Heat Loss from Electrical and Control Equipment in Industrial Plants: Part I—Methods and Scope

Warren N. White, Ph.D.  Anil Pahwa, Ph.D.  Chris Cruz

ABSTRACT

Accurate estimates of heat lost by power equipment facilitate proper sizing of cooling and ventilation equipment required by buildings and industrial plants. Information on heat loss is available in papers published in the 1970s and 1980s, but some of the information provided in these papers is dated and, in some cases, includes overly conservative assumptions. The main focus of this paper is to describe an effort to provide updated information on heat losses by various electric power devices. The information was gathered from equipment manufacturers and relevant standards associated with this equipment. Laboratory tests or mathematical simulations were done to determine heat loss for equipment with insufficient information and to verify published data. A calorimeter was constructed for the testing of equipment. The construction and calibration of the calorimeter are described. Test procedures used in acquiring loss data are described. For each equipment item in the scope of the project, a description is provided as to where and how the loss data were obtained. A summary of areas for future investigation is discussed.

INTRODUCTION

In order to size cooling and ventilating equipment, the HVAC design engineer must be able to estimate with certainty the amount of energy added from various heat sources and lost through various heat sinks located in a room. Heat could be added from several sources such as the presence of many people in a classroom or office, solar radiation through windows, and room lighting. A sink could consist of outside doors and windows in winter or a basement floor or wall that remains at an essentially constant temperature throughout the year. By closely estimating the heat gain in a room or space, the HVAC equipment will not be undersized with insufficient capacity or oversized with costly unutilized excess capability.

Building and industrial plants make use of electrical power for many uses such as lighting, driving motorized devices, HVAC, and energy distribution throughout the structure. All of this electrical equipment contributes to the total heat load. Estimating the total amount of rejected heat is a necessary part of sizing the ventilating and cooling equipment required for the building.

The primary source of information available to the design engineer for estimating the electrical equipment rejected heat is the paper by Rubin (1979). In this often used document, the rejected heat values for transformers, power distribution equipment, motors, switchgear, and power cables, to name a few, were presented in tables for a range of equipment sizes common to indoor equipment. The data presented by Rubin were obtained from the paper presented by Hickok (1978) and from other unspecified manufacturers. Hickok states that the data he presented were obtained exclusively from one manufacturer. At no point in either Hickok’s paper or in Rubin’s paper is there a discussion of measurement procedure or measurement uncertainty. Rubin’s motivation for publishing the data was to aid the HVAC design engineer. Hickok’s motivation in his paper was to aid the factory engineer in identifying plant locations where efficiency could be improved. Hickok’s motivation is easy to appreciate since the energy crisis provided by two oil embargoes made increasing efficiency of existing plants, buildings, and factories the first choice in reducing the costs of production. McDonald and Hickok (1985) later issued an update of Hickok’s paper (1978) with much of the same data.

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The information provided by these papers is dated. Since the oil embargoes of the 1970s, many electrical equipment manufacturers have increased the efficiency of their products. At the same time, advances in power electronics and computer control have made much of the technology reflected in the 1970 equipment obsolete. Another change that has occurred since Rubin published his work is that the manufacturing standards that apply to the various items of power equipment have been re-issued and updated several times. These standards could provide details for measuring the power loss in the equipment where, perhaps, originally none existed. Also, the standards might specify a maximum level of uncertainty for performing the measurements, and any data reported by a manufacturer claiming to follow the standard could be deemed reliable. Thus, there is a need to update the 20-year-old information originally presented by Rubin. A recent addition to the published information regarding motor heat gains is contained in Chapter 29 of the 2001 ASHRAE Handbook—Fundamentals that provides a table of “Heat Gains from Typical Electric Motors” for fractional horsepower AC motors up to 250 horsepower three phase motors.

The purpose of this work is to provide a methodology for estimating the rejected heat of specific electrical equipment by means similar to Rubin and to account for updated data, current testing standards, level of use, and more than one power equipment manufacturer. This paper describes the work done in reaching the stated work purpose. The first part of this paper describes the methods of data collection and equipment testing together with areas for future work. The second part summarizes the data collection and test results and provides a comparison between the recently obtained information and that available from the cited earlier work.

**PROJECT SCOPE**

The scope of the equipment investigated is listed in Table 1. Installed electrical equipment is normally not operated at 100% of full load on a continuous basis since no buffer would exist to accommodate any unanticipated increase in power demand. As a result, it was necessary to be able to determine equipment heat loss at partial loads. In addition to heat loss at fractional loads, it was necessary to account for equipment diversity, i.e., the equipment being used only during a portion of the time.

Early in the project, a distinction between types of heat transfer and operating conditions was drawn. The equipment rate of heat losses determined in this work represents constant values from steady operation. The device rejecting heat is assumed to have reached thermal equilibrium with the surroundings, and no thermal transient process is taking place. Thus, all heat loss occurring in a device is additional heat added to the surroundings. The manner in which the heat transfer takes place is not of concern. Heat convection to the surroundings and conduction to surrounding structures are not hard to appreciate as viable transfer mechanisms. Any thermal radiation is assumed to be absorbed by the surrounding structures (perhaps after several absorptions and re-emissions), and

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Size Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric motors</td>
<td>10–4000 hp (reg. and high efficiency)</td>
</tr>
<tr>
<td>Medium-voltage switchgear (breakers, heaters, and auxiliary compartments)</td>
<td>5 kV, 7.2 kV, and 13.8 kV with 1200, 2000, and 3000 amp breakers</td>
</tr>
<tr>
<td>Unit substation components (including breakers, heaters, bus losses, and auxiliary compartments)</td>
<td>800, 1600, 2000, 3200, and 4000 amp frame sizes</td>
</tr>
<tr>
<td>Transformers</td>
<td>300–2500 kVA and 120/208/600 V units below 300 kVA</td>
</tr>
<tr>
<td>Reactors</td>
<td>Standard sizes</td>
</tr>
<tr>
<td>Panelboards</td>
<td>Standard sizes for 120, 125, and 600 V</td>
</tr>
<tr>
<td>Cable and cable trays</td>
<td>0.6, 5, and 15 kV of widths 12 in.–30 in.</td>
</tr>
<tr>
<td>Battery chargers</td>
<td>100 to 600 amp</td>
</tr>
<tr>
<td>Inverters</td>
<td>20, 30, 50, 75, and 100 kVA—single phase</td>
</tr>
<tr>
<td></td>
<td>150 kVA—three phase</td>
</tr>
<tr>
<td>DC switchgear</td>
<td>125 VDC for 100 to 1500 amp</td>
</tr>
<tr>
<td>Manual transfer switches</td>
<td>0.6 kV for 150, 260, 400, 600, 800, and 1000 amp</td>
</tr>
<tr>
<td>Motor control centers (combination starters, breakers, auxiliary relay compartments, bus losses, and space heaters)</td>
<td>Standard NEMA sizes</td>
</tr>
<tr>
<td>Variable (adjustable) speed drives</td>
<td>25 to 500 hp—three phase</td>
</tr>
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the eventual manifestation of the radiant energy is an increase
in heat load. It should be pointed out that the radiant and
convective split of heat loss is an important part of the cooling
load determination and should not be ignored. The data
provided by this work are the total heat loss. How to split the
loss will be a function of the device, enclosure, load, and appli-
cation.

METHODS OF DATA COLLECTION

The initial stages of the project consisted of a literature
review, review of manufacturing standards for heat loss testing
procedures, e-mailing requests for equipment loss data to the
electrical equipment manufacturers, and examining manu-
facturers’ Web sites and catalogs for heat loss information. The
results of each of these inquiries are described in the following
paragraphs. Based on the results of this initial survey, a test
plan was developed.

Surveys

Outside of the works cited earlier by Hickock, Rubin, and
McDonald, there are no other reported investigations involv-
ing equipment heat loss. One notable and extremely useful
reference uncovered during this search is the text by Anders
(1997), which develops an extensive model of heat loss and
temperature rise of cable bundles. The model presented by
Anders is an extension of the original work of Neher and
McGrath (1957). An updated cable model is presented by
Harsh and Black (1994).

In parallel to the effort of reviewing literature, the manu-
facturing standards for the equipment under study relevant to
heat loss were identified. The identification process began by
creating a list of manufacturing standards relevant to the type
of equipment. This was first attempted by searching manufac-
turers’ Web sites for the specific standards that were followed
in the equipment production. An improved method of accu-
mulating this information was through the Web sites of orga-
nizations such as the National Electric Manufacturers
Association (NEMA) and the Institute of Electrical and Elec-
tronics Engineers (IEEE). In addition to the organizations just
mentioned, standards from the American National Standards
Institute (ANSI) and the Underwriters Laboratory (UL) were
also reviewed. The list of relevant standards was refined by
excluding those standards that did not address equipment heat
loss or efficiency. Standards were found that covered heat loss
measurement procedures for only the equipment categories of
transformers, series reactors, battery chargers, and electric
motors. Many of the standards reviewed were concerned with
temperature rise since high temperatures promote insulation
degradation, yet only few treat heat loss or efficiency. The rele-
vant transformer standards are IEEE Std. C57.12.90, IEEE
C57.12.91, and NEMA TP 1 and NEMA TP 2. For electric
motors, the essential standards are IEEE Std. 112, IEEE Std.
113, IEEE Std. 115, and NEMA MG 1. Standard IEEE C57.16
is the document detailing procedures for measuring series
reactor heat loss, while NEMA PE 5 treats battery chargers. It
was concluded that transformer and electric motor manufac-
turers followed the standards cited from statements made on
various manufacturers’ Web sites. However, no series reactor
manufacturer was found to follow IEEE C57.16. The fact that
standards covering heat loss measurements are followed by
manufacturers is significant since published loss data are
subject to the uncertainty levels specified by the standards;
thus, the quality of the published information can be easily
inferred. Heat loss information was found for battery chargers
in the standard NEMA PE 5, covering utility type battery
chargers; however, no manufacturer was found that claimed to
follow this relevant standard that specifies how battery charger
efficiency is to be determined.

A side benefit of the standards search provided information
regarding the influence of ambient temperature on equip-
ment heat losses. According to the cited standards, environ-
mental temperature has only a small influence on transformer,
motor, or series reactor heat losses.

In this work, one very important source of information is
equipment manufacturers. Manufacturers of a particular
equipment item were located through a search of the NEMA
Web site. This search provided the starting point for any
contact with equipment manufacturers since postal and e-mail
addresses were available.

Contact through e-mail was made to the companies
included on the manufacturer lists to inquire about dissipated
heat from their products. Since a contact was being made with
equipment manufacturers, information not only relevant to the
classification was sought but also information useful to other
parts of the study. For each type of power equipment involved
in the survey, a contact letter was written that explained the
nature of the project and requested information relevant to this
study. The requested information consists of the name and
number of the standards followed in determining the loss
numbers or the procedures used to determine the losses in the
case where no loss determination procedures are specified in
the standards. Also, the manufacturer was requested to supply
loss numbers for its products or to specify the Web pages and/
or public company documents where loss figures are
presented. This step was not done for every piece of equipment
under study, e.g., cables, since it was not expected that power
losses would vary from manufacturer to manufacturer and
excellent mathematical cable loss models are available.

Each of the equipment types was documented regarding
applicable standards, loss measurement methods, availability
of loss data, and results of the manufacturer survey. From the
accumulated data, the equipment was classified into one of
categories. The first category consisted of those products for
which the standards require specific, well-defined tests for
loss determination and reporting in addition to the availability
of published loss information. The third category includes
equipment for which there was no standard either requiring or
describing any heat loss tests and for which no heat loss data
could be found. The second category included all equipment
satisfying neither of the first nor third category descriptions.
Items in the second category represent a wide range of different situations or conditions. The best description for this category is that information was available on equipment heat losses, but the measurement quality was unknown. The first category included transformers and motors. The devices in the second category were reactors, medium-voltage switchgear, circuit breakers, motor control centers, inverters, battery chargers, adjustable-speed drives, plus cables and cable trays. The remainder of the power equipment constituted the third category that includes transfer switches, DC switchgear, and panelboards.

From the assessment determined in the previous activities, a test plan was devised to provide as much of the information as possible for covering the equipment heat losses for the items listed in Table 1. In the case of the first category equipment, the information was gathered from manufacturers' Web sites, catalogs, survey information, and personal contacts. For the equipment in the second and third categories, the test plan involved experimental procedures for building and/or verifying the information necessary to complete this study. Both the steps of the test plan and the necessary experimental apparatus will be described for each of the required equipment items.

**Test Plan and Test Facility**

Ideally, the testing phase of this work would consist of testing a sufficient quantity of the equipment in the second and third categories to provide the necessary information that would allow accurate heat loss predictions for heat load calculations. The testing phase had to provide the greatest amount of information given limited resources. The only way to determine heat loss information for equipment in the third category would be to purchase a sufficient quantity of equipment so that the ranges specified in Table 1 could be adequately covered. The large quantity of equipment to be purchased was necessitated by the lack of published heat loss information. The conclusion drawn about the third category equipment was that no testing of this equipment would be undertaken. Loss information for the second category equipment could be located. The concern of this published loss information was its accuracy, so the aim of testing the second category equipment was to check the published loss data. The loss data checking could be accomplished by testing a reasonable sample of equipment consisting of different sizes. Some of the second category equipment involved large and expensive components such as medium-voltage switchgear, motor control centers, or unit substations. These three equipment examples have much in common besides price and size and consist of many of the same components, such as bus bars, breakers, and space heaters. The strategy developed for determining the heat loss of the three mentioned items was to use a menu approach through a spreadsheet. The spreadsheet would allow the engineer to pick and choose the components making up the equipment in order to calculate the total heat loss. The crucial information in this spreadsheet calculation is the component heat loss. It was then only necessary to check the heat loss data of as many of the components as economically feasible. Finally, it was not possible to test all of the second category equipment due to the expense necessary to purchase a representative sample of products. In those cases where testing was not done, the gathered catalog and Web site loss data were reported with the proviso that no provision for verification of the data accuracy was possible.

The goal of the testing was to determine the heat losses of the equipment under various loads within different environmental temperatures. To facilitate the testing work, an environmental chamber/calorimeter was constructed out of 4-in.-thick Styrofoam. The wall thickness was achieved by gluing two 2-in.-thick sheets of blue construction insulation. Figure 1 illustrates the salient points of the environmental chamber. The interior dimensions of the chamber were 5 ft in height, 2.5 ft in depth, and 3.5 ft in width. Access to the chamber was accomplished by removing one wall. Room temperature air was supplied to the chamber through two variable-speed squirrel cage fans mounted at the base of the chamber. The two fans operated at the same speed. The volume flow rate of the exit air was metered by a vane anemometer mounted in a horizontal exit tube attached to the top of the chamber. An infrared source and detector were mounted on either side of the anemometer blades. The frequency of the detector diode signal was then a measure of the volume flow rate. The detector frequency could be determined using an oscilloscope, or could be determined by the data acquisition system by passing the detector signal through a frequency to voltage converter chip. The calibration of the anemometer was accomplished by mounting the chamber exhaust tube and anemometer on the end of a wind tunnel. The temperature of the inlet air and outlet air was measured by type-T thermocouples with shielded, twisted leads to limit signal noise. The interior temperature of the chamber was measured by four of the same thermocouples. The thermocouples were calibrated by means of a variable-temperature bath. The data acquisition system supplied cold junction compensation. Electric power was supplied to equipment placed in the chamber by three-phase lines passing through the chamber wall. A single-phase line was also passed through the chamber wall to supply power to an array of lightbulbs placed in the bottom of the chamber. The purpose of the lightbulbs was to supply heat in order to maintain the chamber temperature at a specific value and to help calibrate the chamber. The inlet ducts, outlet duct, power cable entry and exit, and thermocouple wire entry were sealed with silicone. The removable wall was held in place while the chamber operated by wooden boards and pipe clamps. The edges of the removable wall were sealed with duct tape. All permanent seams between sides of the chamber were glued, sealed with silicone, and covered with aluminum tape. With the exception of the inlet and outlet ducts, the chamber could be made airtight.

The equipment being tested in this study can be grouped into roughly two classes. The first class consists of items that are connected in series with the electrical supply lines. Some examples of the series devices are circuit breakers, combination motor starters, and series reactors. The second class of
equipment consisted of those devices that are connected from the supply line to the ground. The best example of this equipment class is the adjustable-speed drive. The tested series devices dissipated as much as a few kilowatts that could be measured with a wattmeter.

The chamber was used to provide a constant environmental temperature while the heat dissipation test was being conducted. In order to provide a constant temperature environment, a control system was programmed into the data acquisition system. The heating sources inside the chamber consisted of the device being tested and those lightbulbs that are turned on. The temperature inside the chamber is measured, and if the actual temperature is higher or lower than the desired setpoint temperature, the airflow rate through the chamber is raised or lowered, respectively. The variable-speed drives on the fan motors were driven by a signal from the data acquisition system. The chamber temperature controller was a proportional-integral type that provides an easy way to maintain the actual temperature close to the desired temperature.

In order to test adjustable-speed drives, the drives had to be loaded at the proper horsepower rating. The largest adjustable-speed drive on hand for testing was rated at 60 hp. The power lines supplying the drive were passed through the chamber wall. The lines attached to the load were also passed through the chamber wall. The load for the drive consisted of resistive heating elements mounted inside two 55-gallon drums. This resistive load is included in the illustration of Figure 1. Power from the heating elements was dissipated by running tap water through the drum to a floor drain in the lab. Each drum was capable of dissipating 30 hp. One drum consisted of industrial heating elements, while the other drum was constructed out of 220-volt residential hot water heating elements. In order to determine the dissipated heat, the airflow rate was measured along with the inlet and outlet air temperatures. The dissipated heat was determined by

\[
\dot{Q} = \rho \dot{V} c_p (T_{out} - T_{in}),
\]

where
\[
\dot{Q} = \text{rate of rejected or dissipated heat,}
\rho = \text{density of air,}
\dot{V} = \text{air volume flow rate,}
\]
\[
c_p = \text{specific heat of air,}
T_{out} = \text{outlet air temperature, and}
T_{in} = \text{inlet air temperature.}
\]

The control system was used to change the airflow by varying the fan speed so that the chamber remained at the desired environmental temperature.

In testing the series connected devices, it was necessary to create large electrical currents, which at times consisted of several thousand amperes, to load the test devices at the rated level. Series devices are designed so that the voltage drop across the device is small in order to limit power dissipation; thus, the large electrical currents could be delivered at a very low voltage. Figure 2 illustrates the means by which large currents were created. The creation of the large current was...
accomplished by a single-phase current transformer connected in reverse. The turns ratio of the transformer was as high as 5:2000, which allowed a wide range of currents to be created. Figure 2 shows the single-phase version of this apparatus that was used for the testing of devices such as circuit breakers or motor starters. Figure 3 shows how the test setup is used for measuring the power loss of some three-phase devices. Usually the power loss of these devices was relatively small so that the lightbulbs at the bottom of the environmental chamber were necessary to maintain the desired setpoint temperature inside the chamber. Theoretically, the heat loss from the series device could be used to heat the chamber and to maintain the setpoint temperature. For these situations, the flow rate of the air through the chamber was very small, and the speed controllers on the fans would overheat, trying to drive the fans at a high-current low-speed configuration. The autotransformer used in this test setup was a three-phase device and could be used in creating a three-phase test setup, where each phase of the apparatus appeared similar to Figure 2 with the exception that the two-wattmeter method was used for measuring the three-phase power dissipation. The three-phase test apparatus was required when measuring the power dissipation of series reactors since it was necessary to maintain the proper phase relation between the magnetic fluxes in the reactor legs to ensure proper operation and typical power losses.

The wattmeter in Figure 2 measures the power dissipated by the tested device, the current transformer, and the high current leads connected to the test article. In order to determine the power loss of the test article, the test article was removed from the circuit, and the high current leads were shorted together inside the sealed chamber with the environmental temperature set at the desired level. The autotransformer supplying power to the test circuit was adjusted so that the required current flowed through the high current leads. The power loss created by this configuration was measured by the wattmeter. The test article was then connected in the circuit, and the power dissipation was again measured under the same environmental conditions. The difference between the two readings was the power loss of the device being tested. Pains were taken to ensure that the difference between the two readings was significant. The high current leads consisted of 2/0 AWG welding cable. When very large currents were required, several welding cables were connected in parallel to limit the heat dissipated in the test circuit and to limit the voltage drop in the test circuit.

The lightbulbs in the bottom of the environmental chamber served another extremely useful purpose besides the heating of the chamber for some of the tests. The lights, which consisted of six 200-watt and two 150-watt bulbs, could be turned on and off separately. The single-phase line supplying the lights was connected to a wattmeter so that the power dissipated by the lights and, thus, added to the chamber environment could be determined. This known power input allowed the chamber to be calibrated in terms of the use of Equation 1. Setting the lights to a specific power level and using Equation 1 to calculate the measured power output after all thermal transients in the chamber had expired allowed a calibration curve for the chamber to be developed. Figure 4 shows the calibration curve for the chamber. The slope of the curve is very close to unity. The uncertainty of the measured heat loss was well within the ±10% level established as the target uncertainty for loss measurements made in this work.

It is worthwhile to point out a few miscellaneous details concerning the testing procedures. Support structures were created on which to mount the test articles. All articles tested were placed inside the environmental chamber with the exception of the larger series reactors, which were too unwieldy to easily move and so heavy that they would have crushed the Styrofoam floor of the chamber. The test articles were...
Thermal Chamber Calibration

- Measured Watts
- Curve Fit

Figure 4  Thermal chamber calibration.

mounted at approximately the center of the chamber, both horizontally and vertically. The thermocouples measuring the chamber temperature were all placed close to the test article in such a way as to surround the device being tested. The chamber temperature was determined by averaging the readings of the thermocouples placed close to the test article. The thermocouples sensing the inlet and outlet air temperature were not included in this average. All thermocouple readings were filtered with low pass filters to eliminate noise. Values from the evaluation of Equation 1 were passed through a low pass filter with exponential weighting to eliminate excessive fluctuations in readings. All filtering of measurements was performed by the data acquisition system. Steps were taken to ensure that the uncertainty of measured power loss was within ±10%.

Summary of Data Sources

For each of the equipment items placed in the first and second categories, the data sources developed in this investigation will be described. Also the influence of ambient temperature on heat loss will also be described.

Transformers. Standards for the loss measurement of transformers exist and are observed by manufacturers. Catalog and Web site data for general purpose transformers constructed with either dry-type or insulating liquid-immersed windings were found. From the relevant standards, it was learned that power losses were not a strong function of environmental temperature. The manufacturing standards specify the minimum efficiency for distribution transformers as a function of voltage classification and insulation. Power losses can be determined based on these minimum efficiencies.

Motors. The manufacturing standards applicable to the measurement of motor power losses are observed by the motor manufacturers. Data were acquired from manufacturers’ Web sites and catalogs for a wide variety of horsepower ratings and frame types. For motor power ratings of 200 horsepower and smaller, minimum efficiencies for motors were legislated through the U.S. Energy Policy Act of 1992, providing a means of estimating motor power losses in this range. For motors having ratings of greater than 2000 horsepower, no published information was found. It was discovered that motors in this size range are custom built for which losses could vary according to customer motor specification and applications.

Medium-Voltage Switchgear. Owing to the availability and expense of medium-voltage switchgear, no testing was possible within the scope of this project. While there are proprietary models and software packages used by manufacturers for estimating the heat loss of these devices, the only devices uncovered in this effort were simplified models for determining rejected heat. Likewise, some manufacturers publish some general tables for predicting the heat loss. Although this information was obtained from the latest versions of manufacturers’ documents, some of the information still matches data contained in McDonald and Hickok.
temperature environments and were tested both with and without enclosures. The environmental temperature did not play a significant factor in breaker power losses. The enclosure did play a significant role where it was seen that the power losses increased by a factor of almost 1.5 in some of the breaker loss tests. The factor of 1.5 was chosen since that bracketed all of the enclosure loss data. The reported loss information from manufacturers for low-voltage breakers varied over a wide range. It was not clear if some of the reported data involve enclosures or not. The assumption was made that the reported data for those breaker frames not tested did not involve enclosures. Plots of the peak breaker loss as a function of frame size varied roughly in a linear fashion. These plots were used to predict the breaker losses for those frames not tested. The largest frame for which heat loss was reported by a manufacturer was 5000 amp.

**Unit Substations.** Unit substations can be thought of as low-voltage switchgear. Information from the low-voltage breaker tests was used together with manufacturer component losses for current transformers, power buses, auxiliary compartments, control power transformers, and space heaters. In order to predict the unit substation losses, a spreadsheet was developed. No information on accuracy was available for the manufacturer reported component losses. Owing to the excessive costs, no unit substations were available for testing in this investigation. The influence of ambient temperature on the losses of components not tested could not be determined.

**Series Reactors.** The series reactor is used for both limiting fault current and in filtering inverter-produced noise on electric motor power feeds. Loss information from four different manufacturers was found. Reactors of sizes 4, 18, 200, and 750 amps were tested. For the 200 and 750 amp sizes, two reactors from different manufacturers were tested. The test results compared favorably with the reported loss figures. It was observed that the absolute winding temperature rise must be used to scale the losses so that the manufacturer reported losses would agree with the measured results. According to standards, the losses are reported as if the reactor conductors are at room temperature. Although standards exist for measuring reactor power losses, no manufacturer reporting loss information stated that these standards were observed in the testing of their products. Environmental temperature was not a significant influence on the reactor losses.

**Adjustable-Speed Drives.** Adjustable-speed drives (ASD) are also known as variable-frequency drives (VFD). Drives of 25 and 60 hp sizes were tested in this work. Also, loss information from several manufacturers was found in this effort. The published loss information consisted of power loss as a function of drive rating in horsepower for the standard supply voltages of 230, 460, and 600 volts. So many loss values were available that it was possible to plot the loss as a function of rating for each of the supply voltage levels. A striking linear trend was apparent even though different manufacturers’ data were on the same graph. The linear trends allowed curve fitting of the heat loss information as a function
of rating. The loss test results compared favorably with the manufacturer reported losses. Since the enclosure for the drives are an integral part of the device, no tests were performed without an enclosure. Ambient temperature did not present itself as a significant factor in the size of the heat losses. From published information, it appears that the drive losses vary as a linear function of drive current.

CONCLUSIONS

This document has described a systematic investigation into the quantification of power loss from the various types of electrical equipment found in buildings and industrial plants. The motivation for this study stems from the need of HVAC engineers to be able to accurately predict the equipment power loss in order to correctly size the necessary heating and cooling equipment for the structure. This is the first significant effort in this area in nearly 20 years. The power loss from many types of electrical equipment was determined by a process consisting of several steps. The first step involved discovering those equipment classes for which manufacturing standards exist that detail how power losses are measured and are observed by manufacturers. Loss information published by those manufacturers who claimed to follow these standards was deemed credible and having the same uncertainties as established by the manufacturing standards. The second step in the investigation involved creating and executing a test plan to verify the published loss data for those equipment classes for which loss measuring standards do not exist or are not observed by manufacturers. The testing was carried out to the extent possible. Of the equipment listed in the original project scope, three equipment classes fell into the category where there were no manufacturing standards for measuring losses and no published loss information could be found.

In the instances where tests on equipment items were made, several useful facts were uncovered. In several cases, the test results agreed with published information, such as the adjustable-speed drives and combination motor starters. In some cases, it was not clear how the manufacturer tested the equipment whose losses were being reported, such as low-voltage breakers with or without an enclosure. In this situation, tests performed in this study agree with some of the published information. In the case of series reactors, the tests uncovered that the reported manufacturer loss information must be referred to the expected temperature rise in order to get a realistic estimate of the power loss. For several equipment classes, tests on the equipment were not possible, so the only available avenue was to gather manufacturer loss information and present it in a usable and understandable form.

Areas for Further Investigation

While many significant results were the outcome of this study, work remains to be done in order to complete the information required by the HVAC engineer to correctly size the ventilating and cooling equipment for a given application. A list of the salient areas requiring further attention is presented here.

Panel Boards. It would be possible to accumulate enough equipment to provide sufficient measured data so that a menu and/or spreadsheet approach could be taken to predict heat losses.

DC Switchgear. No information for this equipment, which is finding use in the communication industry, could be found. Due to the high cost of this equipment, it would be necessary to team with one or more manufacturers to accumulate the necessary information.

Medium-Voltage Switchgear. While the menu approach adopted in this work provides a good approach, testing needs to be done to improve the quality of the data going into the menu. The ideal situation would be to work with one or more manufacturers to accumulate this information. The most important information to be gathered here includes breaker losses and enclosure effects. The influence of environmental temperature on losses is, at this point, unknown.

Low-Voltage Breakers. Much testing was done for smaller breakers. More information is required for the larger breakers in this class.

Cable and Cable Trays. Cable losses were predicted from analytical results. The verification of these results through testing would provide a valuable verification and limitation determination of the analytical results.

Battery Chargers and Inverters. The information provided in this study was derived from manufacturers’ data entirely. No testing was possible in this work and there was no opportunity to assess the influence on losses of ambient temperature. This lack of information provides the opportunity for further investigation.

Other Equipment. Another opportunity for future work is to identify equipment categories not included in the original RP-1104 work statement that constitute commonly applied devices. Determining the loss for these devices would then provide a useful addition to the data collection.

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REFERENCES