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Optimal Design of Three-phase Distribution Transformer using Fewer Constraints

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Abstract

This paper presents an optimization process where fewer constraints are used in the design of a three phase distribution transformer. The constraints were applied on two optimization techniques - the Geometric Programming (GP) and the Genetic Algorithm (GA). Eight design variables were tested and the results obtained from the two techniques are comparatively the same.

Keywords: Geometric Programming, Genetic Algorithm, Optimisation, Mass, Transformer, Constraints, Minimisation, Objective functions

Nomenclature
M_{fe} = mass of iron; d_{fe} = density of iron; s_f = stacking factor; d = diameter of core;
H_w = window height; W_w = window width; M_{cu} = mass of copper; d_{cu} = density of copper;
h = height of winding; R_p = radius of primary winding; t_p = thickness of primary winding;
R_s = radius of secondary winding; t_s = thickness of secondary winding; g_1 = gap between core and primary winding; J_p = current density; B = flux density; P = power output
I_p = primary current; E_p = primary voltage; E_t = volt/turn

1.0 Introduction

Transformer was introduced into the power system as a power system transformation device. It usually has efficiency close to 100%. The development of cheaper or reliable transformer is the goal of the power system industry. In the design of three phase distribution transformer, minimization of certain parameters may leads to the production of cheaper and efficient set of products. Optimization is a science of determining the best solution to certain mathematically defined problems, which are often models of physical reality. Optimization involves the setting up of an objective function and making output value to reach a maximum or minimum while keeping all variables within an acceptable limit or range.

Several optimization procedures are used to reduce cost of design of three phase distribution transformers. This includes cost, mass and losses minimization. Toward this researchers have used some optimization techniques in the design of three phase distribution transformer such as, the Genetic Algorithm [1], the Finite Element Method [2], Simulated Annealing [1], Geometric Programming [3] and Mathematica [4]. The constraints used in these techniques are rather bogus and unassuming.

In this work the mass function and a few set of non linear constraints expressed in terms of the primary variables such as the core diameter, the window height has been used for a global optimization using the geometric programming (GP) and genetic algorithm (GA).

2.0 Formulation of the objective function

The objective of the work is to optimally design a three phase distribution transformer by minimizing the mass of the core and copper used in the production of transformer.

Taking the cross section of the limbs and yokes to be the same, the mass of the core M_{fe} is given as

$$M_{fe} = d_{fe} s_f d^2 \left(3H_w + 2(3d + 2W_w)\right) \qquad (1)$$

The mass of copper for both the low and high voltage side is given as,

$$M_{cu} = 6 d_{cu} h_s \pi \left(R_p t_p + R_s t_s\right) \qquad (2)$$

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Combining (1) and (2) we have,

$$M_{fe+cu} = M_{fe} + M_{cu} = d_{fe}s_f d^2\big(3H_w + 2(3d + 2W_w)\big) + 6d_{cu}h_s\pi\big(R_p t_p + R_s t_s\big) \quad (3)$$

Equation (3) is in the standard form for geometric programming formulation and will be used as it is in the simulation.

1. Design Constraints

The following are the constraints used in the design optimization method.

1.1. The flux density constraint

The flux density of the core and the yoke are the same, this arises from the same cross section assumed for both. The flux density B is given as

$$B = \frac{E_t}{\sqrt{2}k_f\pi f d^2} \quad (4)$$

The only variable in this constraint is that of the core diameter. The flux density constraint is an equality constraint and can be expressed as such in GP and GA format.

1.2. The current density constraint

The current density J_p can be expressed in terms of the window height and window width as

$$J_p = \frac{4E_pI_p}{E_tH_wW_wk_w} \quad (5)$$

1.3. The power transfer constraint

The power transfer is given as

$$P = \sqrt{2}\pi f s_f d^2 B J_s h_s t_s \quad (6)$$

1.4. Other constraints

The other constraints are relational ones that will provide the desired results. These are,

$$2W_w = H_w \quad (7)$$

$$h_s = 0.7H_w \quad (8)$$

$$J_p = \frac{J_st_s}{\alpha t_p} \quad (9)$$

$$W_w \geq 2g_1 + 2t_p + g + 2t_s \quad (10)$$

$$R_s \geq \frac{d}{2} + g_1 + \frac{t_s}{2} \quad (11)$$

$$R_p \geq R_s + g_1 + \frac{(t_s+t_p)}{2} \quad (12)$$

2. Design Example

Table 1 shows the input parameters used in the design optimization of a three phase distribution transformer.

Table1:Transfomer Input Parameters

Input parameters	Values
Power (kVA)	500
Voltage (kV)	11/.415
Frequency (Hz)	50
Space factor (k_w)	0.2
Stacking factor (s_f)	0.95
Density of iron kg/m^3	7650
Density of copper kg/m^3	8900
Flux density Wb/m^2	1.3
Current density Wb/m^2	$2.5\text{x}10^6$

2.0 Results and discussion

Table 2:Transformer Design Optimization

Design Variables	Mass minimization by GP	Mass minimization by GA
$H_w(x_1)\ (cm)$	51.68	51.12
$d(x_2)\ (cm)$	17.96	18.59
$R_p(x_3)\ (cm)$	20.55	18.20
$R_s(x_4)\ (cm)$	11.99	12.34
$W_w(x_5)\ (cm)$	25.84	25.56
$h_s(x_6)\ (cm)$	36.17	35.68
$t_p(x_7)\ (cm)$	5.70	5.78
$t_s(x_8)\ (cm)$	5.42	5.49
$M_{fe+cu}\ (kg)$	1962.9	2006.69
η	99.17	99.41

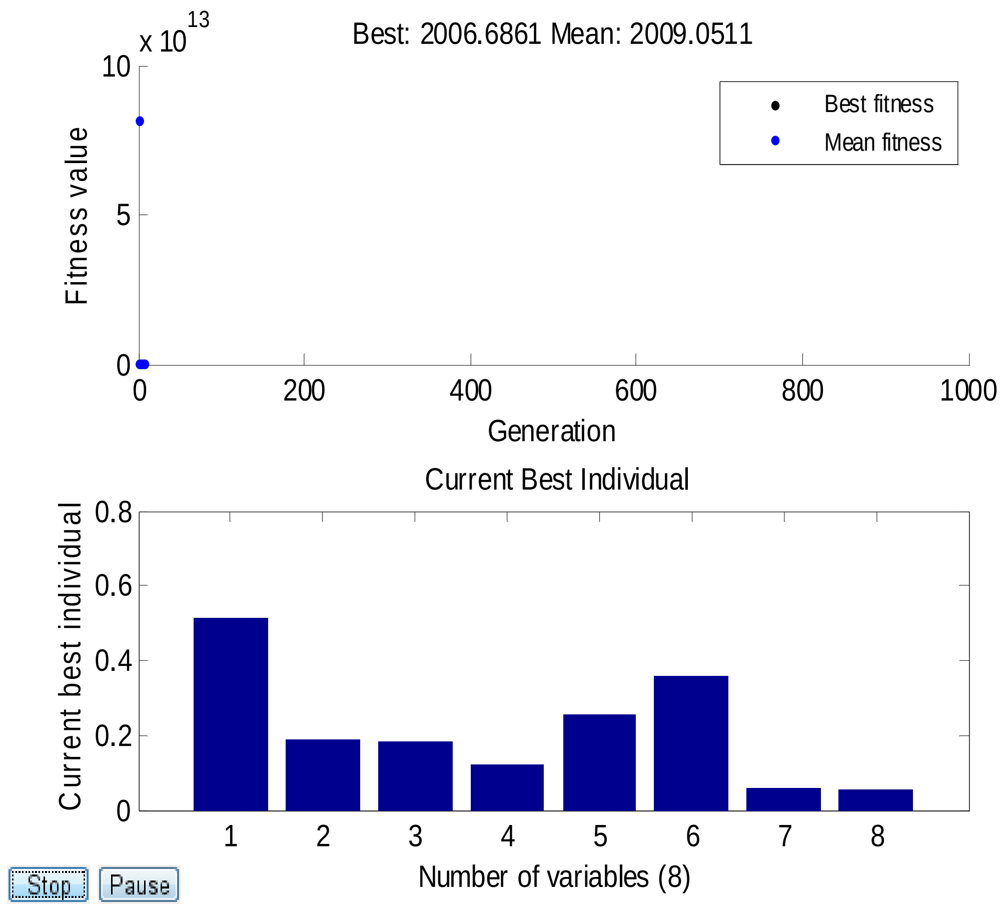

Fig 1: Core and winding variables (x_1-x_7) as presented by GA graph.

From the results presented in Table 2, the transformer design optimization using fewer constraints produces the same values whether GP or GA is used. A GA graph of the simulation is presented in Fig. 1. By comparison the GP produces a faster result as compared with GA.

3.0 Conclusion

Transformers produced with minimal materials hasten the mass production process thereby providing cheaper products. Optimization of a design helps in the minimization of either the cost or mass. This work demonstrates that with fewer constraints the goal set in the design optimization of a three phase distribution transformer can be achieved with minimal time frame.

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