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Optimization of Power Transformer Design using Simulated Annealing Technique

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Abstract

The power transformer is one of the most important equipment in a power system. Optimal design of transformer involves determination of design parameters of a power transformer when a chosen objective is optimized, simultaneously satisfying a set of constraints. In this paper Simulated Annealing (SA) is used for optimization of Power Transformer Design (OPTD).The total mass of core and copper is chosen as objective that is to be minimized. The results obtained indicate that the method has yielded a global optimum. The computation time and mass of active material are much reduced when compared with conventional design results. The efficiency of transformer is found to improve with the application of this algorithm.

Index Terms: Optimization, Power Transformer, Simulated Annealing.

Introduction

The objective of *transformer design optimization* (TDO) is to design the transformer so as to minimize the transformer manufacturing cost, i.e., the sum of materials cost plus labor cost, subject to constraints imposed by international standards and transformer user specification.

The aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer design should be carried out based on the specification given, using available materials economically in order to achieve low cost, low weight, small size and good operating performance.

The transformer design is worked out using various methods based on accumulated experience. Transformer design methods vary among transformer manufacturers. While designing a transformer, much emphasis should be placed on

lowering its cost by saving materials and reducing to a minimum labor-consuming operation in its manufacture. The design should be satisfactory with respect to dielectric strength and mechanical endurance, and windings must withstand dynamic and thermal stresses in the event of short-circuit. In order to meet the above requirements, the transformer designer should be familiar with the prices of basic materials used in the transformer. He should also be familiar with the amount of labor consumed in the production of transformer parts and assemblies.

This paper presents a transformer design methodology based on an artificial intelligence technique. In case of a power transformer design, a design engineer has to consider several aspects of the transformer design such as core shape, size, properties, copper wire size etc and arrives at an optimum design. Improper design results in under utilization of materials.

Several optimization techniques have been reported in the literature. The study of designing power transformers using a computer was pioneered by [1] [2] and [3]. Later, [4] suggested a method for obtaining an optimized design of power transformers. However, procedure was not general and cannot be used conveniently for all power transformer design problems. Several other techniques were also used for design of power transformer [5]-[11]. In [12], attention was focused on a class of single-phase transformers that are employed when a high voltage withstand test is required for verifying the quality of the dielectric insulation of a given component.

Optimum Design of Transformer

Problem Formulation

The optimization of transformer design problem is formulated as an NLP problem, expressing the objective function and constraint functions in term of the specified independent variables. The objective function is expressed as

Optimize f(x)

Such that ‘x’ exists within the n-dimensional feasible region D:

X ε D, where

D = {x | x >=0, g_i(x) <=0, h_i(x) = 0, i=1 to n}

In the above equations, f(x), g_i(x) are real valued scalar functions and vector x comprises the n principal variables for which the optimization is to be performed .The function f(x) is called to be objective function, for which the optimal value of x result in the maximum value for f(x), and these optimal values satisfy the given constraints.

Simulated Annealing Technique

Simulated annealing (SA) is one of the most flexible techniques available for solving hard combinatorial problems. The main advantage of SA is that it can be applied to large problems regardless of the conditions of differentiability, continuity, and convexity that are normally required in conventional optimization methods.

Annealing is the process of submitting a solid to high temperature, with subsequent cooling, so as to obtain high-quality crystals (i.e., crystals whose structure

form perfect lattices) [13]. Simulated annealing emulates the physical process of annealing and was originally proposed in the domain of statistical mechanics as a means of modeling the natural process of solidification and formation of crystals. During the cooling process, it is assumed that thermal equilibrium (or quasi equilibrium) conditions are maintained. The cooling process ends when the material reaches a state of minimum energy, which, in principle, corresponds with a perfect crystal. It is known that defect-free crystals (i.e., solids with minimum energy) are more likely to be formed under a slow cooling process. The two main features of the simulated annealing process are (1) the transition mechanism between states and (2) the cooling schedule. When applied to combinatorial optimization, simulated annealing aims to find an optimal configuration (or state with minimum "energy") of a complex problem. The objective function of an optimization problem corresponds with the free energy of the material. An optimal solution is associated with a perfect crystal, whereas a crystal with defects corresponds with a local optimal solution [14]. The analogy is not complete, however, because in the annealing process there is a physical variable that is the temperature, which under proper control leads to the formation of a perfect crystal. When simulated annealing is used as an optimization technique, the "temperature" becomes simply a control parameter that has to be properly determined in order to achieve the desired results.

The original idea behind the simulated annealing algorithm is the Metropolis algorithm that models the microscopic behavior of sets of large numbers of particles, as in a solid, by means of Monte Carlo simulation. In a material, the individual particles have different levels of energy, according to a certain statistical distribution. The possible lowest level of energy, known as the fundamental level, corresponds with the state where all particles stand still and occurs at temperature 0° K. For temperatures above that level, the particles will occupy different levels of energy, such that the number of particles in each level decreases as the energy level increases (i.e., the maximum number of particles is found in the fundamental level). The distribution of the particles in the various levels varies with the temperature; for T = 0 K, for example, all particles are in the fundamental level; as the temperature increases, more particles are found in higher energy levels but always as a decreasing function of the energy level.

The Metropolis algorithm generates a sequence of states of a solid as follows: giving a solid in state Si, with energy Ei, the next state Sj is generated by a transition mechanism that consists of a small perturbation with respect to the original state, obtained by moving one of the particles of a solid chosen by the Monte Carlo method. Let the energy of the resulting state, which also is found probabilistically, be Ej; if the difference Ej-Ei is less than or equal to zero, the new state Sj is accepted. Otherwise, in case the difference is greater than zero, the new state is accepted with probability.

$$\exp(\frac{Ei - Ej}{k_B T}),$$

where T is the temperature of the solid and $k_B$is the Boltzmann constant. This acceptance rule is also known as Metropolis criterion and the algorithm summarized

above is the Metropolis algorithm [14]. The temperature is assumed to have a rate of variation such that thermodynamic equilibrium is reached for the current temperature level, before moving to the next level. This normally requires a large number of state transitions of the Metropolis algorithm.

For a combinatorial optimization problem to be solved by simulated annealing, it is formulated as follows: let G be a finite, although perhaps very large, set of configurations and v the cost associated with each configuration of G. The solution to the combinatorial problem consists of searching the space of configurations for the pair (G, v) presenting the lowest cost. The SA algorithm starts with an initial configuration $G_o$and an initial "temperature" T_o and generates a sequence of configurations N =N_o. Then the temperature is decreased; the new number of steps to be performed at the temperature level is determined, and the process is then repeated. A candidate configuration is accepted if its cost is less than that of the current configuration. If the cost of the candidate configuration is bigger than the cost of the current configuration, it still can be accepted with a certain probability. This ability to perform uphill moves allows simulated annealing to escape from local optimal configurations. The entire process is controlled by a cooling schedule that determines how the temperature is decreased during the optimization process.

Algorithm

Simulated Annealing

Begin

Initialize (T_o,N_o);

K: = 0;

Initial configuration $\mathbf{S_i}$

Repeat procedure

Do L: =1 to Nk

Generate (Sj from Si);

If f(Sj) ≤ f(Sj) do Si = Sj

Otherwise

If exp($\frac{f(Si)-f(Sj)}{Tk}$) >random [0,1] do Si = Sj;

End do;

K = K+1;

Calculation of the length (Nk);

Determine control parameter (Tk)

Stopping criterion

End;

From the current state Si with cost f(Si), a neighbor solution Sj, with cost f(Sj) is

generated by the transition mechanism. The following probability is calculated in performing the acceptance test:

$$P_T\{\text{Accept Sj}\} = \{1 \quad if \quad f(S_j) \le f(S_i)\}$$

$$\text{or } \{\exp(\frac{f(Si) - f(Sj)}{Tk}), \ if \quad f(S_j) > f(S_i)$$

Implementation of Simulated Annealing Technique for OPTD

The input to the program includes detail like distance between core centre(c), thickness of core (t), width of window(bw), height of window(hw), connection, frequency etc besides the specification values. A set of random values are assigned to the four independent values and the initial total mass of core and copper is calculate. While some of the optimization procedures require an initial feasible starting point, SA does not insist on such a point. That is, the algorithm can arrive at an optimal solution even from anon feasible starting point.

Algorithm

Step 1: Read transformer data, independent variables, constrains and set initial temperature.

Step 2: Formulate of the objective function (i.e, initial mass of core and copper) and calculate the initial mass of core and copper of transformer.

Step 3: Set i=1 compute Xi=Xi+ΔX and calculate the value of objective function (Finew) Also calculate ΔF=Finew-F1.

Step 4: Accept or reject each point using mepropol's criterion.

Step 5: Check if the number cycles is greater than maximum number of cycles go to next step. Otherwise go to step 3.

Step 6: Adjust step size, reset number of cycle.

Step 7: Check if the number of step adjustment is greater than maximum number of cycles go to next step. Otherwise go to step 3.

Step 8: Reduce temperature, reset number of adjustment to 0. Set current point as optimum.

Step 9: Stop, if temperature is low else go to step 3.

Mathematical Model

1. Objective Function: The objective of the design is to minimize the total mass

of copper and core material. The objective function is

$$mc+mcu = \rho_c K_f V_c + \rho_{cu} K_{cu} V_{cu} \quad (1)$$

where mc, mcu are mass of core and mass of copper respectively.

Subject to the following constraint:

$$V2 = 4.44.f.N2.Fdmax.CSF.D.2.Eu \quad (2)$$

$$V1 /V2 = N1/N2 \quad (3)$$

$$NLL<NLL\ max \quad (4)$$

$$LL<LL\ max \quad (5)$$

$$TTL<TTL\ max \quad (6)$$

$$UK, min<UK<UK, max \quad (7)$$

$$Fd\ max<Fdsat \quad (8)$$

$$TTL<THCCR \quad (9)$$

$$\Delta T<\Delta Tmax \quad (10)$$

$$TL<Tlmax \quad (11)$$

$$TW<Twmax \quad (12)$$

$$TH<THmax \quad (13)$$

$$Induced<induced\ LV, max \quad (14)$$

$$Induced\ HV<induced\ HV, max \quad (15)$$

$$Induced\ HV<induced\ HV, max \quad (16)$$

Results and Discussion

High Frequency Design Example

The SA technique was used to design a transformer operating

at 100 kHz. The design inputs are as follows:

S = 1200 VA

Ep = 300 V; Es = 75 V,(rms sine wave voltages)

Frequency f = 100 kHZ

Maximum temperature: Ta = 40° C,ΔT = 60°C

In addition, the following design constraints were imposed:

Rated power factor pf = 0.80(lagging)

Maximum efficiency ηm = 0.97

Maximum voltage regulation VRm = 0.03

Maximum no-Load / full load current Kφ = 0.02

Table 1: Comparison of results obtained using conventional design, SA based OPTD.

Design Variable	min. mass design conventional method	SA based design
c(cm)	0.49	0.49
t(cm)	2.21	2.21
bw(cm)	0.68	0.68
hw(cm)	2.44	2.44
Np	40	40
Ns	10	10
NIp	4	4
NIs	1	1
P	10	10
Acup(mm^2)	1.30	1.30
Acus(mm^2)	5.21	5.21
mc+mcu(g)	157.74	157.31944
$\boldsymbol{n}$%	99.56	99.56

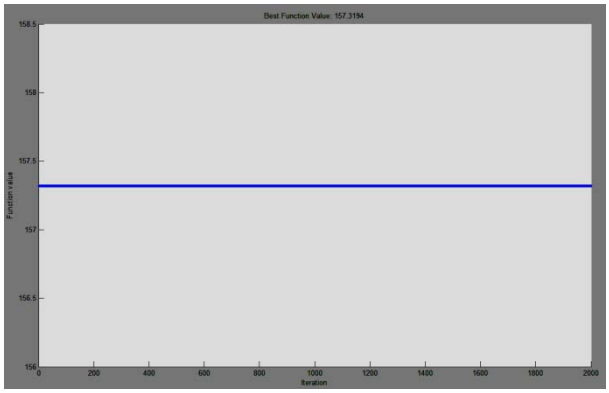

Figure 1: Variation of mass of copper and core with iteration.

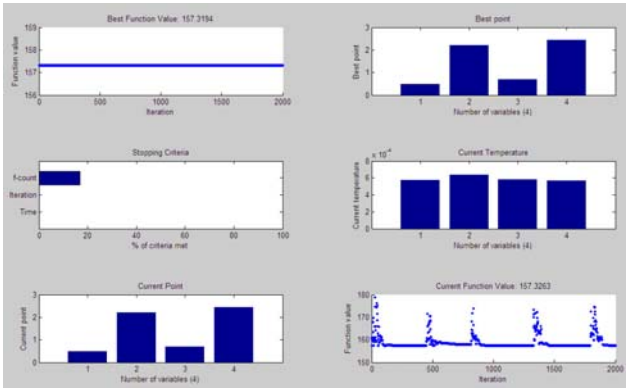

Figure 2: Variation of function value with iteration, best point with no. of variables, stopping criterion, current temperature with no. of variables, current point with no. of variables, current function value with iteration respectively.

Conclusions

In this work, Simulated Annealing algorithm is used for the optimum design of transformer. This procedure employs SA to search optimal values of independent variables. All the important dimensions and constraints have been accounted for. The design is capable of finding a design which is far superior to the conventional design. The SA based design optimization is simple, robust and reliable for design optimization of transformer. Thus SA is a viable tool for obtaining optimal design of transformer.

References

[1] Williams S.B., Abetti P.A. and Magnusson E.F., "Application of digital computers to transformer design", AIEETrans.1956, vol 75, part III, pp728-35.
[2] Williams S.B, Abetti P.A and Mason H.J, “Complete design of power transformers with a large size digital computer", AIEE Trans., 1959, vol 77, Part III, pp1282-91.
[3] Sharpley W.A and Old field J.V. “The digital computer applied to the design of large power transformers", Proc.IEE,1958,vol105, partA,pp112-25.
[4] Adersen 0.W., "Optimum design of electrical machines 'IEEE Transactions on Power Apparatus and Systems, 1967, PAS-86 (6)707-11.
[5] Rubaai A. ”Computer aided instruction of power transformer de sign in the undergraduate power engineering class", IEEE Transactions on Power Systems,1994,9(3),1174-1181.
[6] Jewell W.T. ”Transformer design in the undergraduate power engineering laboratory", IEEE Transactions on Power Systems, 1990,5(2),pp499-505.
[7] Grady W.M, Chan R. Samotyj M.J, Ferraro R.J. and Bierschenk J.L.,"Apc-based computer program for teaching the design and analysis of dry-type transformers",I EEE Transactions on Power Systems,1992,7(2),pp709-717.
[8] Poloujadoff M. and Findlay R.D. “A procedure for illustrating the effect of variation of parameters on optimal transformer design", IEEE Transactions on Power Systems,1986, PWRS-1 (4),pp202-207.
[9] Basak A, Yu C. Hand Lloyd G., "Efficient transformer design by computing core loss using a novel approach", IEEE Transactions on Magnetics,1994,30(5),pp3725-3728.
[10] Hurley W.G., Wolfle W.H. and Breslin J.G., Optimized transformer design: Inclusive of high frequency effects", IEEE Transactions on Power Electronics, 1998, 13(4),pp651-659.
[11] Saravolac M.P., "Use of advanced software techniques in transformer design", in Proc. lEE Colloquiumon Design TechnologyofT&DPlant,1998,pp.9/1-9/11.
[12] Di Barba P, Piovan U, and Savini A, “Optimal shape design of the HV winding of a test transformer", COMPEL: Int. J for Computation and Maths. In Electrical and Electronic Eng., 1998, vol17, no:1,pp128-134.
[13] Aarts E, Korst J. Simulated annealing and Boltzmann machines. New York: John Wiley & Sons; 1989.
[14] Van Laarhoven PJM, Aarts EH. Simulated annealing: theory and applications. Holland: Dordrecht, D. Reidel Publishing Company; 1987.