Energy Loss Considerations in Traction Power Substation Design

Richard L. Hearth

Stoil D. Stoilov
Parsons Brinckerhoff Quade & Douglas, Inc.
Sacramento, California

Energy losses are playing an increasingly important role in the design of railway traction power distribution systems. As utility energy rates continue to follow an upward trend, transit authorities and design engineers alike intensify the search for means to reduce the energy bill without sacrificing system performance. Measures to reach this goal can be classified in several broad categories:

1. Operational procedures that deal mainly with the train schedules and utilize coasting and the like;
2. Employing energy efficient vehicles with chopper control and regenerative braking; and
3. Selecting traction power distribution system parameters, during the design stage, that result in an energy efficient distribution system.

It should be noted that all design measures taken to reduce the energy losses under 2 and 3 normally result in increased capital cost or maintenance expenses, or both. Therefore the overall goal must be to minimize not simply the energy losses but the total system cost, subject to numerous technical constraints.

The problems of specifying energy efficient transformer-rectifier units for traction power substations with AC/DC conversion are addressed in this paper. Such substations, with 12 kV to 35 kV, three-phase, AC voltage input and 600 V to 1500 V DC output, are typical for light rail or rapid transit system applications.

Because the layout of the traction power substations is usually compact, the AC and DC bus bar losses will be neglected. The rectifier transformer and the traction rectifier, complete as a unit with all auxiliaries and the interconnecting bus, account for most of the energy losses of the substation.

Using a classical approach from engineering economics, the present worth method, the total cost of the transformer-rectifier unit may be viewed as consisting of two components:

- Capital cost component and
- Energy loss component.

The capital cost component consists of the equipment price plus any destination or installation charges. The energy loss component consists of the present worth of the annual energy loss cost over the economic lifespan of the unit. It is affected not only by the utility energy rate, and transit system load pattern, but also by several other factors such as the selected amoritization period, the predicted energy escalation rate, and the interest rate.

The sum of the initial capital cost and the energy component loss constitutes the total unit cost. The goal then is to design a transformer-rectifier unit that meets all functional requirements, such as nominal rating, overload capability, regulation, and maximum temperature rise, at a minimum total cost. Such a design will be referred to as the economic design.

TRACTION POWER SUBSTATION LOAD PATTERN

Knowledge of the traction power substation load is essential to the proper evaluation of the energy losses and hence the economic design of the transformer-rectifier unit. The load current from the substation bus follows a highly irregular and shifting pattern, due to the very nature of the transit system operation. The line current of a single train during the acceleration and speed running modes follows a curve similar to the one shown in Figure 1. However, the traction power substations normally operate in parallel on the DC side and during peak periods there are two or more trains running between each two substations. This accounts for a much more complex current curve through each transformer-rectifier unit than the one shown in Figure 1. As each train moves along it will draw current from several substations and the contribution of each substation will depend on the distribution system parameters; the train location; and, to a certain extent, the status and location of the other trains in the vicinity. As a result the current through a substation transformer-rectifier unit will be constantly changing, reaching high peaks when a train (or trains) accelerates in the vicinity of the substation. The current-versus-time or power-versus-time graphs for different system operating conditions are best obtained by computer simulation. This can be done by using specialized computer programs written for traction power system design. A sample graphic output of such a program is presented in Figure 2, which shows substation DC current as a function of time during peak-period operation.

The results from the computer simulations can be

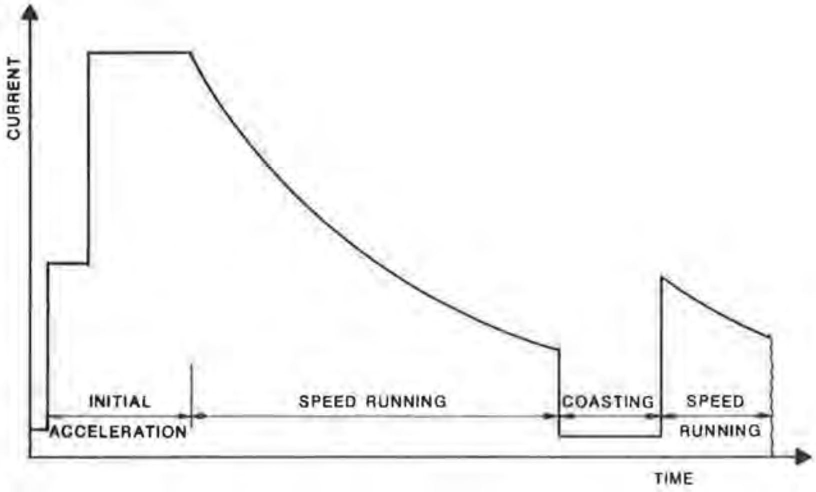

FIGURE 1 Typical LRV current-versus-time curve.

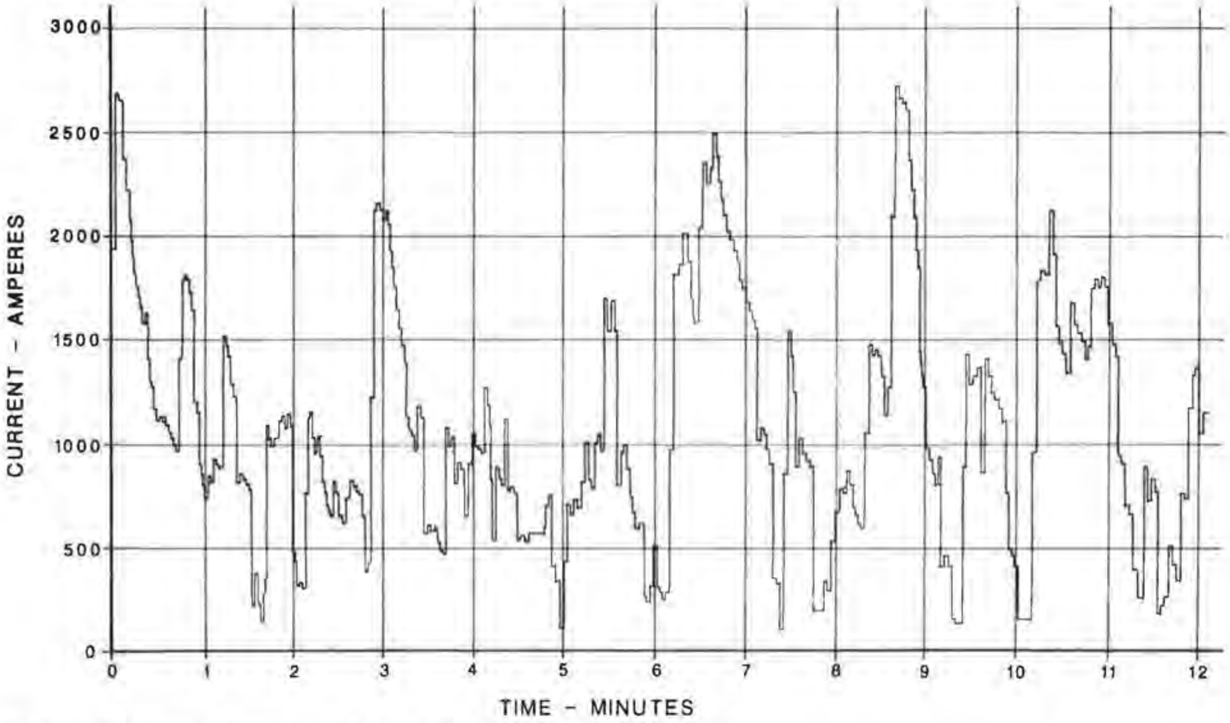

FIGURE 2 Computer simulation of traction power substation current profile

used to construct the load duration curve for the transformer-rectifier unit. Each point on this curve represents load magnitude as a percentage of the nominal transformer-rectifier unit rating and the corresponding time interval the substation load will equal or exceed it. In developing the traction power substation load duration curve, several assumptions can be made that will facilitate the task without significantly affecting the overall objective.

Because of the large number of variables affecting the substation load pattern, such as vehicle characteristics, number of cars per train, headways, peak and off-peak operating plan, and rating and spacing of the substations, it is hardly possible to make generalizations and use a "typical" load duration curve for any traction power system. Each system requires an appropriate analysis to be carried through by computer simulations in order to obtain the substation load duration curve.

Within any particular system there are wide, almost instantaneous, variations of load. In addition, there are hourly, daily, weekly, seasonal, and yearly load variations and these variations change from substation to substation within a system. A simulation of the life of a traction power substation (or system) is not practical even with a computer study; however, a close approximation can be readily obtained by making selective 24-hr simulations and then combining them in a life-cycle mode to produce the typical daily load duration curve.

The transformer-rectifier unit load duration curve represents, in essence, a statistically arranged load-versus-time graph. The time integral of the load duration curve will give the total expended energy. This curve is used as the basis for the evaluation of the energy losses in the rectifier transformer and the traction rectifier. The substation load duration curve of a sample light rail transit (LRT) system is shown in Figure 3.

PRESENT WORTH EVALUATION OF ENERGY LOSSES

Energy losses represent heat dissipated in the transformer-rectifier unit during its operation. For the rectifier transformer the losses are divided for convenience into core and conductor losses, referred to frequently as no-load and load losses, respectively. The core loss consists principally of hysteresis and eddy current losses, which are a function of the frequency and waveform of the voltage, the magnetic flux density, the quality of the steel used in the core, and the core construction parameters. The conductor losses on the other hand are the copper loss (I^2R) caused by the currents flowing in the transformer windings and are dependent on the magnitude and waveform of these currents. Unlike those of conventional power transformers, the current and voltage waveforms in the rectifier transformer are not sinusoidal. The current waveform, for example, is influenced by the rectification circuit employed and the reactance of the transformer, the load, and the supply line. Complex and involved calculations would be necessary to accurately account for the effects of the distorted waveforms on energy losses. Therefore certain simplifying assumptions are usually made such as the ones presented later on, which should allow satisfactory results.

Energy losses at the traction rectifier consist primarily of the heat that is dissipated in the diodes during their conduction period and conveyed to the cooling medium through heat sinks. Additional losses are also incurred in auxiliary devices, such as the interphase reactors, used in certain rectification circuits. These devices can be considered, for simplicity, as part of the overall rectifier assembly.

To evaluate the energy losses in the transformer-rectifier unit and calculate the corresponding present worth, the power losses of the unit for each incremental value of the load duration curve should be known. The typical daily energy losses per transformer-rectifier unit then would be simply

$$\Delta E = 1/1000 \sum_{i=1}^{n} \Delta P_i \cdot \Delta t_i \qquad (1)$$

where

ΔE = average daily energy losses (kWh),
ΔP_i = incremental power losses for a load corresponding to Step i of the load duration curve (W),
Δt_i = duration of power losses ΔP_i (hr), and
n = number of steps of the load duration curve approximation.

The present worth of the energy losses of the whole system then will be

$$P_L = 365 \cdot N \cdot \Delta E \cdot e\,([1/(1+i)] + [(1+K)/(1+i)^2] + \ldots [(1+K)^{n-1}/(1+i)^n]) \qquad (2)$$

where

P_L = system energy losses present worth,
N = number of transformer-rectifier units,
E = transformer-rectifier unit daily energy loss (kWh),
e = utility-weighted energy rate ($/kWh),
K = energy cost escalation factor (per unit),
i = interest rate (per unit), and
n = economic lifespan (years).

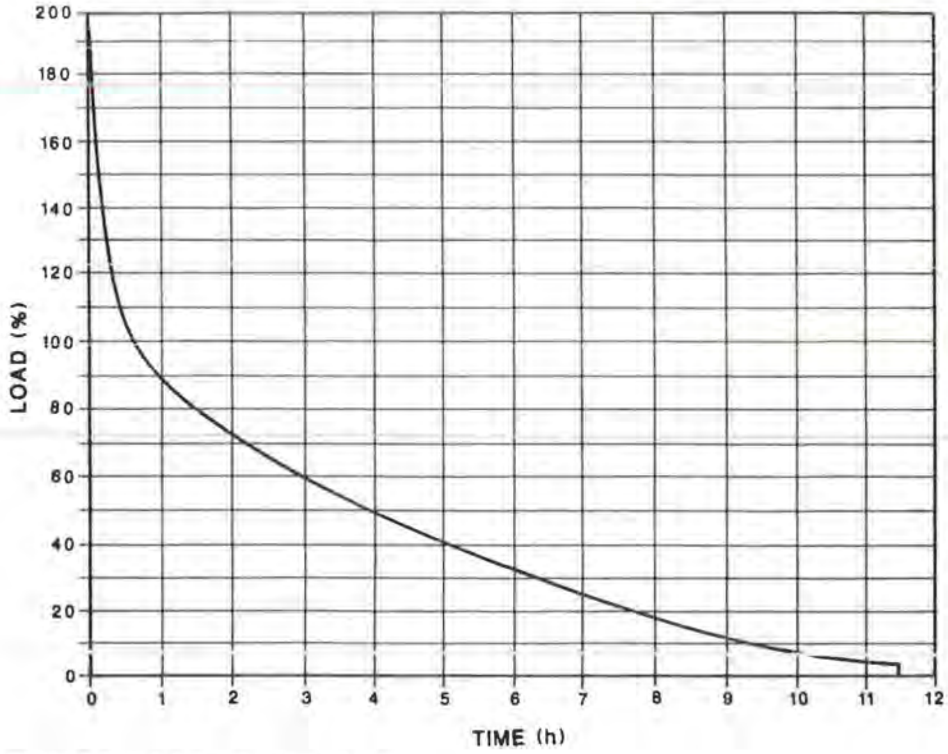

FIGURE 3 Substation daily load duration curve.

Several terms in Equation 2 can be combined in a single parameter, called present worth multiplier (PWM):

$$PWM = 365 \cdot e \cdot \{[1/(1+i)] + [(1+K)/(1+i)^2] + \ldots [(1+K)^{n-1}/(1+i)^n]\} \qquad (3)$$

Then, the present worth of the energy losses is

$$P_L = N \cdot PWM \cdot \Delta E \qquad (4)$$

The overall goal, as stated before, is to minimize the system total cost function (F):

$$F = C + P_L = \text{minimum} \qquad (5)$$

where C is the initial capital cost for procurement of the transformer-rectifier units.

Designing a rectifier transformer that can meet all performance and reliability requirements of the system and at the same time provide a minimum cost function (F) for a specified load duration curve and set of economic parameters is a complex optimization problem. Usually the measures intended for reduction of the power losses result in increased initial cost. A few examples will be given for illustration. Higher grades of steel have smaller specific losses (watts per pound) but are more expensive to buy. Larger conductor sizes reduce the load losses and the winding temperature rise but require more metal and affect the transformer core construction too. Also, the no-load losses, for instance, are a function of the watts per pound loss of the steel employed, the total volume of the core, the flux density, and the core construction. Reducing the flux density by increasing the core cross-sectional area, assuming the number of turns remains constant, will cause the specific core losses (watts per pound) to go down faster than the flux density because of the nonlinear relationship between the two. However, the overall volume of the steel will increase, which will affect the total losses and the cost as well.

GUIDELINES FOR SPECIFYING ECONOMIC TRANSFORMER-RECTIFIER UNITS

It is a normal practice to require the rectifier transformer and rectifier to be designed by the equipment manufacturer. The task of the consulting engineer is to furnish the prospective manufacturer with functional specifications covering all performance, reliability, and safety aspects of the unit. Traction power substation procurement is usually done through a competitive bidding process. Given that different manufacturers often employ or prefer different techniques and manufacturing methods, it is even impractical to enter into the realm of detailed equipment design.

The task facing the specifier then is not how to design a transformer-rectifier unit with an optimum efficiency but rather how to ensure that only such units are being offered by the manufacturers. The guidelines that follow are deemed helpful in achieving this goal.

First, some assumptions and simplifications should be made in regard to the energy loss evaluation. This is necessary in order to avoid certain cumbersome or controversial procedures and establish a common basis of evaluation for all prospective bidders. A sample set of such assumptions follows.

1. The energy losses shall apply to the transformer-rectifier unit as a complete operable assembly.
2. The rectifier transformer no-load loss determination shall be based on a nominal sine-wave voltage and transformer core at room temperature. The average-voltage voltmeter method shall be used with the three wattmeters version.
3. No special or separate core loss measurement of the interphase transformer (coupling reactor) shall be made. The interphase transformer shall be considered as part of the rectifier assembly and its losses measured as an integral part thereof during the specified rectifier test procedures.
4. The rectifier losses shall include the connection bus between the rectifier transformer and the rectifier itself, as well as any auxiliary devices.
5. All power loss measurements during the design or production tests shall be rounded off to the most significant digit of the indicating meter.
6. The reference temperature for the purposes of conductor losses evaluation shall be equal to the rectifier transformer temperature rise at full load plus 20°C.
7. During design tests, both the no-load and load losses of the prototype transformer-rectifier unit shall be measured on a joint transformer-rectifier operation. The design tests shall be performed for each different transformer type to be furnished by the contractor.
8. Load loss measurements during the design tests shall be performed for both Method 1 and Method 3 of Section 8.3.2. of American National Standards Institute C34.2. The difference between the two tests (segregated and lumped losses) shall be used as the rectifier load losses constant for all similar units undergoing subsequent production tests. Two no-load loss tests shall be performed during the design tests as well, one with the rectifier connected to and the other with the rectifier disconnected from the transformer. The difference between the two tests shall be used as the rectifier no-load losses constant for all similar units undergoing subsequent production tests.
9. Load loss tests shall be performed with excited winding sine-wave currents having the same root mean square values as the theoretically ideal rectangular-current waves corresponding to the particular unit loading.
10. No-load and load loss measurements during production tests shall be performed on the rectifier transformer only. Traction rectifier losses shall be assumed to be the same as the ones established during the design tests.
11. The manufacturer shall submit to the engineer for approval a justification of the per unit hysteresis and eddy-current loss components to be used in the transformer excitation losses evaluation.

Second, the specifier has to furnish the prospective manufacturers with all the data they need to design the economic transformer-rectifier unit. In addition to various technical performance and reliability requirements he has to supply the present worth multiplier, calculated from Equation 3, and the transformer-rectifier load duration curve obtained through computer simulations, as described earlier.

Third, the consulting engineer has to find a means of ensuring that the manufacturers will design transformers and rectifiers with economic parameters as intended. The easiest way to accomplish this in a competitive bid situation is to include the present worth of the energy losses in the manufacturer's bidding price. It will be to the manufacturer's advantage to design the transformer-rectifier unit as close to the ideal optimum economic unit as practically possible. Two approaches could be taken.

Penalty Approach

The manufacturer has to furnish and guarantee with his bid offer the maximum transformer-rectifier unit power losses for varying load conditions. The same power losses are used to calculate the present worth of the system energy losses using Equations 1 and 4. The energy loss present worth is then applied as a separate entry in the bid form and added to the total equipment bid price to obtain an adjusted bid price used for bid comparison purposes only. The lowest adjusted bid price will determine the contract award. The successful bidder has to prove during the manufacturing stage through factory tests that his equipment meets the power loss levels he has guaranteed. The specifier may include in the contract documents fallback clauses in case the manufacturer fails to meet the power loss levels. Such clauses may be, for example, penalties in the amount equal to the additionally incurred energy loss cost or a rejection of the equipment.

Incentive Approach

In this case the specifier may require a maximum acceptable daily energy loss level per transformer-rectifier unit and pay the prospective manufacturer a bonus based on the difference between this level and the energy losses of the unit obtained through actual measurements. A value of 3 percent of the transformer-rectifier unit daily energy consumption may be used as a reasonable estimate for the maximum acceptable energy loss level. The value of the bonus is calculated in the same fashion as is energy loss present worth by substituting the energy losses with the energy loss differential (the difference between the specified maximum acceptable energy loss and the actual unit energy loss). The equipment power losses used to calculate the energy losses (and consequently the amount of bonus if any) have to be obtained through factory tests, as they do in the penalty approach. Because the manufacturer is involved in a competitive bid situation, his tendency would be to subtract the anticipated energy bonus from his equipment price in an attempt to lower his bid and thereby increase his changes of success.

SAMPLE CASE

The principles and procedures discussed in this paper were applied in the design and procurement stages of the Guadalupe Corridor LRT system in San Jose, California.

The system consists of 21 mi of double track supplied by 14 traction power substations plus one dedicated substation for the maintenance facility. All substations are rated 1500 kW nominal at 800-V DC output voltage.

The following economic factors were established:

1. Life-cycle analysis term = 20 years,
2. Energy rate = $0.07/kWh,
3. Energy rate escalation factor = 4%/year, and
4. Interest rate = 10%.

These factors substituted in Equation 3 lend a present worth multiplier of $287/kWh.

The following transformer-rectifier unit load duration curve was obtained through computer simulations.

Load (% of full load)	Duration (hr)
200	0.1
150	0.4
100	1.25
75	2.15
50	3.2
25	4.4
0	12.5

After some deliberations, the incentive approach was adopted for implementation in the contract documents. The maximum acceptable substation energy losses level was accordingly set at 285 kWh per day.

Prebid inquiries to manufacturers concerning the energy loss characteristics of their transformer-rectifier units indicated that variations were wider than previously expected. The calculated present worth of the overall system energy loss ranged between $700,000 and $1,200,000.

Because, in the incentive approach, the proposed transformer-rectifier unit loss characteristic and the bonus anticipated by each manufacturer are not explicity stated, it is difficult to make a comparative analysis. On inquiry, however, manufacturers did confirm that they had lowered their bid price in anticipation of an energy bonus from the transit authority.

CONCLUSIONS

Current practice in the design of traction power substations is usually to specify transformer-rectifier unit efficiency for one or several load levels. The efficiency values selected are more or less judgmental and are intended to provide for quality of the product and limit the energy losses to some acceptable level. This approach does not necessarily provide an optimum design from an economic standpoint.

A procedure, based on the present worth method, was developed to specify economically optimum transformer-rectifier units. It requires additional work on the part of the specifier but can result in significant savings over the life cycle of the equipment. The approach described on this paper was applied successfully for the Guadalupe Corridor light rail transit system. It was favorably received by the equipment manufacturers. Although the exact amount of savings achieved is difficult to evaluate, the method can be recommended because of its intrinsic economic advantages.

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