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Design of Piezoelectric Transformer for DC/DC Converter with Stochastic Optimization method

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ABSTRACT

Piezoelectric transformers were adopted in recent year due to their many inherent advantages such as safety, no EMI problem, low housing profile, and high power density, etc. The characteristics of the piezoelectric transformers are well known when the load impedance is a pure resistor. However, when piezoelectric transformers are used in AC/DC or DC/DC converters, there are non-linear electronic circuits connected before and after the transformer. Consequently, the output load is variable and due to the output capacitance of the transformer the optimal working point change. This paper starts from modeling a piezoelectric transformer connected to a full wave rectifier in order to discuss the design constraints and configuration of the transformer. The optimization method adopted here use the MOPSO algorithm (Multiple Objective Particle Swarm Optimization). We start with the formulation of the objective function and constraints; then the results give different sizes of the transformer and the characteristics. In other word, this method is looking for a best size of the transformer for optimal efficiency condition that is suitable for variable load. Furthermore, the size and the efficiency are found to be a trade-off. This paper proposes the completed design procedure to find the minimum size of PT in need. The completed design procedure is discussed by a given specification. The PT derived from the proposed design procedure can guarantee both good efficiency and enough range for load variation.

Keywords: Piezoelectric transformer, Stochastic Optimization, DC/DC converter.

1. INTRODUCTION

Piezoelectric transformers (PT) have several inherent advantages over conventional magnetic transformers: low profile, low cost, no winding, high efficiency, high power density, high operating frequency and they are suited for automated manufacturing. The use of a high rigidity dielectric material means a high degree of insulation. However, when PT is used in a DC/DC converter application, its performances depend strongly of the load and the working frequency, so design of a PT in an application with wide range load variation is a challenge. A design method was proposed by C. Y. Lin. He established the completed design flow of the PT based DC/DC converter [1, 2]. The rectifiers are equivalent to a pure resistor because the characteristics of the PT are well-known when the load impedance is a pure resistor. This equivalent method was widely used to simplify the design procedure, especially in the resonant converter design. However, this equivalent method is only correct when the input voltage and the input current of the rectifier are in phase at the operating frequencies. If there is a phase difference between the voltage and the current, the equivalent impedance should involve the reactive components. Unfortunately, the input voltage and the input current of the PT fed rectifier indeed have phase difference in most cases. The underlying reason lies on the output capacitor of the PT that needs to be charged and be discharged in each period. Moreover, this phase difference varies with operating frequency of PT and load values. That is, the phase difference cannot be neglected. The topic of interest is to analyze the output voltage/current waveforms of the PT directly and then put it into the PT design procedure.

However, in the applications of PT based DC/DC and AC/DC converters, the load impedance is a nonlinear rectifier. The PT characteristics become more complex than the case of the pure resistive load. There were several papers discussed the PT connected with different rectifiers. Ivensky detailed the voltage doublers rectifier by the waveform analysis of the rectifier and using a variable resistor and a variable capacitor to serve as an equivalent rectifier [3]. In addition, Ivensky also made the comparisons between the voltage doublers rectifier and the current doublers rectifier [4]. However, Yaakov focused his research on the characteristic variations for the cases that PT was connected to different rectifiers and did not consider the PT design itself in detail.

On the other hand, it is known that the PT can have the maximum efficiency when the PT output capacitance matches the load impedance. This condition is called the optimal (efficient) loading condition [2, 5]. The load variations prevent the

PT from operating at the optimal loading condition under fixed frequency control such that variable frequency control is widely used in PT based converters [6, 7, 8]. However, variable frequency control may be too sensitive and also too complicated and costly. In fact, PT can operate at fixed frequency with good efficiency if we can be more careful in choosing a proper PT to fulfill all requirements related to the specification. To overcome this difficulty, the physical design constraints including the minimum input voltage, vibration velocity, and the dimensional constraints of the PT configuration must be examined. Especially, vibration velocity is one of the significant physical parameters [9] of PTs. Nevertheless, most papers related to PT optimize design [10] did not introduce this parameter and focused on the numerical prediction [11, 12]. Y.P. Liu proposed a design method of PT in a DC/DC converter based on analyze of the vibration velocity [18-20]. By examining the constraints of the maximum mechanical current and the energy balance this method provides the dimensional dimension of the PT for a wide range of the load.

In this paper, we propose a PT design based on the Y.P. Liu method but with a MOPSO optimization (Multiple Objective Particle Swarm Optimization). We start with the formulation of the objective function and constraints; then the results give different sizes of the transformer and the characteristics. In other word, this method is looking for a best size of the transformer for optimal efficiency condition that is suitable for variable load. Furthermore, the size and the efficiency are found to be a trade-off. This paper proposes the completed design procedure to find the minimum size of PT in need. The specification of the converter developed in this paper is set as follows: the switching frequency is set at near 80 kHz, the input voltage is 30 V, the output voltage is 15 V, and the load power can vary from 0 to 10 W.

The paper can be separated into three parts. In section 2, the model of PT connected with the rectifiers is introduced and the constraints of the PT are detailed. In section 3, the completed design procedure of the PT are developed and demonstrated. In section 4, the results of the proposed stochastic design procedure are presented.

2. EQUIVALENT MODEL AND THEORETICAL ANALYSIS

The electric circuit of a PT-based DC/DC converter is shown in Figure 1. A half-bridge circuit is connected to the PT via an inductor to excite its vibration; then the PT transfers the vibration energy to the output terminal. After passing through a full-bridge rectifier and capacitor C_f , a DC voltage is obtained. In Figure 1 the equivalent circuit of the PT is clearly illustrated. The series circuit $L_m R_m C_m$ represents the impedance of the motional branch of the PT. The input clamped capacitance and the output clamped capacitance are noted, C_1 and C_2 , respectively. The coupling ratios between the electrical and mechanical branches are n_1 and n_2 .

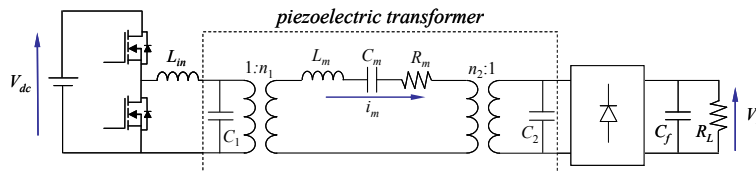


Fig 1. The system block of the PT based DC/DC converter

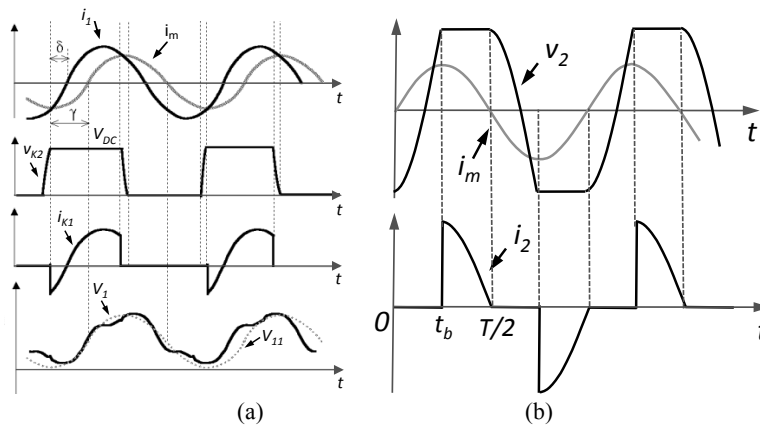


Fig 2. Typical waveforms of the converter (a) input (b) output

Figure 2 shows the key waveforms of the DC-DC converter at the input and output terminals of the PT. The circuit operation is as follows: top switch K_1 and bottom switch K_2 are turned on and off alternately with a short dead time. With resonance of L_{in} and C_1 , voltage v_1 at the input terminal of the PT becomes quasi-sine waveform. The L_{in} - C_1 resonance is set to have lag current in switches when each of them turns on. Finally, switches K_1 and K_2 , capacitor C_1 and inductor L_{in} compose a ZVS driving circuit to excite the PT vibration. The excited vibration velocity is sinusoidal due to the series resonance; this velocity is modeled by a motional current i_m . Based on this assumption, the equivalent model of the transformer can simplify as sinusoidal current source i_m and the output capacitance C_2 connected to the rectifier, as shown in Figure 3. Its corresponding waveforms of the mechanical current $i_m = I_m \sin\theta$, rectifier voltage v_{rec} and the rectifier current i_{rec} are shown in Figure 2(b).

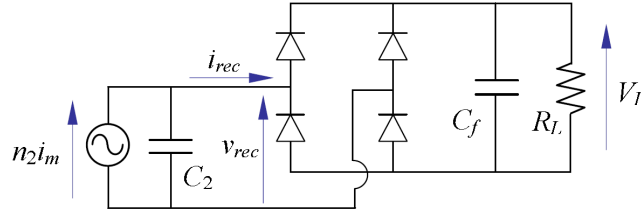


Fig 3. Equivalent circuit of PT fed full-wave rectifier

In Figure 2(b), obviously, the waveform can be divided into four periods. In the first $t \in [0, t_b]$ and third $t \in [\frac{T}{2}, \frac{T}{2} + t_b]$ periods, the diode is blocked and thus there is no current flowing to the load. The PT output capacitor is charging and discharging in the first and third period respectively. Therefore,

$$\frac{1}{\omega C_2} \int_0^{\theta_b} n_2 I_m \sin \theta d\theta = V_L \quad (1)$$

where θ is the phase angle, i.e. $\theta = \omega t$ and $\theta_b = \omega t_b$ represents the phase angle when diode is blocked or called diode block angle; ω and V_L represent the operating frequency and load voltage respectively. In the second and fourth period, diode becomes conducted and the rectifier voltage equals to the sum of the load voltage and the diode voltage drops. In addition, the load current I_o is the average current of the rectifier current. Therefore, the load current can be derived:

$$\frac{V_L}{R_L} = I_o = \frac{1}{\pi} \int_{\theta_b}^{\pi} V_L n_2 I_m \sin \theta d\theta \quad (2)$$

Combining equations (1) and (2), the relationship between load voltage and the mechanical current can be obtained:

$$V_L = \frac{2n_2 R_L}{\pi + 2n_2 \omega C_2 R_L} I_m \quad (3)$$

Furthermore, the efficiency of the converter is:

$$\eta = \frac{P_L}{P_{PTloss} + P_L} \quad (4)$$

where $P_{PTloss} = \frac{1}{2} I_m^2 R_m$ represent the loss in the PT and $P_L = \frac{V_L^2}{R_m}$ represents the load power.

The expression P_{PTloss} of the PT loss shows that for a given load power P_L , smaller mechanical current I_m leads to better efficiency. So mechanical current of the PT is an important design factor. Furthermore, vibration velocity is a physical limitation of the piezoelectric material. If the PT vibration velocity is too large, PTs will generate heat gradually that finally lead to PT breakage. The PT can only dissipate limited and fixed power inside, and the power loss in the PT is strongly dependent on the vibration velocity and the material property. In fact, the vibration velocity can be analogous to the mechanical current, and the power loss in the PT follows the square of the mechanical current. More specifically, the

vibration velocity is in fact the most important physical quantity for PT in steady state applications. The analysis of the mechanical current also implies the vibration velocity is taken into consideration in the PT design. The required mechanical current in the converter is decided by the load characteristics. According to the relationship between mechanical current and the load voltage in Equation (3), the mechanical current can be represented as:

$$I_m = \frac{V_L(\pi+2n_2\omega C_2R_L)}{2n_2R_L} < I_{m,max} \quad (5)$$

In practice, the load impedance is always varied and undetermined. It is not easy to analyze the mechanical current systematically in Equation (5). However, the optimal loading condition (maximum efficiency) can be a good reference load value. The expression of the optimal load is: $R_L = \pi/(2\omega C_2)$.

3. DIMENSIONAL CONSTRAIN OF PIEZOELECTRIC TRANSFORMER

Different types of PT are used in different application. In our DC/DC step-down converter application the best structure of PT is the stacked disk geometry as shown in Figure 4. This stacked disk-type PT owns a high electromechanical coupling and it is symmetric with respect to the radial direction vibration. The first mechanical resonance corresponding to the acoustic wave running along the radius direction was adopted. The multi-layer structure is composed of m_1 input layers (primary side) and m_2 output layers (secondary side), separated by insulating layers m_{iso} . Input layers and output layers are made of the same PZT material. The equivalent circuit of the PT was shown in Figure 1. The relationship between the equivalent circuit and the dimensional parameters of the PT are shown in Table 1. But for design consideration, these dimensional parameters may have manufacturing constraints. For example, the number of the layers should be an integer. All physical quantities cannot be arbitrary large and in most cases prescribed at a specific value. In summary, the value of the equivalent electric components cannot be designed without looking into the dimensional parameters. If we design the electric components first, there may not exist a corresponding PT. It this why in our design method we introduce two constrains: maximum mechanical current and energy balance.

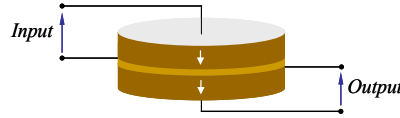


Fig. 4. Stacked disk-type PT

Table 1. The relationship between the dimensional parameter and the equivalent circuit of the stacked disk-type PT

ω_r	L_m	C_m	R_m	C_1	C_2	n_1	n_2
$\frac{\pi N_p}{r}$	$\frac{\rho_m \pi R_3^2 \beta}{1.4}$	$\frac{1}{L_m \omega_o^2}$	$\frac{1}{Q_m} \sqrt{\frac{L_m}{C_m}}$	$\frac{m_1 \pi r^2 \epsilon_{33}^S}{t_1}$	$\frac{m_2 \pi r^2 \epsilon_{33}^S}{t_2}$	$\frac{2\sqrt{2}\pi r d_{31} m_1}{s_{11}^E (1-\nu^2)}$	$\frac{2\sqrt{2}\pi r d_{31} m_2}{s_{11}^E (1-\nu^2)}$
<p><i>PT parameters:</i> ω_o is the natural frequency of the PT (rad/s) r is the radius of the PT m_1 and m_2 are the number of layers of the input section and the output section respectively β is the dimensional parameter, where $\beta = m_1 t_1 + m_2 t_2 + m_{iso} t_3$</p>							

Material properties:

$N_p = 2300$ is the frequency constants of the plane vibration ($\text{kHz} \cdot \text{mm}$)

$\rho_m = 7950$ is the density (kg/m^3)

$\nu = 0.16$ is the Poisson's ratio

$Q_m = 1313$ is the mechanical quality

$\epsilon_{33}^S = 1420 * 8.854 * 10^{-12}$ is the permittivity at constant electrical displacement condition, i.e. constant S (F/m)

$d_{31} = 232 * 10^{-12}$ are the piezoelectric constants (m/V)

$s_{11}^E = 1.14 * 10^{-11}$ is the compliance constant under the constant electric field, i.e. constant E

3.1 Mechanical current constrain

Considering that the vibration velocity can be analogous to the mechanical current, the first constrain in the design of PT is the maximum value of mechanical current. Applying equation (5), Table 1 and the optimal load resistance expression $R_L = \pi/(2\omega C_2)$, the mechanical current can be obtained as:

$$I_{m,max}(m) = \frac{A_m}{m_2} + \frac{A_t}{t_2} \quad (6)$$

where

$$A_m = \frac{s_{11}^E(1-\nu^2)V_L}{4\sqrt{2}d_{31}rR_L} \quad (7)$$

$$A_t = \frac{s_{11}^E \epsilon_{33}^S(1-\nu^2)\omega_r r V_L}{2\sqrt{2}d_{31}} \quad (8)$$

Equation (6) is the governing equation of the PT output section. It should be noted that the radius is usually determined by the operating frequency of the converter. The thickness and the number of layers are the parameters of interest. Equation (6) is interesting as it implies that the number of layers and the thickness influence the magnitude of the mechanical current independently. If the number of layers and the thickness are larger, the mechanical current would be smaller, and the PT becomes more efficient. In such a case, however, the size of PT may be too large. Therefore, it is interesting to find the smaller PT in the same mechanical current condition. The dimensional parameters of Equation (6) only describe the output section, however the real size of the PT includes not only the output section but also the input section. Therefore, the input section will be discussed in the following section with energy balance constrain.

3.2 Energy balance constrain

The input section must transfer enough power to the output section of the PT. The second constrain in PT design is that the input power should be larger than the sum of the power dissipation and the load power, so:

$$\frac{1}{2}n_1V_1I_m \cos\theta_{in} \geq \frac{1}{2}I_m^2R_m + P_L \quad (9)$$

Where θ_{in} is the phase angle between input voltage and the mechanical current. However, equation (9) cannot be solved, as the phase angle θ_{in} is an unknown variable here. The input phase angle is related to the mechanical current, and the mechanical current depends of the output voltage and the PT voltage. For simplicity, the concept of the harmonic balance, which was widely used in the modeling of the resonant power converter, is adopted here [15]. The fundamental harmonics of the input voltage and the rectifier voltage are only of interest as the mechanical current can be viewed as pure sinusoidal. To examine the energy balance, therefore, the input voltage of the PT is assumed to be a sinusoidal source and only the fundamental harmonic of the output PT voltage v_{rec} can be identified by the Fourier analysis:

$$v_{rec} = V_{rec}^s \sin \omega t + V_{rec}^c \cos \omega t$$

Considering sine wave assumption and using parameters in Table 1 the energy balance relationship can be rewritten as follows [18]:

$$0 \geq (m_2 V_{rec}^c)^2 - \left(\frac{s_{11}^E(1-\nu^2)}{2\sqrt{2}\pi r d_{31}} P_L \right)^2 - (m_1 V_1)^2 = -V_{eb}^2 \quad (10)$$

with:

$$V_{rec}^c = \frac{\sin\theta_b - 2\theta_b}{\pi(1 - \cos\theta_b)} V_L \quad (11)$$

Some relationships between the dimensional parameters will be discussed to facilitate the design processes. First, the minimum number of layers in the input section is increased with the number of layers in the output section. It implies that the input section and the output section cannot be designed separately if the small size of the PT is preferred. Secondly, the thickness of the PT input section is introduced in Equation (10), which means it is not a significant parameter for the specification.

3.3 Mechanical losses

In the previous model the mechanical losses in related to resistance R_m . For the optimization of the efficiency of the PT, we must take into account the influence of the dimension and the numbers of layers of the PT in the value of R_m . The reason is that a large number of layers may cause the quality factor (Q_m value) of the PT to decrease especially when the layers are manufactured by gluing. The allowable passing current through the mechanical R_m - L_m - C_m branch is thus becomes smaller. More specifically, the maximum mechanical current and the quality factor of the PT are the function of the total number of layers, i.e. $Q_m = Q_0(m)$. Where Q_0 represents the quality factor in the single piezoelectric layer and m is the total number of the layers. The total number of the layers includes three parts: the layers of the input section, the output section and the isolation, i.e. $m = m_1 + m_2 + m_{iso}$, where m_{iso} is the number of the isolating layers.

Both the quality factors and the mechanical currents can be described as the exponential function of the number of layers by curve fitting method:

$$Q_m = Q_0 e^{-a(m-1)} \quad (12)$$

$$I_{m,max} = I_{0,max} e^{-b(m-1)} \quad (13)$$

where a and b represent the exponential decay rate of the quality factor and the maximum mechanical current respectively, which are decided by the manufacturing process and the gluing material.

4. DESIGN OF PIEZOELECTRIC TRANSFORMER

Two contradictory benchmarks have been adopted herein: compactness, and the efficiency criterion. A bi-objective optimization design is thus required in order to minimize both volume and losses of the PT. Such an approach aims to determine the optimal geometric parameters relative to the desired performance.

An optimization procedure using the MOPSO [21][22] algorithm is then used (Figure 5). Like with most meta-heuristic algorithms, three elements need to be defined: $[p_i; f_{p_i}; g_i]$.

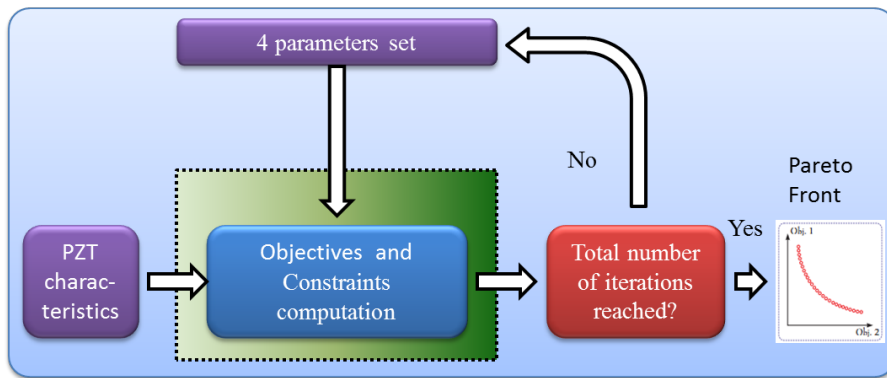


Fig. 5: Optimization process

- p_i : 4 optimization parameters are related to the structure and have been listed in Table 2. To facilitate algorithm convergence, the parameters are reduced to values ranging between 0 and 1.

Table 2. Optimization parameters

Parameter	Name	Min value	Max value
Primary number layers	m_1	1	50
Secondary number layers	m_2	1	50
Primary layer width (μm)	t_1	100	500
Secondary layer width (μm)	t_2	100	500

- f_{pi} : This objective function (to be minimized) is defined as: $f(p_i) = \begin{bmatrix} P_{PT} \\ V_{PT} \end{bmatrix}$

Where $V_{PT} = \sum_{j=1}^N v_j$; v_j is the volume of each PT part (primary, secondary and isolation).

- g_i : The constraints are shown as follows: $g_i = \begin{bmatrix} I_{mec \max} - I_{mec} \\ -V_{eb}^2 \\ P_{min} - P_L \end{bmatrix} \leq 0$ where: $P_{min} = 10 \text{ W}$

The specifications of the converter developed in this paper are listed in table 3. Output power and maximum mechanical current are two important optimization parameters. The designed transformer must provide at the load a power of 10 W under 15 V for an input maximum voltage of 30 V at the frequency of 80 kHz. Another important parameter is the maximum mechanical current, for the mechanical reason the vibration velocity doesn't must be higher than 1 m/s. The exponential decay rate of the quality factor was measured experimentally: several piezoelectric layers were glued together to serve as the specimen to get the experimental model and then the quality factors of each different layers are measured by the impedance analyzer [18].

Table 3. Specification of the PT

	Value
Working frequency (kHz)	80
Input voltage max (V)	30
Output voltage DC (V)	15
Output power (W)	10
Maximum mechanical current (m/s)	1
a : decay rate of the quality factor	0.141

The material proprieties of the *PZT-QA* material used in this optimization process provide by *ELECERAM TECHNOLOGY Co., Ltd* and the relationship between the equivalent circuit and the dimensional parameters of the PT are shown in table 1.

The volume is calculate with this relation:

$$Vol = \pi r^2 (m_1 t_1 + m_2 t_2 + m_{iso} t_{iso}) \quad (14)$$

The optimization tool is then defined: iterations number, particles number, parameters intervals and constraints evaluation. The pair of "objective functions" was simulated for fifty particles (PT transformers) and five hundred generations. The result of this optimization is a Pareto Front (PF) shown in Figure 6.

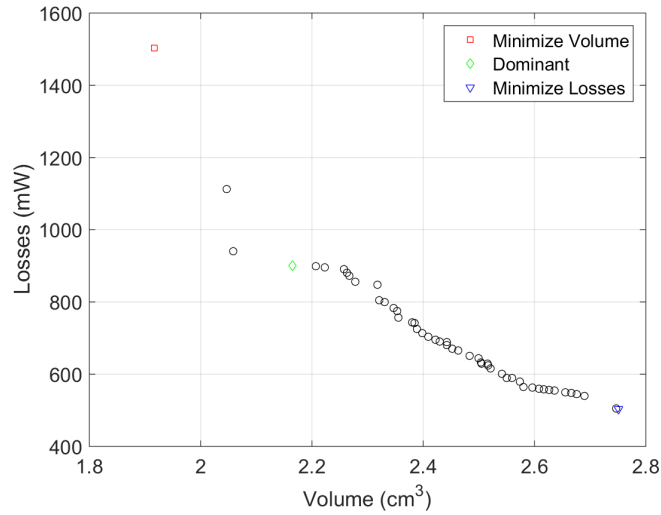


Fig. 6. Pareto front

The Pareto front shown in Figure 6 presents all calculated geometry of the PT for different sizes (volume) and losses. The losses, for each geometry, are calculated for the maximum output power (10 W) and the load resistance of 22.5Ω . The choice of geometry of the transformer is a trade-off between the size and the efficiency. To discuss the choice of the size of the PT, 3 geometries of PT are presented in Figure 7: (a) the first one minimizes the PT volume, (b) the second one is the dominant PT (best compromise between losses and volume) and (c) the third one minimizes the PT loss.

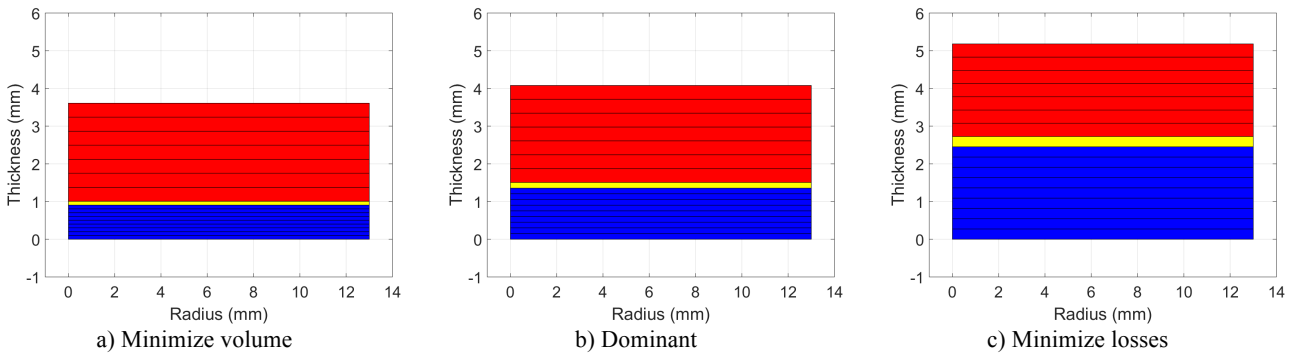


Figure 7. PZT geometry

In figure 7, the primary layer of PT is in red, the secondary layer in blue and the insulation layer in yellow. Table 4 gives all geometrical data of the 3 selected transformers. These results show that for the given specifications (input voltage 30 V, output power 10 W) the primary size of the transformer doesn't change. To decrease the size of the PT, the thickness of the output layers decreases, that mean that the output capacitance C_2 increases. If output capacitance C_2 increases, for the same power in the load, the mechanical courant (vibration velocity) is higher and thus the mechanical losses also.

Table 4. Size of the PT

	PT (a)	PT (b)	PT (c)
Radius r (mm)	13	13	13
Primary number of layers	7	7	7
Secondary number of layers	9	9	9
Primary layer thickness (μm)	400	400	400
Secondary layer thickness	100	200	300
Insulation layer thickness	100	200	300
Total volume (cm^3)	1.92	2.17	2.75
Loss at 10 W (W)	1.5	0.9	0.5

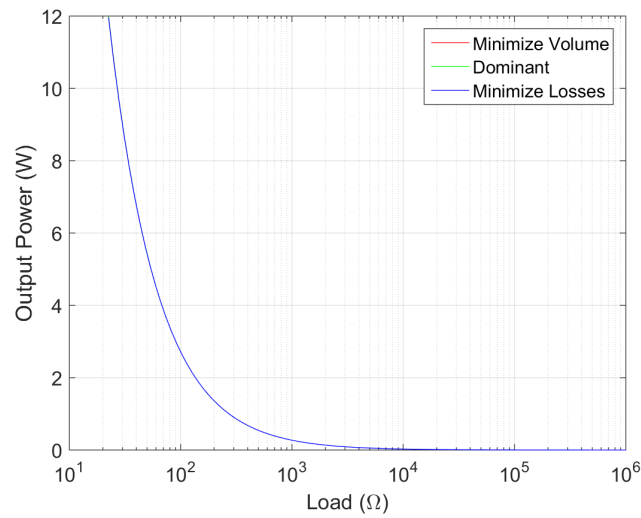


Fig. 8. Output power for the 3 geometries of PT

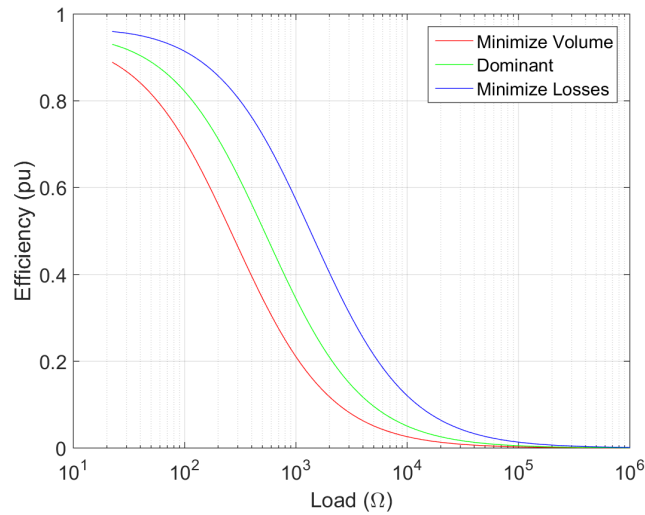


Fig. 9. Efficiency for the 3 geometries of PT

Figure 8 presents the output power as a function of the resistance load R_L for the 3 geometries of transformer. All 3 geometries provide 10 W for an output voltage of 15 V and a load of 22.5 Ω . Figure 9 presents the efficiency of the 3

geometries. Maximum efficiency is obtained for the output power of 10 W ($R_L = 22.5 \Omega$ and $V_L = 15$ V). The best efficiency is obtained with the structure that minimized the losses (96 %). The structure that optimizes the volume has an efficiency of 89 %.

5. CONCLUSION

This paper presents a complete and systematic method to design a stacked disk-type piezoelectric transformer in the application of DC/DC converter with regulated output voltage. Because the output voltage is regulated, the typical optimal loading condition of PT is not the key point in designing. The mechanical current and energy balance are the key parameters to design the PT. The reason is that larger size of PT leads to better efficiency. The expediency solution between the size and the efficiency is thus required to obtain. The optimization procedure using the MOPSO algorithm is carried out. The optimization parameters and objective function was defined. Three design criteria were established: the maximum value of mechanical current; the energy balance and the minimal value of the output power. The results show that optimal structure of the transformer is a trade of between the size and the losses.

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