$$

The influence of the workpiece deformation is simulated by the voltage sources E1 and E2. The current i_4 represents the electromagnetic pressure on the workpiece walls:

$$i_4 = p_{em} = \frac{\mu_0 \cdot N^2}{2 \cdot h^2} \cdot i_2 \cdot (2 \cdot i_1 - i_2), \qquad (4)$$

and it is simulated by a nonlinear controlled voltage source E3 in series with an equivalent resistor. The equations of motion for the workpiece included mechanical equations are simulated by the equivalent circuit comprising the sources G1, G2, G3 and I1.

The v_{18} potential represents the radial velocity v of the walls, and the i_6 current represents the radial deformation x. The switch S1 is opened when the stress exceeds the yield point and the total pressure is positive (the elastic properties of the workpiece are negligible).

4. NUMERICAL SIMULATION OF MAGNETIC PULSE FORMING

The application consists of magnetic pulse forming of an aluminum tube having 30 mm inner diameter and 1 mm wall thickness. The forming coil has 8 turns copper conductor, with cross section area of 5x3 mm. The gap between coil and tube is 2 mm wide and the thickness of insulation between coil turns is 2 mm. The electrical circuit consists of a 200 μF capacitor bank initially charged at 4 kV.

The numerical simulation of transients in an magnetic pulse forming installation using PSPICE software is presented in Figure 6.

These figures show the variation in time, during the process, of important electromagnetic and mechanical quantities: the electric potential of capacitor bank, the current through forming coil, the electromagnetic pressure acting on tube wall, and the corresponding deformation.

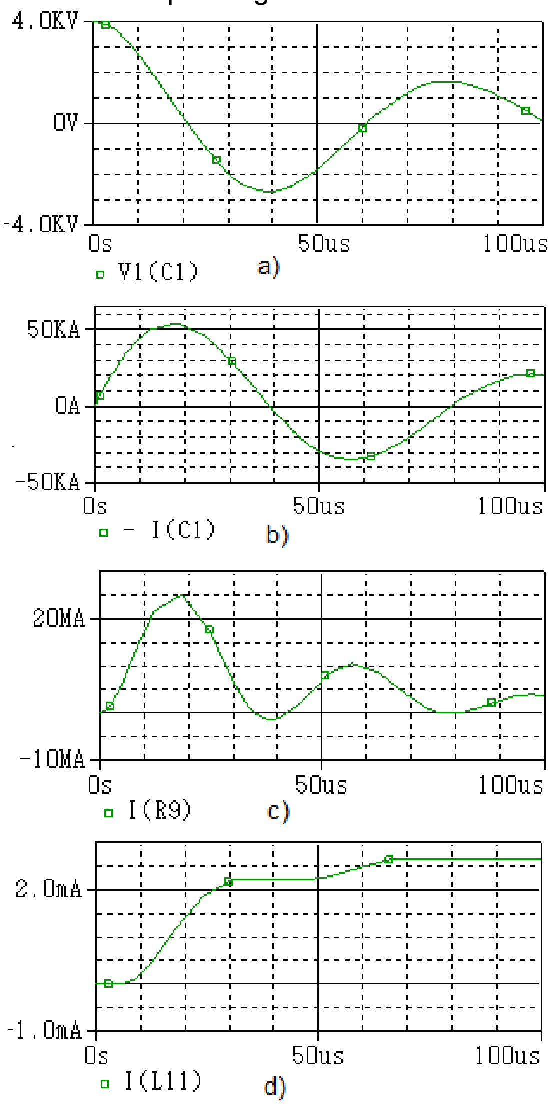


Fig.6. The numerical simulation of magnetic pulse forming installation using PSPICE: a) The time variations of capacitor voltage; b) The time variations of the forming coil current; c) The electromagnetic pressure; d) The radial deformation

The simulations were performed for several values of capacitor voltage and results obtained agreed with results from finite element model simulations [4].

Finite element model are developed using ANSYS Multiphysics as a support. The transient electromagnetic field phenomena are sequentially coupled with mechanical /structural phenomena. The electromagnetic part of model assumes the magnetic field – electrical circuit coupling and in the structural part, the deformed workpiece are considered as viscoplastic material with rate dependent material properties.

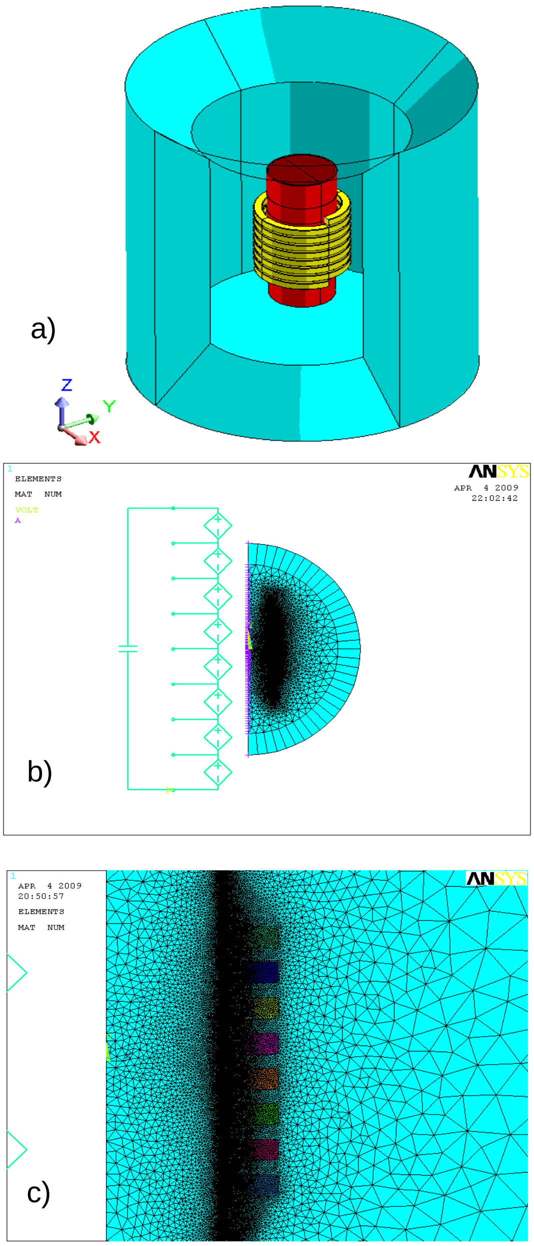


Fig.7. The 3D electromagnetic field computation domain (a), the 2D one with coupled electrical circuit (b) and mesh details (c)

The geometric parameters for cylindrical configuration and material properties (γ_{Al}, ρ_{Al}, σ_{0Al}, λ_{Al}, η_{Al}, δ_{Al}) are the same in the PSpice model and the finite element model (ANSYS Multiphysics).

In the finite element model the coil region is considered a solid conductor, taking into account the non-uniform distribution of current density in cross-section. The mesh adapted to the current distribution in the massive conductors is illustrated in Figure 7.

Figure 8 presents the variation in time of the capacitor voltage and of the coil current and Figure 9 present the deformed tube in the magnetic and in the structural computation domain.

Maximum deformation of the workpiece reaches about 2.5 mm on radial direction and results obtained agreed with results from PSPICE model. It can be observed that the main part of the forming process ends after a (quasi)period of the damped oscillation of coil current.

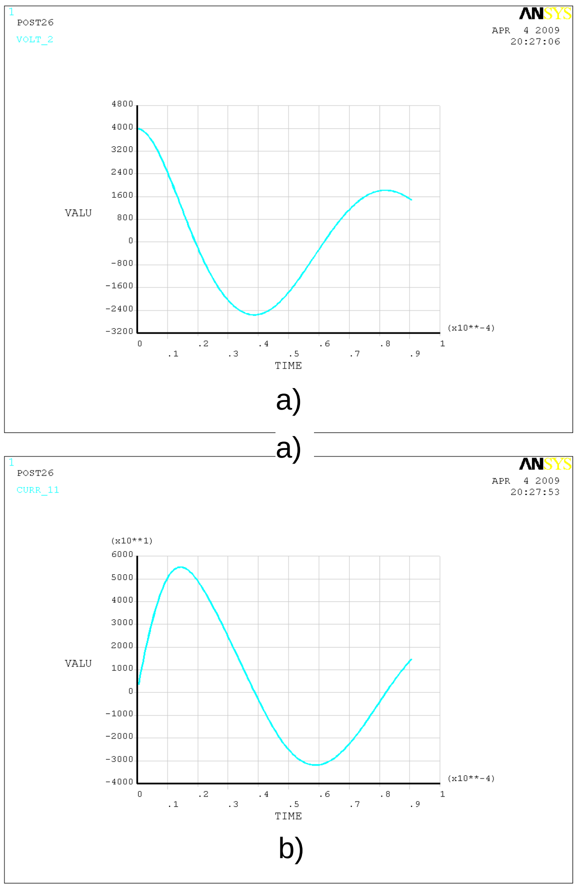


Fig.8. The variations of capacitor voltage (a) and of the forming coil current (b).

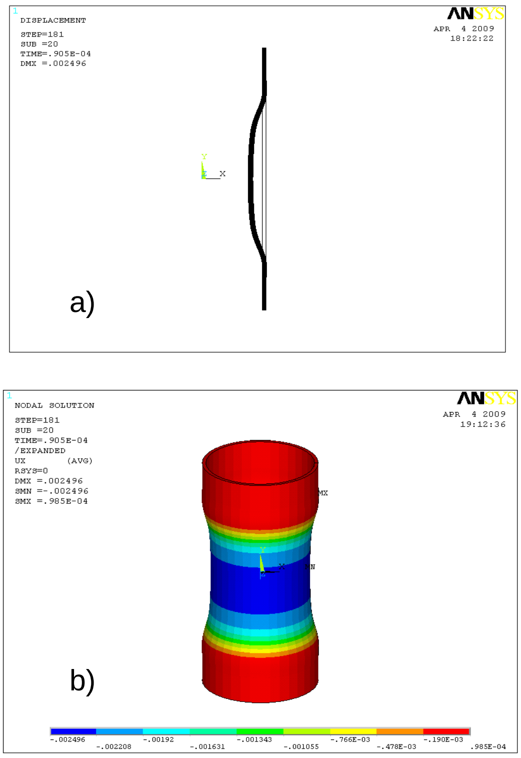


Fig.9. The deformation of tube wall at the end of the process in the magnetic (a) and in the structural computation domain (b)

5. USING GAS AND PSPICE MODEL FOR OPTIMIZATION OF MAGNETIC PULSE FORMING INSTALLATIONS

By combining PSPICE program with genetic algorithms, it can operate in the so-called sequential manner in which sequential simulation tasks are run, with the ability to influence the operation, according to the previous simulation results. By performing successive runs of different types of analysis and by modifying the model parameters, simulations can lead to achieve an optimal behavior of the model in terms stated of the user. The control algorithm is defined by the circuit file that is written in accordance with some syntactical rules, that is a source text to generate PSPICE circuits. Commands to define the variables for Pspice analysis should be executed to control PSPICE operation. The results of simulation are received in the out file, and are than processed mathematically.

The operation of the GAs coupled with the PSPICE program is presented in Figure 10 [6].

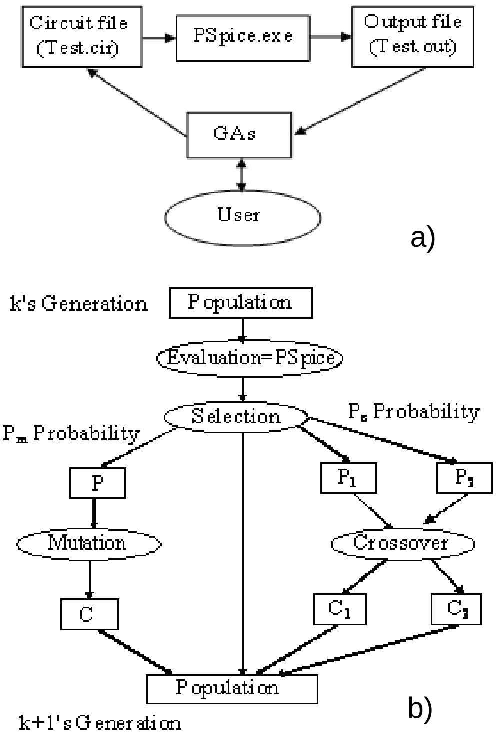


Fig.10. The mixture of the PSPICE program and the genetic algorithm: a) the principle of method; b) logic diagram

In the design problem concerned in this paper, only two design parameters were used, namely the U_0 voltage and the C_0 condenser.

These parameters are used in the genetic search and each generation their new values are written in the test.cir file, which is input to PSPICE program.

As objective function, in series the deformation of the tube, later the deformation, together with the efficiency was used. These values are computed based on the results obtained in test.out file.

Study case 1

The design parameter V_{C1} in the domain 1000÷7000V was considered, while de capacitor C_1 has the constant value 200μF.

GAs used a population of 50 individuals and was applied for 50 generations. The Fitness function used is given by relation (5):

$$\text{Fitness} = \frac{1}{1 + (X_{goal} - X_{max})^2} \qquad (5)$$

where X_{goal} is a constant imposed, and X_{max} is the maximum value of the deformation that is found in the PSPICE output file. The obtained results are shown in Table 1.

Table 1. The solutions for study case 1

Defor-mation	The best solution	Other solutions in roud of the optimal solution finding with AG		
[mm]	V_{C1} [V]	V_{C1} [V]		
1	3284.7	3434.2	3175.6	3331.6
2	3999.9	4145.8	4088.1	4054.3
3	4532.1	4580.1	4520.1	4532.1

Study case 2

The following design parameters were considered:

V_{C1} in the domain 1000÷7000V and C_1 in the domain 100÷400μF.

GAs used a population of 30 individuals and was applied for 25 generations. The Fitness function used was also given by relation (5). The obtained results are shown in Table 2.

Table 2. The solutions for study case 2

Defor-mation	The best solution		Other solutions finding with AG	
[mm]	V_{C1} [V]	C_1 [uF]	V_{C1} [V]	C_1 [uF]
1	3150.6	291.0	3117.2	304.7
2	3965.4	273.9	3668.2	301.6
3	6284.9	137.4	4142.5	316.4

Study case 3

The Fitness function used was given by relation (6):

$$Fitness = \alpha \cdot O_1 + (1-\alpha) \cdot O_2 \quad (6)$$

$$O_1 = \frac{1}{1+(X_{goal} - X_{max})^2} \cdot 1000 \quad (7)$$

$$O_2 = \eta = \frac{W_m}{W_t} \cdot 100 \ [\%] \quad (8)$$

Objective O_2 is referred as Efficiency in the Table 3.

The total energy is given by relation (9):

$$W_t = \frac{C_1 \cdot U_0^2}{2} \quad (9)$$

and the mechanical energy is established by using relation (10):

$$W_m = 2\pi \cdot r_{20ext} \cdot h_1 \cdot \int I(E_3) \cdot V(18) \cdot dt \quad (10)$$

I(E3) and V(18) are obtained from the out file produced by PSPICE program.

Since multiple objectives are converted into one objective, the resulting solution to the single objective optimization problem is usually subjective to the parameter settings chosen by the user. Moreover, only one solution can be found in one run.

Accordingly, multiple values in [0.1,… 0.9] interval were considered for α and multiple runs of GAs were performed, with a population of 50 individuals. The GAs evolved for 50 generations. The obtained results for X_{goal} = 3 mm are presented in Table 3.

Table 3. The solutions for study case 3 (X_{goal} = 3 mm)

	Defor-mation	Capacitor value	Voltage value	Efficiency
No.	x	C_1	U_0	η
	[mm]	[μF]	[V]	[%]
1.	3	124.66	6607.72	6.386
2.	3	145.71	6117.06	6.400
3.	3	161.09	5795.39	6.261
4.	3	163.34	5754.88	6.165
5.	3	169.10	5669.71	6.250
6.	3	188.79	5382.50	6.218
7.	3	189.14	5376.80	6.217
8.	3	232.57	4850.21	6.005
9.	3	278.29	4454.78	5.912
10.	3	380.10	3833.40	5.498

We note that the genetic algorithm used was implemented in Matlab.

6. CONCLUSIONS

In this paper we present results of numerical simulation of magnetic pulse forming applied to compression of tubular conductor using PSPICE software. This approach is very useful in numerical analysis of magnetic pulse forming devices, giving the main characteristics of these installations.

The results presented in the paper are in a good agreement with the data from with results from finite element model simulations (obtained in Ansys Multiphisics environment).

We tried to show how genetic algorithms can be coupled with Orcad PSpice simulation environment to an engineering design optimization problem, which can use a fitness function derived from a simulation process.

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