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Optimum Transformer Design for a Pulsed Power System

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

ORNL/TM-10620
Dist. Category UC-20

Fusion Energy Division

OPTIMUM TRANSFORMER DESIGN FOR A PULSED POWER SYSTEM

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Date published: November 1987

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ABSTRACT

Electromagnetic forces resulting from peak pulsed current require special design consideration to prevent failure of the coils of the transformer. Procedures for interleaving transformer windings to reduce both electromagnetic short-circuit forces and reactive voltage drop while reducing procurement costs are described. The basics of transformer design principles and cost trade-offs are included to enhance understanding of the interleaving procedures.

1. INTRODUCTION

Repetitive pulsing of a power supply permits heat from the losses to average itself over the length of the duty cycle. This is not true, however, in the case of the electromagnetic forces. Transformer windings of a pulsed supply must be designed to withstand the repeated shock load of the electromagnetic forces that result from the peak pulsed current. Inadequate force containment is often a cause of transformer coil failure.

This report describes procedures that lower transformer procurement costs while reducing force stress in the windings. The basics of transformer design principles and cost trade-offs are included to enhance understanding of the procedures.

The rated megavolt-ampere (MVA) capacity and the cost of a transformer are determined by the following characteristics: (1) the no-load output voltage, (2) the thermal rating, and (3) the ratio of the pulsed current to the equivalent steady-state current. The "times normal" ratios (discussed in Sect. 2.2.1) of the pulse current and the fault current are indicators of the capability of the transformer windings to withstand electromagnetic force. A higher times normal current achieves lower costs because of a lower rated capacity, but it also results in higher winding stress during the pulse. Because of short duty cycles, pulsed transformers commonly do not reach their thermal limit. The electromagnetic forces of a fault current therefore become the new criteria for establishing cost and design characteristics.

As the times normal current is increased to reach a permitted force level, the voltage drop is correspondingly increased. Voltage drop is objectionable because it represents wasted transformer capacity and also results in a higher demand level from the utility grid or the stored-energy system. It is possible to increase the force limit and decrease the voltage drop simultaneously through the use of interleaving procedures.

Various methods of interleaving and their respective applications are described here. Appendixes A and B give comparative examples to illustrate the benefits of interleaving.

2. TRANSFORMER COST ELEMENTS

The MVA level at which a transformer can operate continuously is a basis for determining the procurement cost of the transformer. Three principal areas contribute to the cost of a transformer with a specified pulsed-output requirement and duty cycle:

1. the thermal requirement while pulse power is being delivered,
2. the capability of the windings to withstand the peak electromagnetic forces of fault current, and
3. the degree of regulation and resultant voltage drop (see Sect. 2.3).

The duty cycle factor determines whether forces or temperature becomes the limiting factor (see Sects. 2.1 and 2.2).

2.1 THERMAL REQUIREMENTS

Heat produced by the pulse current can average itself over the time between pulses. This capability reduces the MVA requirement by an rms duty cycle factor equal to the square root of the average duty cycle. Because of short duty cycles, pulsed transformers frequently do not reach their thermal limit. A shorter duty cycle permits a higher application of pulse MVA to a given level of rated MVA without overheating.

2.2 ELECTROMAGNETIC FORCES

When the thermal limit does not prevail, electromagnetic fault force becomes the new limit that defines the design. It can therefore be stated that the strength, size, steady-state MVA, and cost of a pulsed transformer are often dictated by its peak level of electromagnetic stress.

Force is produced by a current-carrying conductor located perpendicular to and inside a magnetic field (see Appendix B). This force is proportional to the square of the current in the windings. The high current of a secondary fault produces forces that require mechanical design considerations for the core and coil assembly.

2.2.1 Times Normal Current

The ratio of fault current to the equivalent steady-state current of the power supply is referred to as the "times normal current." This ratio is an indicator of the short-circuit force level that must be contained. The American National Standards Institute (ANSI C57.12.00 and C57.12.90) requires that all power transformers be designed to withstand the forces that would result from a "bolted" fault. Because of the repetitive nature of a duty cycle, the pulse current should be set to a level that is substantially less than the times normal level of fault current.

A pulse transformer cannot fully benefit from its smaller value of required thermal kVA, because it must withstand the electromagnetic force that occurs at pulse MVA. For example, the conductor size of the windings can be reduced thermally but only to the point at which it has mechanical strength to contain the fault forces that will exist at the percent impedance and peak MVA of the pulse condition.

2.2.2 The Interleaving Procedure

The technique of interleaving (see Fig. 1) divides the ampere turns of the winding into separate groups. Multiple interleavings of the primary and secondary coils can be used and/or two coils per phase rather than one. Each interleaving reduces the percent reactance and the force stress by half, permitting a higher times normal pulse ratio and thus lower costs (see Appendixes A and B).

Interleaving has greater cost benefits for a liquid-filled transformer than for a dry type. Dry-type designs suffer a penalty in this regard because they require a greater number of insulating barriers between interleaved groups and this results in higher costs.

Short duty cycles have the opportunity for the greatest cost improvement. A recent transformer design made for the Lawrence Livermore National Laboratory required a peak MVA of 25.1 at 1.3% duty cycle and an impedance of 7.6%. The equivalent steady-state thermal rating was 3 MVA at 0.9% impedance. Under short-circuit conditions the transformer would experience 110 times normal current. Normally, this would be considered prohibitive because it is far greater than the 25 times normal limit required by ANSI. However, cost effectiveness was obtained by subdividing the design into two coils per phase, each wound in a low-high-low configuration. The force stress in the windings of this design was reduced to one-fourth that of the original design. In effect, this design had an unheard-of force capability with only a moderate increase in conductor cross sections.

2.3 REGULATION (VOLTAGE DROP AT FULL LOAD)

Voltage drop is equal to the pulse current multiplied by the total impedance of the system and the transformer. It is desirable to reduce the voltage drop to minimize the rating of the equipment that must be purchased. Because the no-load

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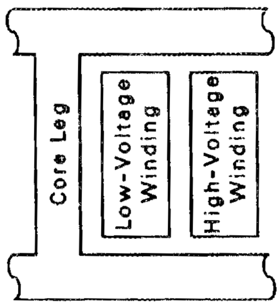
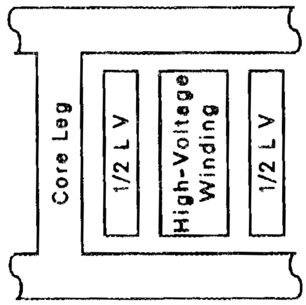
	Standard Arrangement	Interleaved Arrangement
Coil Configuration		
Number of low-high groups	1	2
Force per group	1 per unit	$(0.5)^2 = 0.25$ per unit
Conductor area per group	1 per unit	0.5 per unit
Conductor stress (psi)	1 per unit	0.25/0.5 = 0.5 per unit
Reactance	1 per unit	0.5 per unit
Conclusions	For the same number of ampere turns, interleaving reduces the pounds per square inch of electromagnetic stress in the conductor and the reactance of the transformer by one-half. This allows a reduction of half the required MVA capacity (for a given level of pulse MVA) without exceeding the permissible conductor stress.	

Fig. 1. Interleaving relations.

voltage is a determinant of the MVA rating but cannot be fully used at full load, its excess value represents wasted MVA capacity. Voltage drop is also objectionable because it increases MVA demand from the power grid or source of stored energy.

3. DESIGN TRADE-OFFS AND OPTIMIZING PROCEDURES

3.1 BASIC TRANSFORMER DESIGN RELATIONS

A brief introduction to the basic considerations of transformer design is presented to enhance understanding of the interleaving procedure. Some of the major considerations follow; also, see Appendixes A and B.

$$\%IX \propto \frac{\text{turns}^2}{\text{coil height}} , \tag{1}$$

$$\%IX \propto \frac{1}{\text{number of turn groups}} , \tag{2}$$

$$\text{Force} \propto \left(\frac{\text{ampere turns}}{\%IZ}\right)^2 , \tag{3}$$

$$\%IZ = (\%IX^2 + \%IR^2)^{0.5} , \tag{4}$$

$$\%IR \propto \text{number of turns} , \tag{5}$$

where

%IX = percent reactance,
%IR = percent resistance,
%IZ = percent impedance.

3.2 SIZING A PULSED TRANSFORMER

3.2.1 Usual Procedure

The usual procedure for sizing a pulsed transformer is as follows:

1. Determine the full-load current, voltage, and approximate MVA.
2. Assume a standard %IZ for the transformer at the MVA determined in item 1.
3. Calculate the combined impedances for the transformer and the power grid.
4. Determine the voltage drop for the combined impedances, and add it to the required full-load voltage determined in item 1.
5. Recalculate the MVA rating of the transformer, using the no-load voltage of item 4 rather than the full-load voltage of item 1.

3.2.2 Proposed Procedure

The procedure proposed for sizing a pulsed transformer is as follows:

1. Perform the same steps described in Sect. 3.2.1 but choose a lower impedance for the transformer. Generally speaking, the lower the transformer impedance, the greater is the potential for reduced costs.
2. The impedance chosen in item 1 can be no lower than that permitted by the short-circuit forces. Appropriately interleave the ampere turns into separate groups to the point at which the short-circuit forces are met.

3.3 METHODS OF INTERLEAVING

3.3.1 Interleaving the Primary and Secondary Windings

The most common configuration used for interleaving is known as low-high-low. Figure 1 illustrates and functionally compares a standard noninterleaved arrangement with a low-high-low arrangement. Note that both the mechanical force stress in the windings and the percent reactance of the transformer are cut in half.

3.3.2 Use of Two Coils per Phase

ANSI C34.2-196B, Circuit 31, is frequently used for 12-phase operation. To obtain the required 30° shift, Circuit 31 uses two secondaries, one wye connected and one delta connected. The usual practice is to orient the two secondaries axially, one over the other, on each leg of a three-phase core.

Substitution of three two-coil, single-phase assemblies (see Fig. 2) for this standard arrangement gains the following results:

1. An additional means of interleaving is accomplished. The reactance and forces are therefore reduced to one-half of the original, the same reduction produced by low-high-low interleaving.
2. The two bridges are completely decoupled, which is desirable.
3. The flux flow in each core is single phase, permitting operation at a flux density that is approximately 7% higher (resulting in a smaller core).

Figure 3 compares the single-coil and the two-coil concepts.

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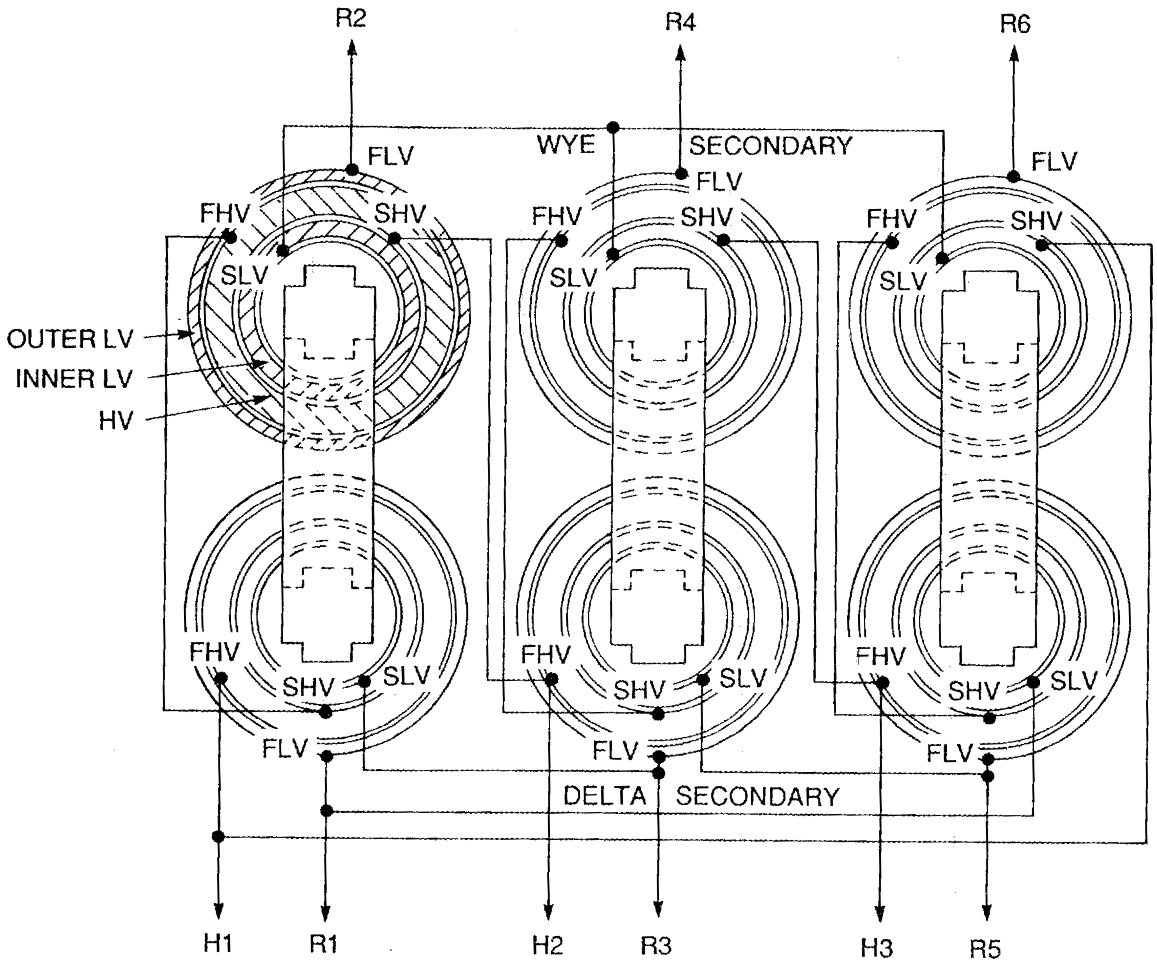

Fig. 2. Top view of 12-pulse core and coil assembly. (SLV represents the start lead of low-voltage winding; FLV, the finish lead of low-voltage winding; SHV, the start lead of high-voltage winding; and FHV, the finish lead of high-voltage winding.)

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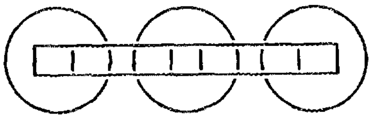
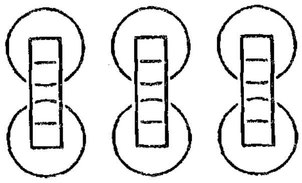
	One Three-Phase Assembly	Three Single-Phase Assemblies
Coil Configuration	Delta and Wye Secondaries oriented vertically to each other on each of the three coil legs 	Delta Secondaries  Wye Secondaries
Number of low-high groups	1	2
Force per group	1 per unit	0.25 per unit
Conductor area per group	1 per unit	0.25 per unit
Conductor stress (psi)	1 per unit	0.25/0.5 = 0.5 per unit
Reactance	1 per unit	0.5 per unit
Conclusions	The reduced force and reactance of three single-phase assemblies has a net effect of lower costs.	

Fig. 3. Twelve-phase configurations for ANSI Circuit 31.

4. CONCLUSIONS

The concept of interleaving, as applied to pulsed transformer design, can provide substantial cost savings.

Pulsed transformers frequently do not reach their thermal limit. Consequently, electromagnetic forces become the limiting factor for defining the design requirements.

By an interleaving of the transformer windings, both electromagnetic short-circuit forces and reactive voltage drop can be significantly reduced, and purchase of a transformer with lower capacity is therefore permitted.

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R. Feinberg, *Modern Transformer Practice*, The Macmillan Press Ltd., London, 1979.

APPENDIX A

TRANSFORMER REACTANCE

The leakage flux between the primary and the secondary windings of a transformer is the part of the magnetic flux that does not link both of the windings. The leakage flux determines the reactance and is usually the predominant component of transformer impedance.

DETERMINATION OF THE PERCENT LEAKAGE REACTANCE

The percent leakage reactance is determined by[1]

$$\%\mathrm{IX} = \frac{2.01afin^2}{eh \times 10^5} ,$$

where

$\%\mathrm{IX}$ = transformer percent reactance between the reference winding and the winding that shares its mutual flux,
a = effective leakage area (in.^{2}),
f = frequency (Hz),
i = rms rated current in the reference winding (A),
n = number of turns in the reference winding,
e = rms rated volts of the reference winding,
h = effective length of the leakage path (in.).

ILLUSTRATION OF REDUCED REACTANCE OF INTERLEAVING

Reactance is a function of the number of turns squared.

Referring to Fig. 1 and to the preceding discussion, we find that %IX for low-high is

$$\%\mathrm{IX(LH)} = Kn^2 ,$$

where K is a constant of proportionality.

The low-high-low grouping can be visualized as being two separate transformers, each containing half of the low-voltage winding and half of the high-voltage winding:

$$\%\mathrm{IX/group} = K(0.5n)^2 .$$

The total %IX is the sum of both groups:

$$\text{Total \%IX(LHL)} = 2 \text{ groups} \times K(0.5n)^2$$
$$= 0.5Kn^2 \ .$$

Therefore,

$$\text{\%IX(LHL)} = \frac{\text{\%IX(LH)}}{2} \ .$$

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1. D. G. Fink and J. M. Carroll, *Standard Handbook for Electrical Engineers*, 10th ed., Sect. 11-43, McGraw-Hill, New York, 1968.

APPENDIX B

TRANSFORMER ELECTROMAGNETIC FORCE

The interaction of the main leakage flux and the winding current results in forces that tend to move the outer winding radially outward and the inner winding radially inward. The forces are proportional to the square of the current in the windings. At full load these forces are small, but under short-circuit conditions very large forces are applied to the core and coil clamping structure and to the conductor itself.

The radial force in a two-winding transformer is[1]

$$F = \frac{2(3.141)^2(In)^2 d}{h \times 10^7} ,$$

where

F = force between windings (N),
I = the winding current (A),
n = the number of turns,
d = the mean diameter of the windings (m),
h = the winding axial length (m).

Fault current during a secondary short circuit is limited principally by the transformer impedance (Z). It can therefore be approximated that the electromagnetic force between windings during a short circuit is proportional to $(In/Z)^2$.

An axial component of the radial force exists because the ampere turns of each winding are not exactly balanced. End clamps, windings, and insulation must be designed to withstand these forces.

ILLUSTRATION OF REDUCED FORCE STRESS THROUGH INTERLEAVING

Electromagnetic short-circuit forces between the transformer windings are given by

$$F \propto \left(\frac{\text{ampere turns}}{\text{impedance}}\right)^2 .$$

If either the amperes per winding or turns per winding are halved by an interleaving procedure, the force stress is reduced by $(1/2)^2$, or it becomes only one-fourth of the original force stress:

$$\text{Winding stress} = \frac{\text{force}}{\text{winding area}} ,$$

where winding stress is in pounds per square inch (psi).

The winding area per interleaved group is also halved by the interleaving procedure:

$$\begin{aligned}\text{Interleaved winding stress} &= 100\%\ \text{psi} \times \frac{25\%\ \text{force}}{50\%\ \text{area}} \\ &= 50\%\ \text{psi} .\end{aligned}$$

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