Application of Differential Evolution for Audio Transformers Optimization

Lukas Kouril, Martin Pospisilik, Milan Adamek, Roman Jasek

Abstract— In audio applications transformers are still employed due to several of their features. They are helpful at noise optimisation in circuits where two blocks are connected, having different output and input impedance. For example, when connecting a low-impedance microphone to an amplifier the input of which is of high impedance, not only the impedances are matched by the transformer, but the voltage gain obtained due to the high turns ratio lets the constructer decrease the gain of the amplifier stage as well, which contributes also to decreasing of the noise. Unfortunately, the design of such transformer is very complex, combining electrical, mechanical and geometrical issues. Therefore the authors of this paper decided to create an algorithm that helps the designer to design the transformer according to the requirements by means of Differential Evolution. The description of this method as well as its results is described in this paper.

Keywords—Audio transformers, artificial intelligence, Differential evolution, electrical circuits.

I. Introduction

EVOLUTIONARY algorithms are computational methods inspired by natural processes generally described as Darwin's theory. The similarity of those algorithms with processes which occur in nature is fairly close. Both of these are aimed on optimization. The optimization which proceeds in the nature can be considered as a way how to select those best of individuals (organisms) whose abilities to survive and adapt to surrounding environment are the highest. Thanks to organic variability ensured by mutation and cross-over it is possible to expect even improved abilities of descendants of them in the next generation. The abilities of individuals can be imagined as objects of optimization. In the case of evolutionary algorithms the individuals have a form of vectors. The parameters of the vectors represent the "abilities" which are subsequently optimized. Mutation and cross-over processes are realized by vectors transformations and mathematic computations (see below). The results of optimization by evolutionary algorithms can be unexpectedly (and positively) surprising because of ability of evolutionary algorithms to exceed local extremes especially. In this paper, the optimization of an audio transformer design by means of the differential evolution is described in order to show how the complex design of the transformer can be simplified by using the methods of artificial intelligence.

Except optimization, evolutionary algorithms can be used for function approximation, pattern recognition etc.

There are many of evolutionary algorithms (e.g. SOMA [9], [10]) but in this research, the Differential evolution [6-8] was chosen as one of them thus a short description of Differential evolution and its parameters can be found below.

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II. Problem Formulation

Any audio small-signal transformer can be modeled with an equivalent circuit (see [5]) and a set of appropriate equations. This set of equations is not easy to solve manually, because there are many mutual dependences. On the other hand, methods of artificial intelligence seem to be ideal for such evaluation. For the purpose of this paper, the transformer described in [4-5] has been considered to be optimized. A basic method of determining whether such transformer can be manufactured or not is to be found in [4] as well as the tables of standardized dimensions of the transformer cores and usually employed wires. In this paper the solution of the set of the equations by means of the differential evolution is described.

A. Basic Transformer Equations

In low-power audio transformers the number of primary winding turns is not determined primarily by the power of the transformer and its core induction but by the frequency response of the transformer at low frequencies. This is because the power and the core induction is usually low enough to be neglected but the inductance of the primary winding together with the resistances at the primary and the secondary part of the transformer create a frequency dependent divider (see the equivalent circuit of the transformer in [5]). By recalculating the parameters to the primary side of the transformer one can for the range of low frequencies obtain the following equation:

$$Z_{PRI} = RP + \frac{1}{\frac{1}{RX} + \frac{1}{j \cdot 2\pi f LP} + \frac{1}{N^2(RS + RL)}} \quad [\Omega] \qquad (1)$$

Where ZPRI is the impedance at the primary winding of the transformer, RP is the resistance of the primary winding, RS is the resistance of the secondary winding, RL is the load resistance, N is the transformer conversion ratio, LP is the primary winding inductance and RX represents losses in the core as an additive resistor. Usually RX can be neglected while RG as the internal source resistance must be considered to create a voltage divider together with Z_{PRI}. Then the minimum frequency f_{min} is determined as follows:

$$f_{min} = \frac{(RG + RP)(RS + RL)\frac{1}{N^2}}{2\pi LP \cdot \left(\frac{1}{N^2}(RS + RL) + (RG + RP)\right)} \quad [Hz] \qquad (2)$$

Therefore there is a need to express the minimum LP that is necessary to achieve the required fmin:

$$LP = \frac{(RG + RP) \cdot \left(\frac{RS + RL}{N^2}\right)}{2\pi \cdot f_{min} \cdot \left(\left(\frac{RS + RL}{N^2}\right) + RG + RP\right)} [H] \qquad (3)$$

The number of the primary winding turns n_1 is then determined by the required LP according to [3] as follows:

$$n_1 = \sqrt{\frac{LP\left(\frac{l}{\mu_r} + l_{air}\right)}{1{,}26Sk}} \cdot 10^5 \qquad (4)$$

Where S is the core mass cross-section in [cm^2] as can be found in the appropriate table (see [4]), k is a constant considering the inaccuracy and losses (usually k = 0.9), l is the average length of a magnetic line of force inside the core mass, μ_r is the relative permeability of the core sheets (usually from 1,000 to 5,000) and l_{air} is the width of the air gap between the sheets E and I caused by the inaccuracy of the sheet cutting (usually 10^{-4}). However it is not easy to determine the number of the secondary wiring turns. In order to consider the attenuation caused by RP and RS the correction factor m representing the relative winding resistance to the source and load resistances shall be employed. Then the following equations can be applied:

$$m = \frac{\left(RP + \frac{RS}{N^2}\right)}{RG + \frac{RL}{N^2}} \cdot 100 \quad [\%] \qquad (5)$$

$$n_2 = \left(1 + \frac{m}{100}\right) \cdot n_1 \cdot N \qquad (6)$$

At this point the equation for the required core mass cross-section according to the power of the transformer can be applied backwards to check whether the inductance in the core is low enough not to cause an ineligible distortion. According to [3] the following equation can be deduced:

$$B = \frac{3243.24 \cdot U_{i\,max}}{f_{p\,min} \cdot S \cdot k \cdot n_1} \quad [T] \qquad (7)$$

For ordinary EI sheets the B should not be higher than approximately 0.5 T. $U_{i\,max}$ stands for maximum input voltage of the transformer and $f_{p\,max}$ is the lowest frequency at which the distortion caused by the non-linearity of the core is observed (usually $f_{p\,max} > f_{max}$ as at the lowest frequencies the distortion is not observed too strictly and/or high level signal is not supposed to occur).

Another problem to be solved consists in determining the primary and secondary winding resistances that must be found in order the equations (1) to (7) could be evaluated. The resistances depend on the cross-sections of the appropriate wires and their length which is determined by the number of the turns and the average length of one turn for the predefined core sheets. Assuming the specific electrical resistivity of a copper wire is 0.0178 Ω mm^2/m, following expressions can be used:

$$RP = \frac{0.0178 \cdot n_1 \cdot o}{S_1} \quad [\Omega] \qquad (8)$$

$$RS = \frac{0.0178 \cdot n_2 \cdot o}{S_2} \quad [\Omega] \qquad (9)$$

Where: S_1 is the primary winding wire cross-section in [mm^2], S_2 is the primary winding wire cross-section in [mm^2], n_1 is the number of primary winding turns, n_2 is the number of secondary winding turns and o is the average length of a single current turn for the predefined core.

It is also usual to define primary to secondary winding resistance ratio that can be in specific cases employed for the purpose of the noise optimization (without considering the Barkhausen's noise):

$$r = \frac{RP \cdot \left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2}{RS} \qquad (10)$$

The attenuation caused by the transformer due to the resistances and the load can be expressed as follows:

$$A = -20\log_{10}\left(\frac{\frac{RL}{\left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2}}{\frac{RS + RL}{\left(N \cdot \left(1 + \frac{m}{100}\right)\right)^2} + RG + RP}\right) [dB] \qquad (11)$$

At high frequencies the performance of the transformer is dependent on the leakage inductance of all windings and parasitic capacities that occur on all windings, among them and between the windings and the transformer core. These parameters are highly dependent on the internal winding arrangement. If the winding arrangement is made in the way described in [4-5], the following equations can be used to express the parameters:

$$n_{l1} = \frac{\lceil n_1 \rceil}{\lfloor h_w - 2t_f \rfloor \cdot d_{out\,1}} \tag{12}$$

$$n_{l2} = \frac{\lceil n_2 \rceil}{\lfloor h_w - 2t_f \rfloor \cdot d_{out\,2}} \tag{13}$$

$$t_w = n_{l1} \cdot d_{out\,1} + 2 \cdot n_{l2} \cdot d_{out\,1} + t_f + 2 \cdot t_{iz} \tag{14}$$

The meanings of the variables from (12), (13) and (14) are as follows: n_{l1} is the number of layers of the primary winding, n_{l2} is the number of layers of one section of the secondary winding (symmetrical two-section winding is considered!), t_f is coil former mass thickness, t_{iz} is the isolation between the sections thickness, $d_{out\,1}$ is the outer diameter of the primary winding wire and $d_{out\,2}$ is the outer diameter of the secondary winding wire (considering the isolating lacquer). The total thickness of the coil t_w should be slightly lower than the maximum sheet window height t_0 but not much in order all the above mentioned equations were valid. Generally the requirement for the evolutionary synthesis can be specified as follows:

$$0.8 \cdot t_0 < t_w < 0.95 \cdot t_0 \tag{15}$$

According to [3] the leakage inductance LL can be expressed as follows:

$$LL = \frac{1.68 \cdot n_1^2 \cdot o \cdot (4 \cdot t_{iz} + t_w)}{h_w} \cdot 10^{-6} \ [H] \tag{16}$$

More complicated situation occurs at expressing the parasitic capacities. The prevailing resonant frequency of the transformer can be estimated using the consideration that according to the internal transformer arrangement (see [4-5]) only those capacities cannot be neglected:

- Primary winding capacity C_p,
- Primary to secondary winding capacity C_{ps} that can be expressed directly due to the circuit configuration (see [4]),
- Secondary winding capacity C_s that will at the primary part of the transformer seem as C_s',
- Secondary winding to the core C_{SC} capacity that will at the primary part of the transformer seem as C_{SC}'.

The capacity is spread across the whole winding and to be evaluated generally, it shall be calculated on one side of the transformer. Following approximations may be used to estimate the total capacity and the prevailing resonant frequency of the transformer. First of all a capacity between a two of layer may be estimated according to (17)

$$C_{2l} = \frac{885 \cdot o \cdot h_w \cdot \varepsilon_r}{t} \cdot 10^{-14} \quad [F] \tag{17}$$

Where: ε_r is a relative permittivity (usually $\varepsilon_r = 3$) and t is the distance between the two layers that is determined by the thickness of their isolation (see (18)).

$$t = d_{out} - d_{in} \tag{18}$$

If the winding consists of more than two turns, the voltage is spread across the whole winding and the capacity decreases according to the number of layer which is described by (19).

$$C = \frac{1{,}33}{n_l}\left(1 - \frac{1}{n_l}\right) C_{2l} \quad [F] \tag{19}$$

The n_l parameter stands for the number of the layers (see (12), (13)). Thus it is more convenient to use more layers of the winding. According to (17) the capacities C_{PS} and C_{SC} can be evaluated as well. The t parameter then depends on the thickness of the isolation layer t_{iz} or the core former mass thickness t_f :

$$t_{PS} = \left(\frac{d_{out\,1} - d_{in\,1}}{2}\right) + \left(\frac{d_{out\,2} - d_{in\,2}}{2}\right) + t_{iz} \tag{20}$$

$$t_{SC} = \left(\frac{d_{out\,2} - d_{in\,2}}{2}\right) + t_f \tag{21}$$

When recalculating the C_S and C_{SC} to the primary side, the following equations shall be employed:

$$C'_{SC} = \left(\left(1 + \frac{m}{100}\right) \cdot N\right)^2 \cdot C_{SC} \tag{22}$$

$$C'_S = 2 \cdot \left(\left(1 + \frac{m}{100}\right) \cdot N\right)^2 \cdot C_S \tag{23}$$

In (23) the multiplying by 2 refers to the two parallel secondary windings of the transformer. The total wiring capacity recalculated to the primary side of the transformer can be then expressed as follows:

$$C_{tot} = C_P + C_{PS} + C'_S + C'_{SC} \tag{24}$$

According to [2] the resonant frequency of the transformer may be expressed according to (25):

$$f_r \approx \frac{1}{\pi\sqrt{\frac{2}{3} C_{tot} LL}} \quad [Hz] \tag{25}$$

The unpleasant fact is that when loaded, the transformer exhibits the resonant frequency to be somewhat lower. Usually the (26) approximation is employed:

$$f_r' = 0{,}71 f_r \quad [Hz] \tag{26}$$

All the above mentioned equations has been converted into the C code and employed in the optimization task driven by the Differential

B. Brief Insight into Differential Evolution

Differential evolution (described e.g. in [7, 8]) strictly comes out of above mentioned. In the case of Differential evolution, it is considered optimization as origination of new descendants with improved parameters in the dependence on their predecessors. The basis of optimization is a definition of specimen. The specimen represents a general description of individuals thus number of parameters ("abilities" which will be optimized) and their range. In this research, the specimen has appearance as vector containing four parameters. These are:

- Minimal transferred frequency f_{min},
- Index of wire parameters set for the primary winding $i_{primary}$,
- Index of wire parameters set for the secondary winding $i_{secondary}$,
- Index of isolation layer i_{tps}.

The ranges for the optimization have been predefined as follows:

$$f_{min} \in \langle 0; 100 \rangle \, [Hz] \tag{27}$$

$$i_{primary} \in \langle 1; number\ of\ rows\ in\ T_{wires} \rangle \tag{28}$$

$$i_{secondary} \in \langle 1; number\ of\ rows\ in\ T_{wires} \rangle \tag{29}$$

$$i_{tps} \in \langle 1; number\ of\ rows\ in\ T_{isolation} \rangle \tag{30}$$

Where: T_{wires} is a table containing parameters of available wires (see [4]) and $T_{isolation}$ is a table containing available thicknesses of the isolation layer.

Table 1. Available thicknesses of the isolation layer

Available thickness [μm]			
100	200	300	400

Then an initial generation of individuals is created (or generated because the parameters of each individual are set randomly in accordance with ranges stated in specimen). Now the optimization starts.

The optimization is consisted of individual evaluations. It means that all individuals occurred in the current generation are evaluated thus their cost values are computed. The vector transformations and mathematic computations which ensure mutation and cross-over proceed as follows as well as the mathematic expression of Differential evolution (see [8]).

Within optimization, individuals of the current generation are subsequently selected. The selected individual is known as a current individual. Additionally, other three individuals are randomly selected. The first two of randomly-selected individuals are subtracted. The result is a new vector which is known as the differential vector. As the next step there is a mutation. The mutation has a form of multiplication of the mutation constant and the differential vector. The result of multiplication is also new vector. This one is known as the weighted differential vector. Now, there is created the noise vector (31) as an addition of the third randomly-selected individual and the weighted differential vector.

$$v = x_{r_3,j}^G + \underbrace{F \cdot \overbrace{\left(x_{r_1,j}^G - x_{r_2,j}^G\right)}^{\text{differential vector}}}_{\text{weighted differential vector}} \tag{31}$$

As the final operation there is an origination of the test vector (32). The test vector is originated as a cross-over of the noise vector and the current individual selected in the beginning.

$$x_{i,j}^{test} = \begin{cases} \overbrace{x_{r_3,j}^G + F \cdot \left(x_{r_1,j}^G - x_{r_2,j}^G\right)}^{\text{noise vector (31)}}{}^{*} \\ x_{r,j}^G \end{cases} \tag{32}$$

$$^{*}if\ rand_j(0,1) \le CR \vee j = k$$

In this moment, the cost values of the current individual and the test vector are computed. These are results of evaluation by the cost function (3). The cost function represents a set of conditions which are basis of optimization.

$$x_i^{G+1} = \begin{cases} x_r^{test}\ if\ f_{cost}(x^{test}) \le f_{cost}(x_i^G) \\ x_i^G \end{cases} \tag{33}$$

The one of the current individual and the test vector with better evaluation passes to the next generation.

As mentioned above, all individuals of the current generation are subsequently selected thus the evaluation of these individuals proceeds and the next generation is originated. The optimization process is similarly repeated in the next generation. The optimization ends when the number of generation is reached.

The Differential evolution has several parameters which are necessary to set and which were mentioned in (31-33). These parameters are:

- NP which means number of population. This is how many individuals are in one generation.
- F as a mutation constant.
- CR as a cross-over value.
- G which represents number of generation which are subsequently created while optimization proceeds.

While designing transformer by Differential evolution there were tried different settings of mentioned parameters. The mostly used ones are presented in Table 2.

Differential evolution occurs in several variants. The differences of these variants consist of origination of the noise vector. This research utilizes DE/rand1/bin variation which considers origination of the noise vector as an equation (31).

Table 2. Values of parameters used by Differential evolution

Parameter	Value
NP	1000
G	10000
F	0.8
CR	0.4

C. The Cost Function and its Influence to the Optimization

While designing transformer it is necessary to consider several conditions. The optimized parameters of transformer which are results of differential evolution have to meet these conditions too. It can be ensured by the cost function which evaluates individuals which encodes parameters of transformer. The conditions which parameters of transformer have to accomplish have been defined as follows:

- f_{min} – minimal transferred frequency in [Hz] – desired value,
- f_{min_max} – minimal transferred frequency in [Hz] – the highest (worst) value that can be tolerated,
- m – the optimal relative resistance of the windings,
- m_{max} – the maximum relative resistance of the windings that can be tolerated,
- r – the primary to secondary winding resistance ratio,
- r_{min} – the minimal acceptable primary to secondary winding resistance ratio,
- r_{max} – the maximal acceptable primary to secondary winding resistance ratio,
- B – the optimal maximum core induction in [T] to be reached at the frequency $f_{p\,min}$,
- B_{max} – the maximum tolerable core induction in [T] to be reached at the frequency $f_{p\,min}$,
- att – optimal attenuation of the transformer in [dB],
- att_{max} – maximal tolerable attenuation of the transformer in [dB],
- t_0 – core window height according to the type of the core (see Table 4 and/or [4]),
- t_w – total winding thickness.

The above mentioned parameters must comply with the following equations:

$$f_{min} \leq f_{\min max} \tag{34}$$

$$m < m_{max} \tag{35}$$

$$r_{min} < r < r_{max} \tag{36}$$

$$b < b_{max} \tag{37}$$

$$att < att_{max} \tag{38}$$

$$att < att_{max} \tag{39}$$

$$0.8 \cdot t_0 < t_w < t_0 \tag{40}$$

If any parameter of those encoded in individual is not in accordance with any of these conditions or leads to the computation of parameter which exceeds mentioned conditions, the individual is penalized and excluded from next optimization. The condition (40) refers to (15), others are defined by the designer according to his requirements.

Similarly, there exist conditions which have opposite effect on optimization. These are:

$$r = r_{id} \tag{41}$$

$$att = att_{id} \tag{42}$$

$$tps = tps_{id} \tag{43}$$

Where r_{id} is the ideal r preferred by the designer, att_{id} is the ideal attenuation preferred by the designer and t_{ps} is the thickness of the primary to secondary wiring isolation chosen according to Table 1 and t_{ps} id is its ideal value preferred by the designer. When encoded parameters of individual lead to the accomplishing of above conditions there is given preference to the individual.

III. Optimization processing

The optimization task was defined according to the schematics presented in [5] and the requirements defined in [4]. As can be seen in [4], the results achieved by a simple analytic algorithm led to a transformer with quite low resonant frequency. The aim of this task was to reach the optimized solution driven by the evolutionary algorithm under the same requirements and considerations. The basic requirements are enlisted in Table 3. As well as in [4] the EI38/20 core has been chosen which results in the further parameters specified in Table 4. The available wires are enlisted in Table 5.

Then a set of equations has been converted into the C language and the Differential evolution algorithm was applied on this set. The set includes the equations (3) to (26) excluding (15), provided that at (11) the (44) is applied:

$$att = -A \tag{44}$$

Furthermore the restrictions have been specified according to the equations from (34) to (40) where (40) refers to (15) with slightly broadened high boundary and also the (41) to (43) preferred values were specified.

The parameters of the Differential evolution were set

Table 3. Basic requirements on the transformer

Parameter	Description	Values		
		Optimal	**Minimal**	**Maximal**
RG	Total signal source resistance	RG =500 Ω		
RL	Total load resistance	RL = 2 x 200 kΩ		
CL	Total load capacity	CL = 50 pF		
N	Conversion ratio	1 : 2 x 10		
f_{min}	Minimal transferred frequency	f_{min} = 15 Hz		$f_{min\ max}$ = 25 Hz
$f_{p\ min}$	Minimal frequency at which full power is estimated to occur			$f_{p\ min} = f_{min\ max}$ = 25 Hz
$U_{i\ max}$	Maximal input voltage			$U_{i\ max}$ = 2 V
S_{min}	Minimal accepted wire cross-section		$S_{min} = 7.10^{-4}\ mm^2$	
Att	Attenuation of the transformer	att_{id} = 3 dB		att_{max} = 4 dB
t_{ps}	Primary to secondary isolation layer thickness	$T_{ps\ id}$ = 100 μm	See Table 1	
m	Relative primary and secondary winding resistance to the total resistance of the source and the load	m_{id} = 5		m_{max} = 20
r	Primary to secondary winding resistance ratio	r_{id} = 1	r_{min} = 0.25	r_{max} = 4
B	Core induction at $f_{p\ min}$			B_{max} = 0.3 T
d_in_1	Inner diameter of the primary winding wire	See Table 5		
d_in_2	Inner diameter of the secondary winding wire			
d_out_1	Outer diameter of the primary winding wire			
d_out_2	Outer diameter of the secondary wiring wire			
S_1	Primary winding wire cross-section			
S_2	Secondary winding wire cross-section			

Table 4. EI38/20 core parameters

Parameter	**Value**
Core mass cross-section	$S = 2.4\ cm^2$
Total height of the coil section	t_0 = 6.5 mm
Coil former material thickness	t_f = 0.5 mm
Average length of a single turn	o = 84 mm
Average length of a magnetic line of force inside the core mass	l = 71.5 mm
Core window width	h_w = 19 mm
Estimated air gap caused by the inaccuracy of the transformer sheets cutting	l_{air} = 0.1 mm
Core mass relative permeability	μ_r = 1,000

accordingly to the Table 2.

According to the specifications described above, the Differential evolution has provided several results the most suitable of which are enlisted in Table 6.

The verification of the results is quite easy. The mechanical issues can be proven by calculating the thickness of the whole winding manually and checking whether the winding will fit into the core window. The electrical parameters may be proven by employing the equivalent transformer circuit (see [5] using the parameters found by the Differential evolution. Because all the parameters must be recalculated in the primary side, C_{SC}' and C_S' parameters must be used instead of C_{SC} and C_S. Moreover, the RL, CL and RS must also be recalculated to the primary side according to the following equations:

$$RL' = \frac{RL}{\left(\left(1 + \frac{m}{100}\right) \cdot N\right)^2} \qquad (45)$$

Table 5. Normalized transformer wires

Nominal diameter d_{in} [mm]	**Outer diameter d_{out} [mm]**	**Nominal wire cross-section [mm^2]**
0.03	0.05	0.0007
0.04	0.06	0.0013
0.05	0.07	0.0020
0.056	0.078	0.0025
0.063	0.088	0.0031
0.071	0.095	0.0039
0.08	0.105	0.0050
0.09	0.118	0.0063
0.1	0.128	0.0078
0.112	0.15	0.0099
0.125	0.165	0.0122
0.132	0.172	0.0136
0.14	0.18	0.0153
0.15	0.19	0.0176
0.16	0.2	0.0200
0.17	0.216	0.0226
0.18	0.227	0.0253
0.19	0.238	0.0282
0.2	0.25	0.0314

$$RS' = \frac{RS}{\left(\left(1 + \frac{m}{100}\right) \cdot N\right)^2} \qquad (46)$$

$$CL' = \left(\left(1 + \frac{m}{100}\right) \cdot N\right)^2 \cdot CL \qquad (47)$$

The frequency responses and input impedance dependences on the frequency for all of the solutions are enlisted in Table 6.

From all the results the best 4 were chosen in order to be compared. According to the estimated electrical parameters, simulations described in [5] were processed. The results can be seen in the following pictures, describing the frequency response of the transformers in the specified circuit as well as the input impedance dependence on the frequency, that is influenced not only by the transformation ratio but with the parasitic parameters of the transformer as well (for example the main resonant frequency can be identified as a deep slump in the input impedance, at low frequencies the input impedance decreases to zero due to the limited primary winding inductance that causes loss of the coupling between the primary and secondary winding for frequencies close to zero and so on).

In the frequency response graphs the amplification of the signal by the transforming ratio is not taken into account as it is not implemented in the simulation model (see [5]). Therefore when the frequency response is at for example – 5 dB and the transforming ratio N = 10, it means that the signal is amplified ten times with the attenuation of 5 dB, resulting in the + 15 dB wholeall gain (instead of + 20 dB as could be expected accordint to the transforming ratio N).

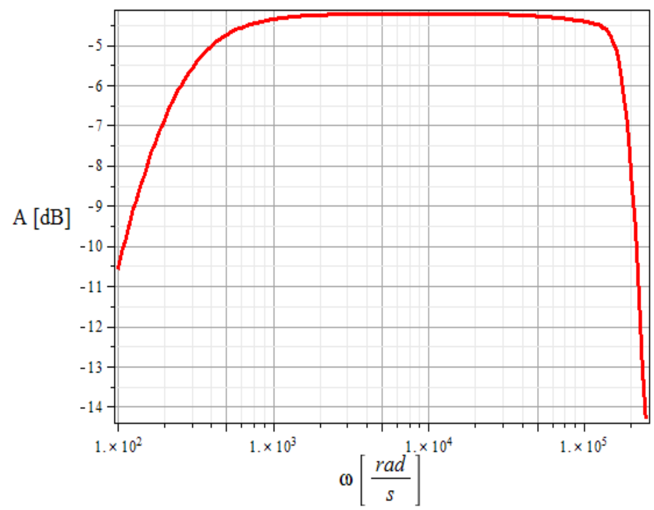

Fig. 1. Frequency response of the transformer according to the Solution 1

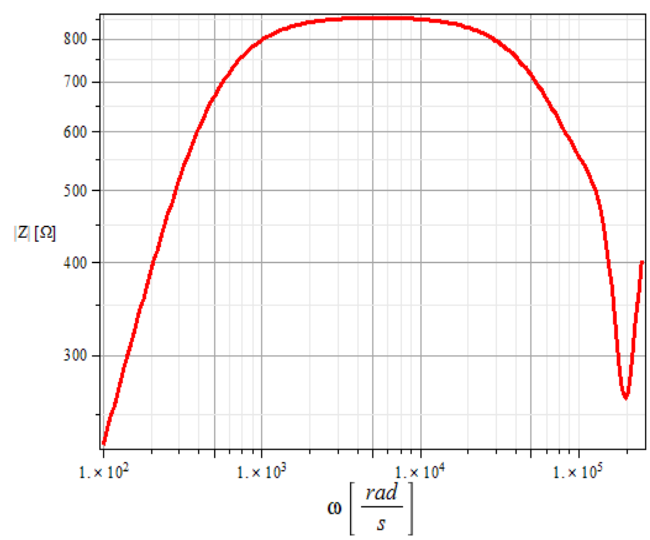

Fig. 2. Input impedance response to the frequency for the transformer according to the Solution 1

Table 6. Most suitable results gained by the Differential evolution

Parameter	Description	Results			
		1	2	3	4
f_{min}	Minimal transferred frequency	19.68 Hz	19.81 Hz	17.82 Hz	19.84 Hz
S_1	Primary winding wire cross-section	0.0153 mm^2	0.0153 mm^2	0.0122 mm^2	0.0153 mm^2
$d_{in\ 1}$	Primary winding wire inner diameter	0.14 mm	0.14 mm	0.125 mm	0.14 mm
t_{ps}	Primary to secondary isolation layer thickness	0.1 mm	0.0 mm [1)]	0.3 mm	0.2 mm
S_2	Secondary winding wire cross-section	0.0007 mm^2	0.0007 mm^2	0.0013 mm^2	0.0007 mm^2
$d_{in\ 2}$	Secondary winding wire inner diameter	0.03 mm	0.03 mm	0.04 mm	0.03 mm
LP	Magnetizing inductance	1.83 H	1.79 H	0.92 H	1.73 H
n1	Primary winding turns number	1,075	1,059	763	1,043
n2	Secondary winding turns number	2 x 12,855	2 x 12,656	2 x 8,988	2 x 12,468
RP	Primary winding resistance	105 Ω	103.47 Ω	93.49 Ω	101.94 Ω
RS	Secondary winding resistance	2 x 13,729 Ω	2 x 13,517 Ω	2x 5,169 Ω	2 x 13,316 Ω
r	Primary to secondary winding resistance ration	1.09	1.09	2.51	1.09
B	Core induction at $U_{i\ max}$ and $f_{p\_min} = f_{min}$	111.76 mT	113.46 mT	157.5 mT	115.15 mT
Att	Attenuation	3.0 dB	3.0 dB	2.73 dB	2.99 dB
LL	Leakage inductance	7.8 mH	7.14 mH	4.39 mH	7.8 mH
C_P	Primary winding capacity	367.71 pF	367.71 pF	544.81 pF	367.71 pF
C_{PS}	Primary to secondary winding capacity	444.59 pF	446.04 pF	441.6 pF	443.09 pF
C_S	Secondary winding capacity	2 x 48.06 pF	2 x 48.06 pF	2 x 57.35 pF	2 x 49.40 pF
C_{SC}	Secondary winding to transformer core capacity	26.24 pF	26.24 pF	26.24 pF	26.24 pF
f_r'	Estimated resonant frequency of the loaded transformer	30.73 kHz	32.15 kHz	38.69 kHz	30.49 kHz
t_w	Total wiring thickness	6.28 mm	6.08 mm	5.86 mm	6.38 mm
nv_1	Number of primary winding layers	11	11	7	11
nv_2	Number of secondary winding layers	2 x 36	2 x 36	2 x 30	2 x 35
m	Winding resistance to total resistances ratio	19.6 %	19.6 %	17.82 %	19.5 %
RL'	Load resistance recalculated to the primary side of the transformer	706 Ω	706 Ω	720.6 Ω	707 Ω
CL'	Load capacity recalculated to the primary side of the transformer	7,080 pF	7,080 pF	6,938 pF	7,000 pF
C_{tot}'	Total parasitic capacity of the transformer recalculated to the primary side of the transformer	13,737 pF	13,737 pF	15,413 pF	13,500 pF

[1)] No primary to secondary isolation applied at all.

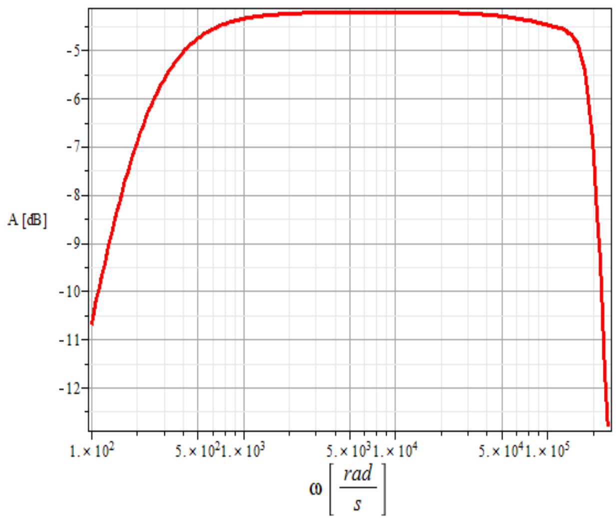

Fig. 3. Frequency response of the transformer according to the Solution 2

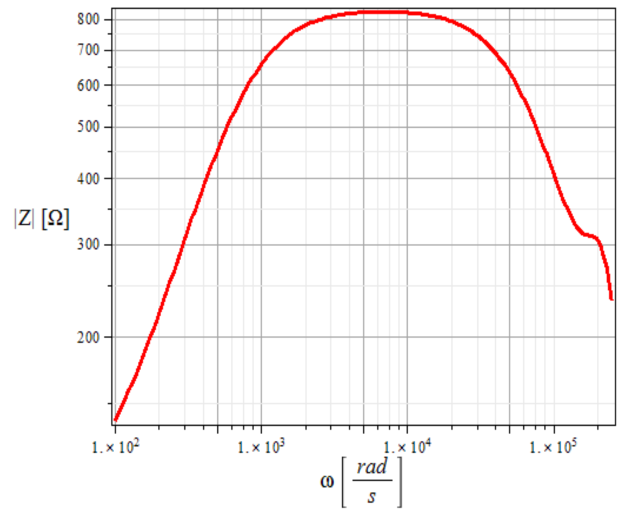

Fig. 6. Input impedance response to the frequency for the transformer according to the Solution 3

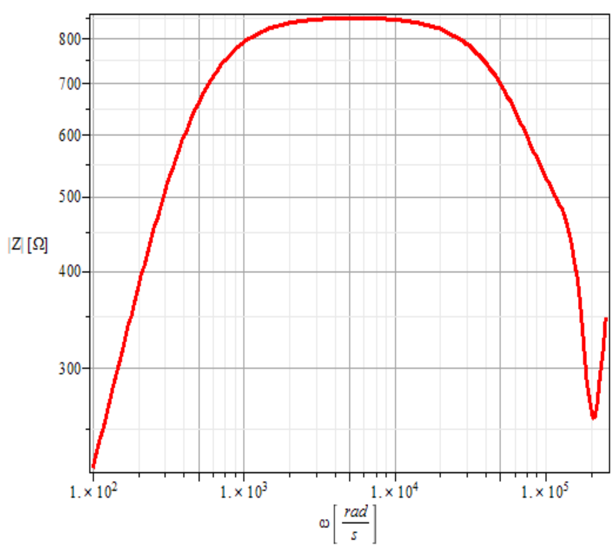

Fig. 4. Input impedance response to the frequency for the transformer according to the Solution 2

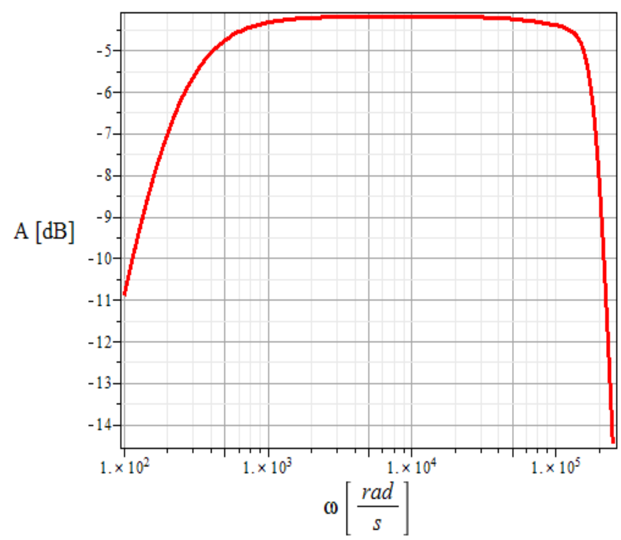

Fig. 7. Frequency response of the transformer according to the Solution 4

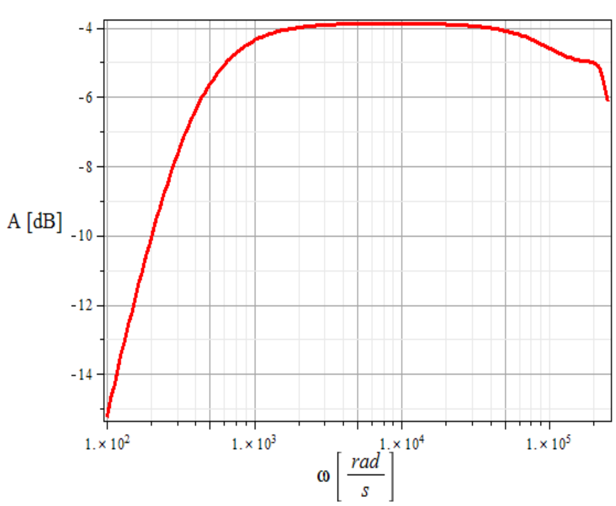

Fig. 5. Frequency response of the transformer according to the Solution 3

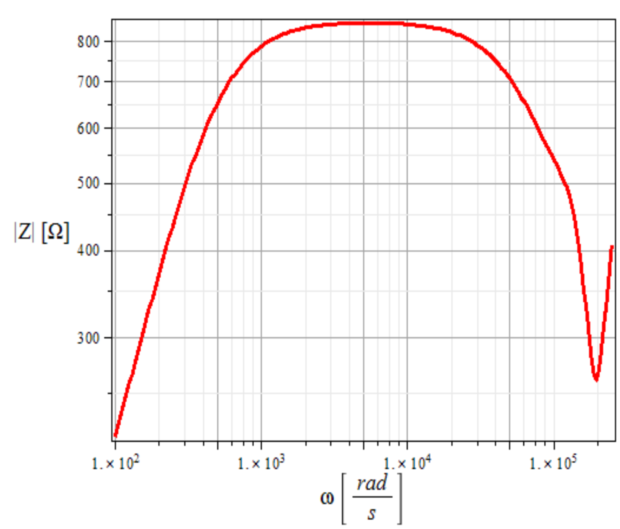

Fig. 8. Input impedance response to the frequency for the transformer according to the Solution 4

IV. RESULT DISCUSSION

As obvious, the results obtained by the Differential evolution are quite heterogeneous and it is up to the designer to choose the proper one. For the purposes specified in [4] and [5] the most suitable is probably the solution number 1. The transformer should work properly within the boundaries required by the designer and should exhibit greater performance, mainly the better resonant frequency, compared to the one constructed only upon the basic estimations described in [4].

The simulation of the results obtained by the Differential evolution agreed with the requirements except of evaluation the f_{min} parameter that was usually higher than expected. This is caused by the recursions among the applied equations. This problem could be solved by changing the order of the sequence of the equations and/or by repeating the evaluation iteratively. This is a topic for the further research. The basic parameters of the transformers are summarized in the following table.

Table 7. Simulation results summary

Parameter	**Transformers**			
	1	**2**	**3**	**4**
Minimal frequency 1)	30 Hz	30 Hz	55 Hz	30 Hz
Maximal frequency 1)	30 kHz	30 kHz	40 kHz	27.5 kHz
Resonant frequency	30 kHz	33 kHz	42 kHz	28 kHz
Total gain	15.8 dB	15.8 dB	16.1 dB	16.0 dB

1) For 3 dB decrease

V. CONCLUSION

In this paper the description of how the Differential evolution can be applied in the audio transformers design is provided. By means of the Differential evolution a small step-up transformer with relatively high frequency range at high ohmic load on parallel secondary winding has been proposed. Because this subject seems to be quite perspective, the authors decided to continue in this research in order to create more general solution for different transformer types and configurations.

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