Transformer Loss Evaluation Leads To Lower Costs

Optimization of design considers cost of materials, rate structure, electrical losses and user's rate of return

The cost of energy losses dissipated in a transformer over its life can be as high as five times its initial cost. Energy costs are expected to continue escalating at a much faster rate than the cost of material or labor. For this reason, a growing number of buyers are not only giving consideration to, but also quantifying and evaluating, the efficiency of electrical equipment. Transformer efficiency is no exception. The purchase decision is based not just on the initial purchase price but also on the cost of installation, maintenance and the energy cost over the life of the unit.

This article addresses the various types of transformer losses, the design optimization method commonly used by manufacturers for obtaining the minimum cost transformer, considering material and operating costs, and the impact of loss evaluation on transformer design.

What information should be included in the specifications for power transformers with regard to loss evaluation? Merely mentioning that the transformer will be evaluated based on efficiency is not enough. In many cases, the electrical consultant does not spell out the evaluation method for fear of divulging proprietary- information. This lack of communication is detrimental to the user in that it prevents the manufacturer from optimizing his design for the specific user application. This in effect defeats the purpose of loss evaluation. A complete specification for a loss evaluated power transformer should include:

- Evaluated cost per kW of losses.
- Percent of transformer rated load for the evaluation.

Types Of Losses

Transformer losses fall into two categories — no-load losses and load losses. No-load losses consist of all losses that arise from energizing the primary winding at rated voltage, with the secondary winding open circuited. These include losses due to eddy currents, magnetic hysteresis, winding resistance to exciting current, and the losses of dielectric materials. Most such losses occur because of iron in the transformer core, thus they are commonly called "iron loss." The no-load losses are the same regardless of load as shown in Fig. 1.

Load losses are those that vary with load current. They are caused by I^2R loss in the transformer windings, and eddy currents induced by stray fluxes within the transformer structure. Most of these losses occur in the windings, so they are commonly known as "copper loss"; however, this term is somewhat ambiguous because aluminum is commonly used for transformer windings. These losses vary as the square of the load current as shown in Fig. 1.

Because no-load losses are not load dependent, their value expressed as a percentage of transformer load decreases as the load increases. Load losses, however, are proportional to current squared; their value as a percentage of transformer load increases as load increases. The total losses (TL) at any load level (Y) that the transformer experiences can be obtained from the rated no-load (NL_R) and load losses (LL_R) as follows:

$$TL_Y = NL_R + (LL_R)(Y^2)$$

TL_Y = Total losses in watts at load Y

NL_R = No load losses in watts at rated voltage

LL_R = Load losses in watts at rated load

Y = Percent of transformer rated load expressed as a decimal

It is interesting to note that the total transformer losses as a fraction or percent of kVA load will always be the minimum when the no-load losses are equal to the load losses. Accordingly, transformer efficiency is maximum at a certain loading where the load losses are equal to the no-load losses. This relationship between load level and efficiency is shown in Fig. 2.

Transformer Design Optimization

Design optimization is not new to transformer manufacturers. What is new is the objective of the optimization process. Before the transformer loss evaluation era, the manufacturer was mainly concerned with his costs just as the user was mainly concerned with the initial price. The objective of the optimization process was to minimize the cost function. Computer programs modeling the cost of a transformer and taking into account the costs of the conductor material and magnetic steel, as well as the cost of the tank, cooling tubes, insulation fluid and other items,

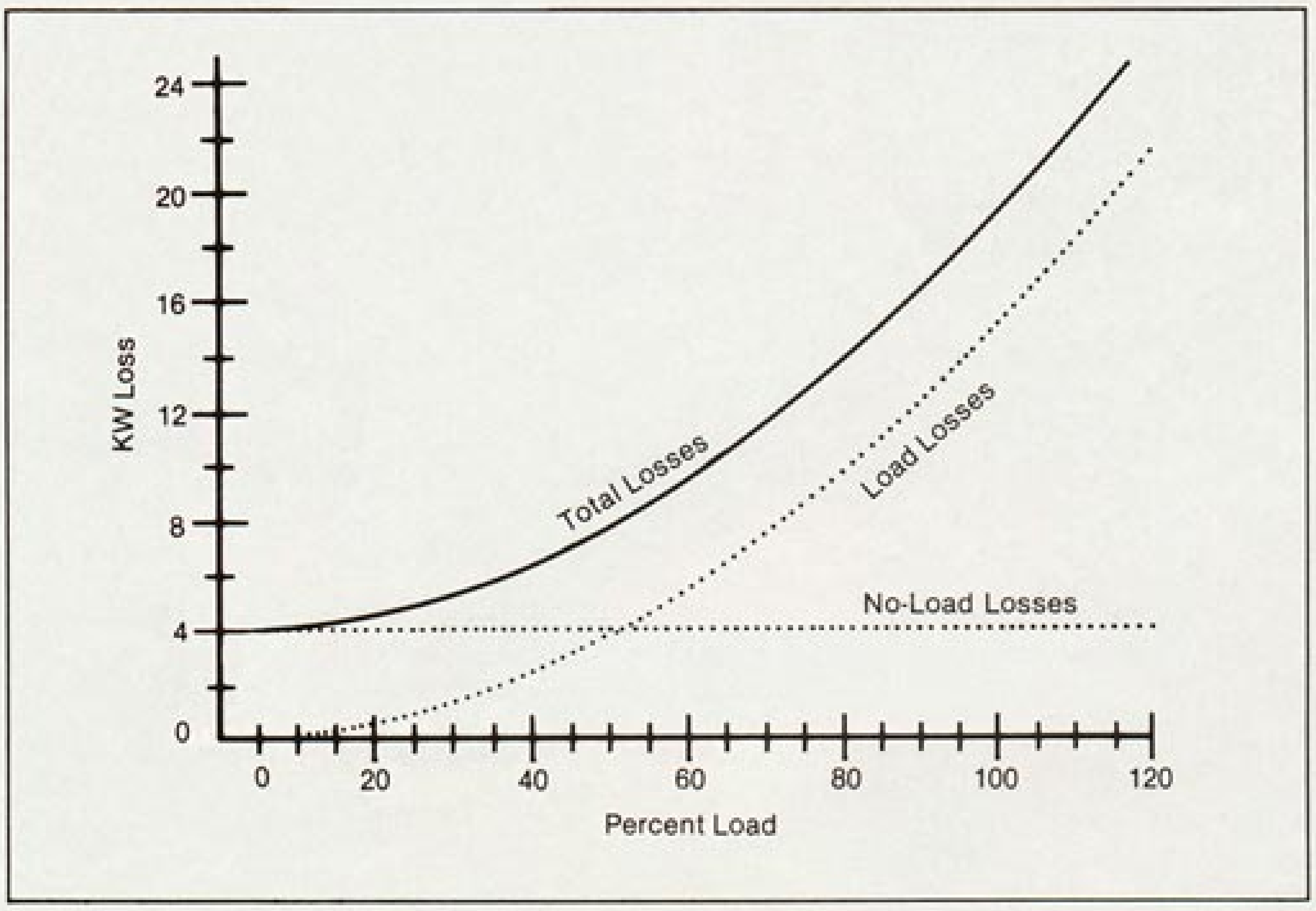

Fig. 1. Losses as a function of load of a typical 1500 kVA transformer.

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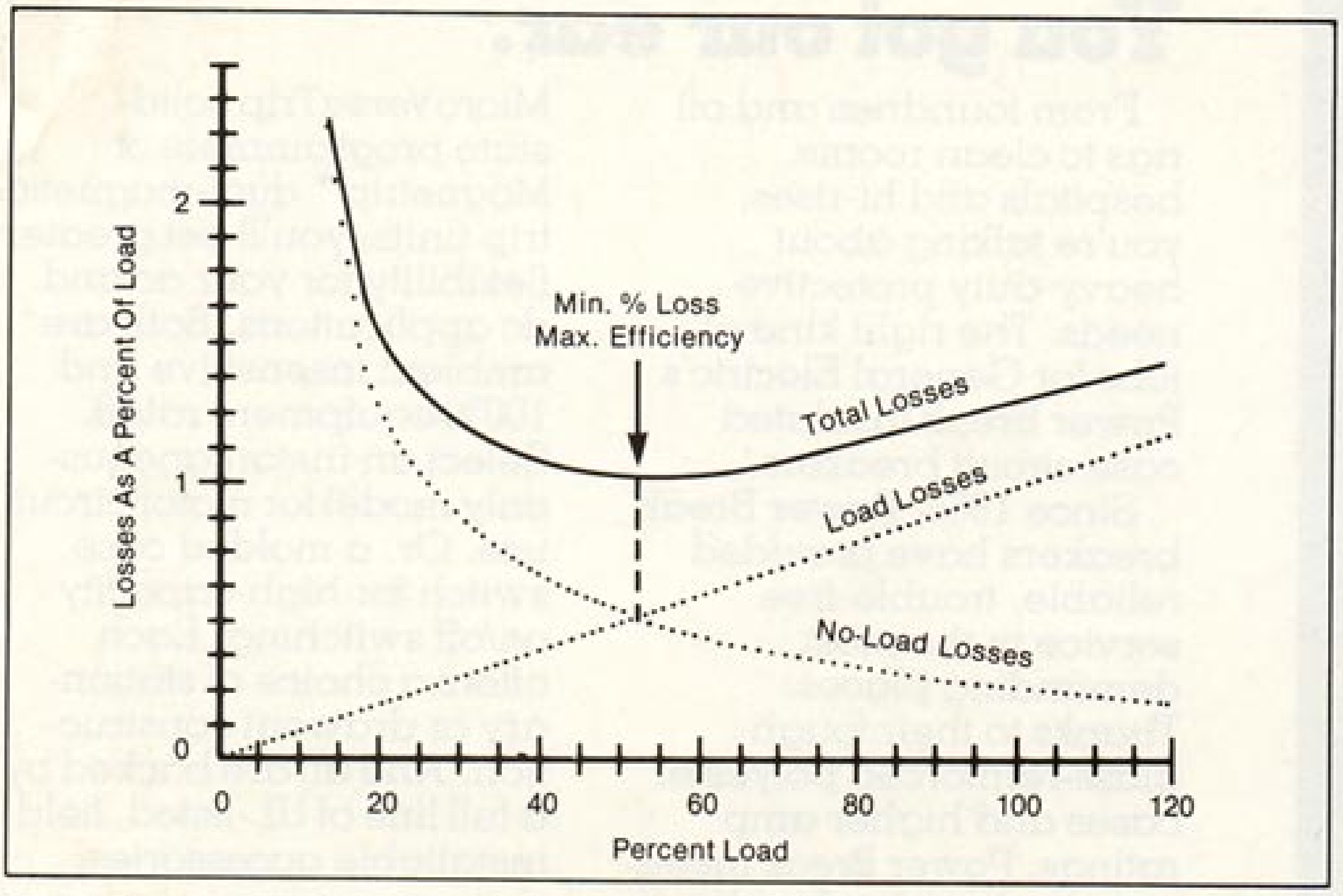

Fig. 2. Relationship between no-load and load losses, percent load and efficiency for a typical 1500 kVA transformer.

can be very sophisticated. For the sake of illustration, however, consider a simple transformer cost model as follows:

Cost = F1 x MS + F2 x CO

F1, F2 = Cost factors including cost of material as well as labor in \$ per pound

MS = Magnetic steel, core material in pounds

CO = Conductor material, copper or aluminum in pounds

Within some design limits, the manufacturer could trade off one material for another in order to reduce his cost but still produce the same functional transformer. For example, more core material could be used to carry larger amounts of magnetic flux and reduce the number of turns per leg, thus reducing the amount of conducting material. Depending on the relative costs of these two materials, this material trade off might result in a lower transformer cost. Today, with the high cost of energy, the electrical consultant's evaluation is based on transformer efficiency as well as initial purchase price. A common consultant's evaluation model is:

$$EP = IP + (P1 \times NL_R) + (P1 \times LL_R \times Y^2)$$

EP = Evaluated price

IP = Initial price (transformer price to user)

P1 = Unit cost of losses (\$/kW value representing the capitalized cost of energy saved over some relevant economic period)

NL_R = No-load losses at rated voltage in kW

LL_R = Load losses at rated load-in kW

Y = Percent of rated load expressed as a decimal

Manufacturers have adopted the user evaluation model to optimize their design. The initial price of the transformer is related to the cost of the transformer to the manufacturer as follows. Note that K is a multiplicative factor covering overhead, research and development, and profit above material and labor costs.

IP = K x Cost (of transformer)

Replacing IP for K x Cost in the equation for solving EP (evaluated price):

$$EP = K \times Cost + (P1 \times NL_R + P1 \times LL_R \times Y^2)$$

which can be summarized as:

EP = Initial Price + Capitalized cost of losses.

If the user were designing his own equipment, he would minimize the above evaluated price model in order to obtain the most cost effective transformer for his application. This optimization can be accomplished by the manufacturer if the missing information is provided by the electrical consultant who knows his client's loads and electrical system characteristics.

All the parameters except for P1 and Y in the evaluated price model equation are available to and controllable by the manufacturer. The evaluation price for the losses (P1) as well as the percent expected load (Y) are determined by the user's application. By providing this information to the manufacturer, the electrical consultant in effect forces the bidder to minimize the evaluated price subject to the consultant's own determination of the cost of losses. The result is that the manufacturer custom designs a transformer that is the most economical for the application.

If the consultant is evaluating the transformer losses and does not communicate his cost of losses (P1 and Y), the manufacturer will provide either his standard design or make a guess at the cost of losses. In either case, the consultant is not allowing manufacturers to optimize their design.

For illustration purposes consider a manufacturer that has three available designs priced as shown in Fig. 3.

Consider further a user whose cost of losses for evaluation purposes is \$1000/kW over the economic life of the transformer. Derivation of the \$/kW figure will be discussed later in the article. During the first few years of operation, the transformer is expected to operate at about 75% of rated load. The user, therefore, elected to evaluate the transformer at 75% load using the evaluated price equation. The evaluated prices for the above three designs are shown in Fig. 4.

Design	No Load Losses-Watts	Total Losses-Watts	Base Price	High Efficiency Premium	Initial Price
A	4000	19,000	\$12,500	—	\$12,500
B	3000	17,000	12,500	600	13,100
C	3000	15,500	12,500	2,900	15,400

Fig. 3. Hypothetical design and cost parameters for three different transformers.

Design	Initial Price	Capitalized Cost of Losses	Evaluated Price
A	\$12,500	\$12,438	24,938
B	13,100	10,875	23,975
C	15,400	10,031	25,431

Fig. 4. Evaluated prices for the three different transformers represented in Fig. 3.

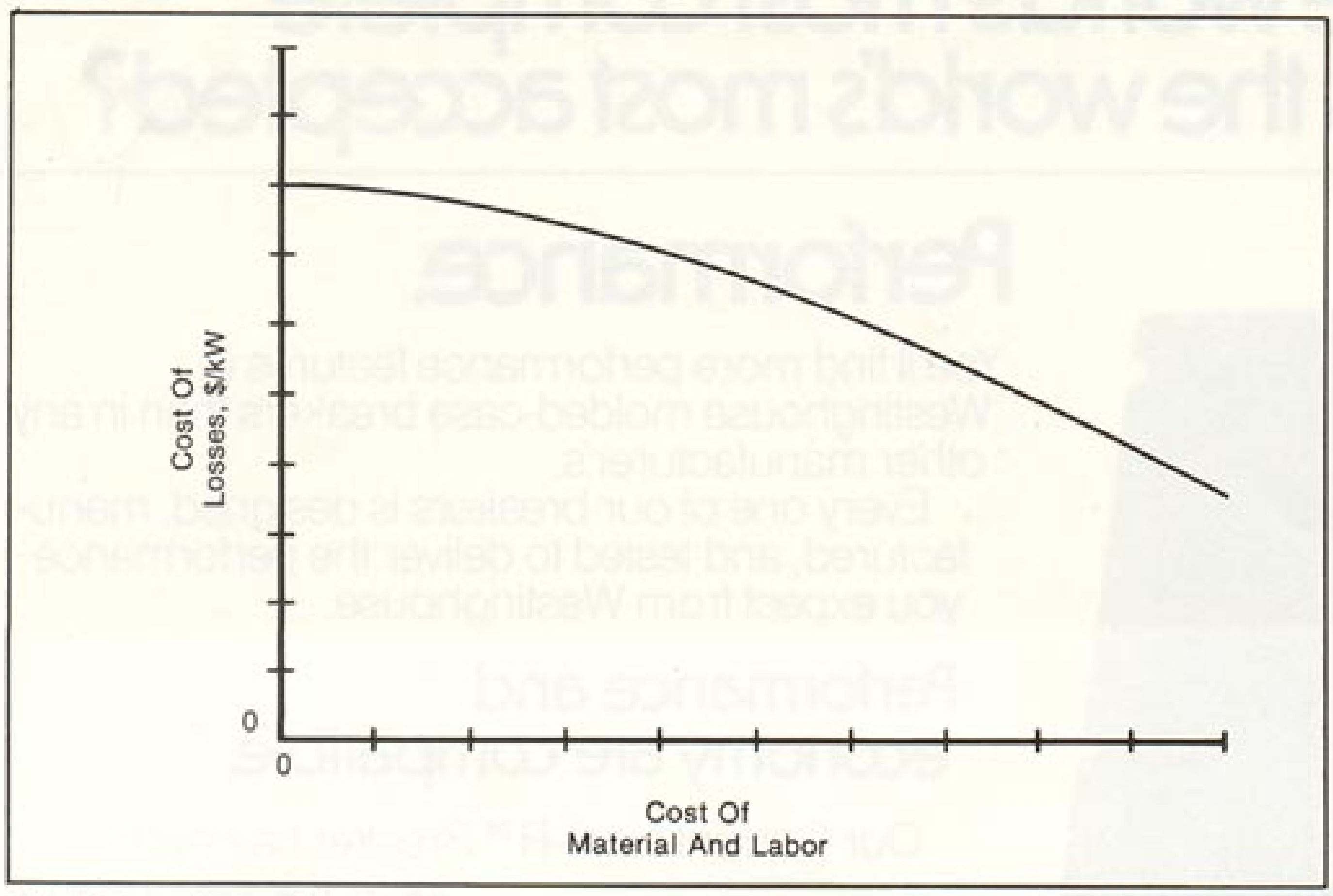

Fig 5. Cost of material of an optimized transformer compared with the cost per kW of losses.

For this application, the B design is the most cost effective. In practice, the manufacturer has virtually an unlimited number of designs available for the same functional transformer. Not knowing the user's evaluation, the probability that the manufacturer will offer design B is very slim. Thus both parties to the transaction end up losing. This example illustrates another point. The often heard request to "quote the lowest losses" is meaningless unless the user specifies the evaluation criteria. Here design C has the lowest losses, but it is definitely not the best for the application at hand.

Effect Of Loss Evaluation On Design

Depending on the values of the loss evaluation parameters, P1 and Y, the amount of electrical steel, winding conductor material, insulation, core parts, tank size and cooling capacity will all be affected. An optimized design will generally have more conductive material as well as more magnetic steel in order to be more efficient. The initial price of an optimized design will therefore be higher and its losses will be lower than a non-optimized standard loss design. Figure 5 shows the relationship between the amount of active material (core and windings) in an optimized transformer and the unit cost of losses ($/kW) in the optimization process.

The evaluated price to the user is the sum of the initial price and the capitalized cost of losses. The capitalized cost of losses decreases at a much faster rate than the increase in the initial price, the latter being the result of the additional material used.

The initial price for an optimized design will generally be higher than a standard unit; however, the lower operating costs will more than make up for the premium price. In few years of operation, full payback of the premium is realized due to the lower cost of ownership and a net return on this additional investment starts to accumulate.

Impedance

Another design parameter, commonly assumed to be affected by the transformer efficiency, is the impedance. This is a misconception because the resistance component (which directly affects losses) of a transformer's impedance is insignificant. Transformer impedance can be specified independently of the transformer losses or efficiency. Consider the classical definition of impedance Z:

$$Z = \sqrt{R^2 - X^2}$$

Strictly speaking, changing R, the resistive component of the impedance, will affect Z. However, this impact is easily controllable by the designer. The reactance X is a function of the geometry of the magnetic flux path linking the primary and secondary winding. The designer has considerable leverage and can modify this path to increase or decrease X. Furthermore, because the values of X are substantially larger than those of R (the X/R ratio for small power transformers is generally between 6:1 and 12:1), very little change in X is required to compensate for a change in R in the above formula. For a typical power center transformer, $Z = 5.75\%$ and $X/R = 6.6$. Then $R = 0.86\%$ and $X = 5.69\%$. For example, if it were possible to eliminate the resistive component altogether, the impedance Z will be equal to X or $Z = 5.69\%$, a change of only 1.04% as follows:

$$\frac{5.75 - 5.69}{5.75} = 1.04\%$$

The variation is well within the ANSI tolerance of ±7.5% of nominal impedance.

Although not rigorous, this analysis de-mystifies the relationship between the losses and the impedance. From a practical point of view, both can be independently specified.

Derivation Of Loss Evaluation

Transformer loss evaluation is basically simple. The evaluation methods fall into two general categories — payback methods and discounted cash flow methods. The main drawback of the payback methods is that they do not take into account the time value of money. On the other hand they are very simple to use. Payback is defined as the ratio of an incremental investment to an incremental annual savings, and it represents a period of time (years) required to recover the incremental investment.

The cost of losses (P1) for the evaluation using the gross payback method (the method that is simple to use) can be derived as follows:

$$P1 = C \times H \times N$$

Where:

C = Cost of energy in $/kWH
H = Hours per year the transformer is energized
N = Number of years to payback

The following method, adapted from various discounted cash flow evaluations, is in a form that will allow the calculation of P1, the equivalent capital investment per kW of losses saved. This equation takes into account the time value of money. Hence, the calculation results in a realistic evaluation of cost of transformer losses.

$$P1 = C \times H \times \frac{(1 + i)^n - 1}{i\,(1 + i)^n}$$

Where:

C and H are as described for the payback method.

n = Last period in which cash flow occurs or economic life of equipment in years.
i = Effective required rate of return.

The effective rate of return, i, is obtained as follows:

$$i = \frac{100 + r_2}{100 + r_1} - 100$$

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- *Indoor Medium Voltage Current Limiting Fuses.* Since there is no industry standard for dimensions, cross-referencing of these fuses is often difficult. There are two basic and common types. The "E rated" fuse is intended for line-side application of 2.4 kV through 34.5 kV power transformers in switchgear. The "R rated" fuse is for use in 2.4, 4.8 and 7.2 kV fusible combination motor starters.

There is no ampere rating for "E rated" fuses as such, but rather an "E" rating. The E number means that, for 100 E or less, the fuse must open within 5 minutes on 200% to 240% of the E rating. Over 100 E, the fuse must open within 10 minutes on 220% to 264% of the E rating. With this information and applicable catalog data such as time/current curves, the proper fuse is selected. At least one manufacturer provides selectivity tables between E rated fuses and low-voltage fuses on the secondary of the transformer.

The R rated fuses are selected with the knowledge that they open only on short circuits with the overload relays handling overloads. Fuses are chosen with melting time/current characteristics which cross the overload relay curves at 6 to 8 times the full load motor current. These fuses are normally selected by the controller manufacturer.

- *Other Unclassified Low Voltage Fuses.* There are certain fusible protection devices that are not classified by UL. For the most part, these devices are made for use in various equipment. Electrical consultants will seldom specify these fuses but consultants should be aware of them for the occasions when these fuses are used. These protection devices include cable protectors, fusible circuit breaker current limiters and semiconductor fuses.

- *Fuses For Supplementary Overcurrent Protection.* These fuses are covered by UL standard 198G and consist of fuses termed by UL as miniature, micro and miscellaneous. These fuses will not fit fuseholders intended for classes CC, H, J, K, L, R or T. They are normally used within equipment and are not used on branch or feeder circuits. The following items are subordinate to this category:

—*Miniature Fuses.* At times referred to as "glass fuses", since their tubes are often made of glass, they are of the type seen in automobiles and electronic equipment. Their dimensions are from 0.197 inches to 0.281 inches in diameter and from 0.787 inches to 1.4375 inches in length, although the most common size is ¼ inches by 1¼ inches. Their use is generally selected by the designer of the equipment in which the fuse will be used. There is a very wide proliferation of both "slow-blow" (time delay) and "fast-acting" (non-time delay) types.

—*Micro Fuses.* These are used in electronic circuits where extreme miniaturization is required. They have many shapes and their ratings do not exceed either 10 A or 125 V. The interrupting rating is not over 50 A.

—*Miscellaneous fuses.* Often termed in the fuse industry "midget" fuses, these protection devices are cylindrical and measure at least 13/32 inches in diameter and 1½ inches in length. Even though these fuses may be of the same dimensions, they may be rated for any voltage from 125 V up to 600 V and up to 30 A. The most common types include 250 V non-time delay and 250 V with time delay of 12 seconds at 200% (except 5 seconds for a fuse rated 3 A or less). (Some manufacturers' time delay fuses may have a lesser voltage rating for certain ampere ratings.) There are also fuses with the same time delay at 500 V and non-time delay at 600 V. Short circuit ratings may be 10 kA, 50 kA or 100 kA.

Summary

To provide effective protection for a client's electrical system, a thorough knowledge of circuit protection devices is needed. Fuses serve an important role in this area. As there are many types, it is important to be knowledgeable about how each operates. Ratings are not the only criteria. Recognition should be given to future electrical system maintenance by specifying fuses that will minimize possible replacement of a spent fuse by the wrong type. ■

Editor's Note. This is the first of a two-part article on fuses. A future issue of Electrical Consultant *will carry the second article which will concentrate on fuse terminology, performance, electrical characteristics and application criteria.*

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Transformer Loss

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Where:

r_2 = Required rate of return (in percent per year).

r_1 = Escalation of electrical power cost (in percent per year).

This discounted cash flow method is a powerful analytical tool used to calculate the capitalized cost of energy dissipated as losses over the economic life of the transformer. To be applied properly it is important to be aware of implied assumptions of this closed form equation:

- The kWh saved is assumed to be uniform over the economic life of the equipment.
- It ignores the carrying charges of the incremental investment.
- It ignores the tax savings due to depreciation as well as tax credit on the incremental investment.

On the other hand this DCF method has the following advantages:

- It takes into account the time value of money.
- It takes into account the required corporate rate of return as well as escalation of energy costs.
- It allows an economic evaluation using a relatively simple and concise formula.

In summary, more electrical consultants today are basing their specifying decisions not only on purchase price, but also on cost of installation, maintenance and cost of energy over the life of the equipment. The user's loss evaluation parameters are important design parameters for the transformer manufacturer. A complete specification for loss evaluated transformers should include the cost per kW of losses saved (P1) and the percent of load for evaluation (Y).

Transformer impedance can be independently specified and it is only marginally effected by transformer efficiency. Communications between the electrical consultant and the manufacturer is essential in order to obtain a transformer design that is cost effective for the specific user application. ■

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