"WEIGHT ALGORITHMS FOR ADIABATIC TRANSFORMERS FOR PULSED HIGH POWER SYSTEMS"

R. P. McNall and D. L. Lockwood
Thermal Technology Laboratory, Inc.

and

A. S. Gilmour, Jr.
State University of New York at Buffalo

ABSTRACT

A transformer design computer program developed by Thermal Technology Laboratory, Inc. has been used in a mode whereby it automatically minimizes the weight of a transformer with any given set of operating parameters. Four classes of adiabatic transformers (wherein heat capacity is used to absorb heat generated) for use in pulsed power systems have been investigated in detail. Two of these were at power levels in the 10 to 50 MW range and the other two were in the 1 to 5 MW range. In each power range, three-phase sinusoidal and single-phase square wave transformers were analyzed in detail. The three phase transformers would be used in conjunction with alternators. The single phase units would be used in inverters.

This paper gives a brief description of the transformer design program and then summarizes the results of weight studies on over 120 optimized transformers designed for operation at various powers, voltages, frequencies and pulse durations. Algorithms, developed for calculating transformer specific weight as functions of these parameters are given.

INTRODUCTION

This study was part of the power conditioning portion of the High Power Study recently supported by the Air Force Aeropropulsion Laboratory and performed by The State University of New York at Buffalo. Four classes of transformers were investigated in detail. Two of these were at power levels in the 10 to 50 MW range and the other two were in the 1 to 5 MW range(for use with the auxiliary load). In each power range, three phase sinusoidal and single phase square wave transformers were analyzed in detail. The three phase sinusoidal transformers would be used to boost the output voltage of an alternator. The single phase transformers would be used in inverters.

The transformer study was carried out with the assistance of Thermal Technology Laboratory, Inc. (TTL). Individual transformer designs were performed using the TTL transformer design computer program. This program was used in a mode whereby it automatically minimized the weight of a transformer with any given set of operating parameters. Designs utilizing external cooling (by freon for example) and "adiabatic" (wherein the heat capacity of the transformer material is used to absorb the heat generated) were examined in detail. Also, the use of cryogenics was taken into consideration. For the operating periods under consideration(120 seconds maximum) the "adiabatic" designs were found to produce substantially lower specific weights than the designs utilizing external cooling. Thus, only the results of the "adiabatic" design studies are included in this report. An ambient temperature of 160°F (71°C) and a maximum wire temperature of 500°F (260°C) were assumed for these studies. If liquid nitrogen could be used for cooling the transformer prior to the start of a mission, the studies show that a weight reduction by a factor of at least four could be realized.

It should be pointed out that, for the transformer designs analyzed for this study, the current density in the conductors was about 13000 A/in^2 and it was assumed that all of the conductor losses were stored in the conductors. It was assumed that none of the heat diffused into the insulation. By comparison, it should be noted that in the Garrett, thermal lag alternator designs which were also part of the AFAPL High Power Study, a current density in the conductors of 15000 to 16000 A/in^2 was used. The diffusion of heat into the insulation was taken into account and a temperature rise from 130°F to 400°F was found to occur. It appears, therefore, that if heat diffusion into the insulation was taken into account in the transformer design, that the maximum conductor temperature would probably be below 400°F.

Because of the high operating frequencies anticipated for the transformers, the conductors were assumed to be Litz wire. It was found that if no ac resistance effects occurred and if, as a result, solid conductors could be used, the reduction in transformer weight would be only six per cent. Thus, the use of Litz wire at all frequencies anticipated seems justified to eliminate unnecessary heating.

The use of multiple secondaries on transformers to eliminate the need for rectifier balancing networks was examined. While the use of multiple secondaries appears to be desirable from a circuit performance point of view, no reduction in the overall specific weight of the system is expected to result. The reason is that any weight reduction in the rectifier stacks is offset by an increase in the transformer weight. All transformers were designed to have maximum interleaving of primary and secondary layers to minimize leakage inductance.

TRANSFORMER DESIGN PROGRAM

The transformer design program is an improved version of a program previously supplied to the Air Force Aeropropulsion Laboratory.[1] The primary advantage of the program given here over the previous program is that it automatically designs a minimum weight transformer for a given set of operating conditions.

The main input parameters required in using the program given here are the following:

Output voltage

Primary line-to-line voltage

Operating frequency

Initial conductor temperature

Final conductor temperature

On time (operating period)

Single phase or three phase

Output power

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14. ABSTRACT

A transformer design computer program developed by Thermal Technology Laboratory, Inc. has been used in a mode whereby it automatically minimizes theweight of a transformer with any given set of operating parameters. Four classes of adiabatic transformers (wherein heat capacity is used to absorb heat generated) for use in pulsed power systems have been investigated in d.etail. Two of these were at power levels in the 10 to 50 MW range and the other two were in the 1 to 5 MW range. In each power range, three-phase sinusoidal and single-phase square wave transformers were analyzed in detail. The three phase transformers would be used in conjunction with alternators. The single phase units would be used in inverters.

15. SUBJECT TERMS

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Litz wire or solid wire

Sine wave or square wave operation

The program produces a complete design for the minimum weight transformer. Some of the relationships developed for use in the program include:

1. Bare Wire Diameter = 0.3255598727 * EXP (-0.116042 * Wire Gauge Number)
2. Insulated Wire Diameter = 0.32226 * EXP (-0.11316 * Wire Gauge Number)
3. Conductor Current Density = SQRT (Conductor Density * Conductor Specific Heat/Initial Conductor Resistivity Temperature Coefficient* ALOG(1 + Initial Conductor Resistivity Temperature Coefficient * (Final Conductor Temperature - Initial Conductor Temperature))/ Initial Conductor Resistivity/On Time)
4. Number of Litz Wire Strands = INT(Conductor Current/Conductor Current Density/Strand Cross-Sectional Area + 1).
5. Litz Wire Diameter = 1.17 * Insulated Strand Diameter * SORT (Number of Litz Wire Strands)

The transformer design procedure computes the design properties of a transformer subject to a given set of independent parameter values by means of an iterative convergence procedure. In general, the design procedure is as follows:

1. As an initial approximation the transformer efficiency and winding resistances are assumed to be 100% and zero respectively.
2. The input power and current are computed from the assumed efficiency and specified output power and input emf.
3. The necessary number of turns in the primary and secondary windings are computed from the specified core cross-sectional area, maximum magnetic induction density, minimum operating frequency, winding emf, and I x R drop.
4. Dependent physical dimensions are determined.
5. Winding resistances and transformer losses are computed.
6. Transformer efficiency is computed.
7. Steps (2) through (6) are repeated using the newly computed winding resistance and the geometric mean of the previously assumed efficiency and the newly computed efficiency until the difference in the efficiencies is less than a user specified maximum allowable error.
8. The remaining dependent transformer design parameters are computed.

Optimal transformer designs are arrived at through a grid search procedure which allows ranging of specified independent transformer parameters over user specified ranges (e.g., core area, conductor size, number of primary and secondary layers, etc.). In addition, bounds may be set on derived transformer parameters (e.g., minimum efficiency, maximum per unit resistance and reactance, one or more physical dimensions, etc.). For each combination of ranged parameter values (along with the fixed independent parameter values), the program computes the design properties of a transformer by means of the previously discussed iterative convergent procedure. The program keeps track of the ranged independent parameter values associated with the optimal transformer design as defined by the user specified optimization objective function. The optimal constrained and unconstrained design (if different) are recomputed and listed after completion of the grid search procedure

ALTERNATOR TRANSFORMERS

As was pointed out previously, three phase sinusoidal transformers for use in boosting the output v tage of an alternator were analyzed in detail. In a dition, single phase and polyphase sinusoidal transformers were very briefly examined. For a given set operating conditions, the optimized weights of these transformers were found to be well represented by th of a three phase trnasformer.

Over sixty point designs for optimized weight were established to enable the development of transformer algorithms valid over the complete range of system parameters for the High Power Study. Each of these designs contains detailed specifications for a transformer for operation under the given set of operating conditions.

Figures 1 through 4 contain the specific weight of some of the optimized three phase transformers th were designed in the 10 MW to 50 MW power range. Al included in these figures are curves representing th specific weight predictions from the following algorithm:

$$S_{TA}\text{ (main)} = .0505\left(\frac{\tau}{120}\right)^{0.337}\left(\frac{V_o}{100}\right)^{-.0413}$$

$$\text{X}\ \left[.693 + .307\left(\frac{P}{25}\right)^{-.79}\right]$$

$$\text{X}\ \left[.931 + .069\left(\frac{V_o}{100}\right)^{1.3}\right]$$

$$\text{X}\ \left[.242 + .758(f_a)^{-.926}\right]\ \text{lb/kW}$$

where

τ = total run time during mission in seconds

P = power level in megawatts

V_o = dc load voltage in kilovolts assuming zero conduction overlap in rectifier

f_a = alternator frequency in kHz.

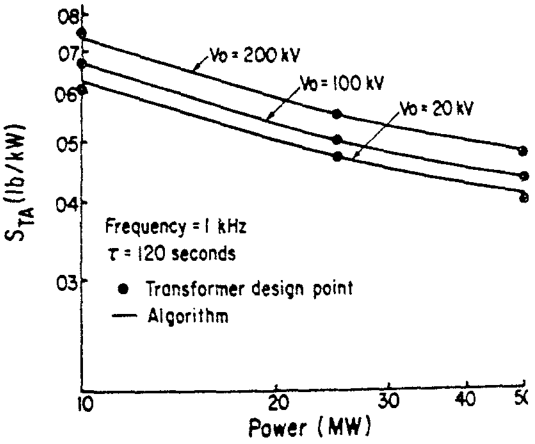

Fig. 1. Specific weight of three phase transformer as a function of operating power level.

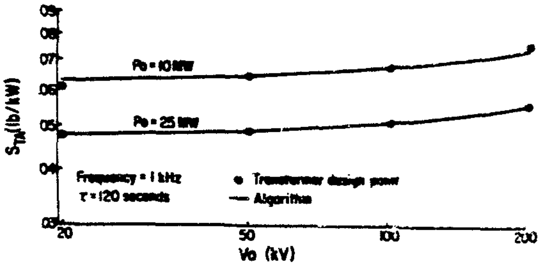

Fig. 2. Specific weight of three phase transformer as a function of dc output voltage of rectifier (conduction overlap = 0).

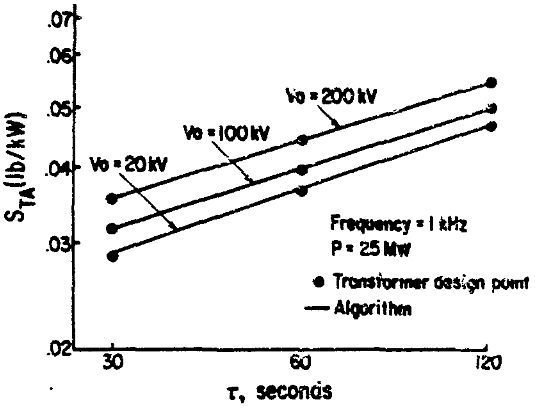

Fig. 3. Specific weight of three phase transformer as a function of total operating time during a mission.

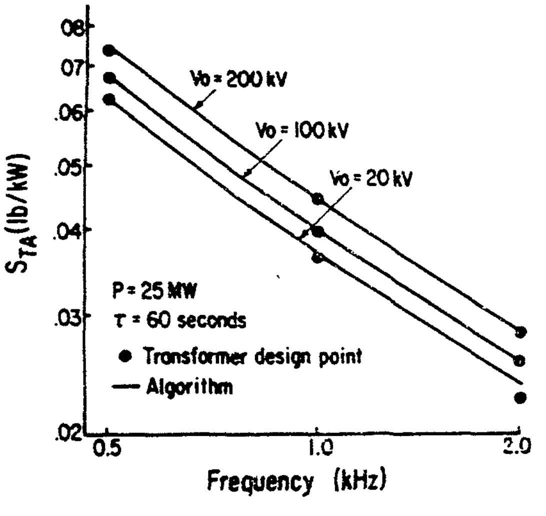

Fig. 4. Specific weight of three phase transformer as a function of frequency

This algorithm is designated S_{TA}(main) to differentiate it from S_{TA}(aux) which is given in a following paragraph. S_{TA}(main) is valid over the power range from 10 MW to 50 MW. It should be noted that the input voltage to the transformer is not a variable in the algorithm for S_{TA}(main). This is because the transformer weight was found to vary less than one per cent as the input voltage (line-to-line, rms) was varied from 1 kV to 5 kV. It should also be noted that the factor .0505 gives the specific weight of this transformer when

τ = 120 seconds

P = 25 megawatts

V_o = 100 kV

f_a = 1 kHz

The algorithm that was derived to give the three-phase-sinusoidal transformer specific weights over the power range from 1 MW to 5 MW is

$$S_{TA}(\mathrm{aux}) = .1275\left(\frac{\tau}{120}\right)^{.281}$$
$$\times\ \left[.612 + .388\left(\frac{P}{2.5}\right)^{-.985}\right]$$
$$\times\ \left[.608 + .392\left(\frac{V_o}{200}\right)^{.71}\right]$$
$$\times\ (f_a)^{-.767} \qquad \mathrm{lb/kW}$$

The factor .1275 gives the specific weight of this transformer when

τ = 120 seconds

P = 2.5 megawatts

V_o = 200 kV

f_a = 1 kHz

INVERTER TRANSFORMERS

Over sixty single phase, square wave transformers for use in series inverters at frequencies in the range from 5 kHz to 10 kHz were designed. Figures 5 through 7 contain the specific weights of some of these optimized transformers in the power range from 10 MW to 50 MW. Also included in these figures are curves representing specific weight predictions from the following algorithm:

$$S_{TI}(\mathrm{main}) = .0094\left(\frac{\tau}{120}\right)^{.302}\left(\frac{V_o}{200}\right)^{-.095}$$
$$\times\ \left[.479 + .521\left(\frac{P}{25}\right)^{-.614}\right]$$
$$\times\ \left[.880 + .120\left(\frac{V_o}{100}\right)^{1.33}\right]$$
$$\times\ \left(\frac{f_i}{100}\right)^{-.754}\left(\frac{V_{in}}{5}\right)^{-.089} \ \mathrm{lb/kW}$$

where τ, P, and V_o are as given for the alternator transformer, f_i is the inversion frequency and V_{in} is the input voltage to the transformer in kilovolts.

The algorithm that was derived to give the single-phase square-wave transformer specific weights over the power range from 1 MW to 5 MW is

$$S_{TI}(aux) = .0263\left(\frac{P}{2.5}\right)^{-.426}\left(\frac{V_o}{200}\right)^{.274}$$

$$X\left(\frac{\tau}{120}\right)^{.219}\left(\frac{f_i}{10}\right)^{-.8} \text{ lb/kW}$$

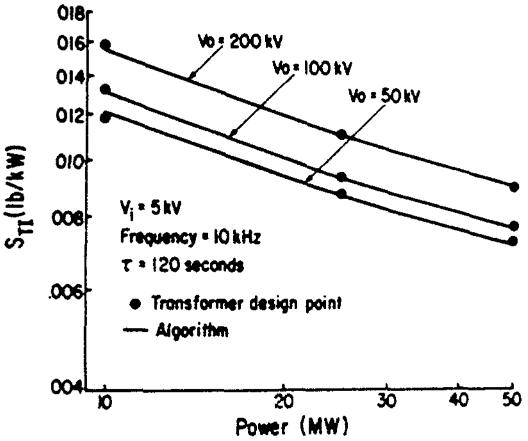

Fig. 5. Specific weight of inverter transformer as a function of operating power level.

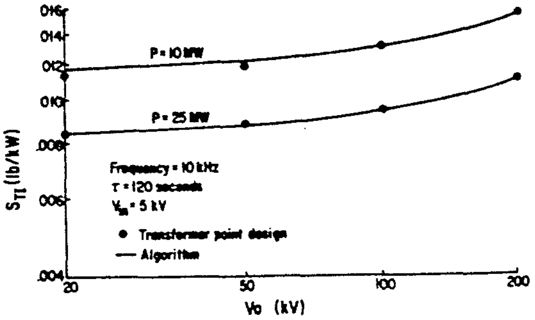

Fig. 6. Specific weight of inverter transformer as a function of dc output voltage of rectifier.

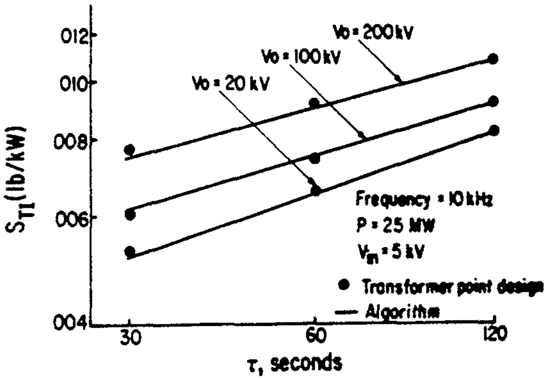

Fig. 7. Specific weight of inverter transformer as a function of total operating time during a mission.

SUMMARY

Algorithms are given for the specific weights o adiabatic transformers (wherein heat capacity is used to absorb heat generated) for use in pulsed power systems. These algorithms were derived from weight calculations made using a transformer design computer program that automatically minimizes the weight of a transformer with any given set of operating parameter Four classes of transformers were investigated in detail. In the 10 to 50 MW power range, the specific weight of a 1 kHz transformer with a maximum operatin period of 120 seconds and an output voltage of 20 kV was found to be about .05 lb/kW. At 10 kHz the specific weight of a transformer operating under similar conditions would be only .01 lb/kW. Somewhat higher specific weights were calculated for transformers operating in the 1 to 5 MW power range.

REFERENCE

1. R. Haumesser, D. Lockwood, R. McNall, Jr., and J. Welsh, "Final Technical Report on Development of Lightweight Transformers for Airborne High Power Supplies, Volume II. Computer Users Manual;" AFAPL-TR-75-15.