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Improved Thermal Modeling Tools for Substation Equipment

Improved Thermal Modeling Tools for Substation Equipment

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PRODUCT DESCRIPTION

The ratings of substation terminal equipment often limit power flow through transmission circuits. Capital investment in terminal equipment is generally modest in comparison to lines, transformers, and underground cables. Replacement difficulties are centered more on service availability than on cost. Detailed manufacturer test data is often unavailable for older equipment but ratings are simpler to calculate than for lines. Certain types of terminal equipment are tolerant of over-loading and problems involving the public safety are limited since the equipment resides within a fenced substation. However, failure of terminal equipment can yield service outages leading to major economic losses.

This project developed improved thermal models to support the use of infrared imaging technology as a means of inspecting substation terminal equipment and showing that terminal equipment could be safely and reliably operated above its “nameplate” rating. The project had several aspects:

- Determining cost/reliability tradeoffs for terminal equipment
- Investigating measurement techniques for use in the substation environment
- Identifying and improving thermal model algorithms
- Developing Substation Terminal Loading (STLOAD) software to allow “off-line” rating and temperature calculations
- Integrating the revised thermal models into the EPRI Dynamic Thermal Circuit Rating (DTCR) software.

Results & Findings

Infrared imaging is an attractive option because temperature measurements can be made in the field without requiring an outage and measurements can be made on terminal equipment of multiple types at multiple locations at the same time. Field measurements of “in-service” equipment can be accomplished by the use of infrared imaging cameras if the equipment surface is prepared— “painted white”—but only if the circuit load is at least 30% of the rating.

This project developed thermal model algorithms based on open process standards developed by IEEE, ANSI, IEC, and other organizations. These models are more sophisticated than simple “ambient-adjusted” models but not so complex as to require detailed physical and electrical data from the utility user. Initial models for strain bus and bushings have been implemented and tested in Version 1.0 of the STLOAD software, which is now available as an EPRI product. The program draws heavily from the EPRI Power Transformer Loading (PTLOAD) software and allows for transient and cyclic rating calculations. The plotting and report tools used in PTLOAD are also available in STLOAD. STLOAD uses an expanded version of the EPRI thermal model library (TML4.DLL), which is common to PTLOAD and DTCR.

The terminal equipment models were also incorporated into Version 4.0 of the DTCR software. In this version of DTCR, entire transmission circuits can be dynamically rated, including lines, cables, transformers, and terminal equipment.

Challenges & Objectives

This project provides a solid basis for the rating of substation terminal equipment. Because of the relatively modest cost of such equipment and because of the shear numbers of switches and other devices in most utilities, the use of individual equipment monitoring devices is not economically justified. The primary challenge is to properly rate terminal equipment in an inexpensive way.

Applications, Values & Use

Given the recent emphasis on equipment thermal rating transparency as reflected in recent standards such as FERC FAC-008, the clear explanations and models described in this report should be of considerable use to EPRI members.

EPRI Perspective

EPRI has supported an extensive list of projects intended to allow member utilities to more fully utilize the capacity of existing power equipment without reducing system reliability. The program has amassed field data for many operating situations and developed software such as DTCR. The substation terminal equipment models developed in the current project have been integrated into both DTCR and a new software program called STLOAD, which is intended for "off-line" rating calculations. These software implementations make the technical results of the study more accessible to members.

Approach

As part of an effort to clarify and improve the present methods of determining thermal ratings for substation terminal equipment, the project team used infrared imaging cameras to make measurements of equipment temperatures in several substations. The team developed thermal models for terminal equipment and integrated them into the STLOAD and DTCR software packages in order to allow dynamic rating of entire circuits. In view of the difficulty of obtaining thermal parameters for aged terminal equipment, the team made limited test results available.

Keywords

Ambient-adjusted ratings
Ampacity
Dynamic ratings
Substations
DTCR
PTLOAD
STLOAD

ABSTRACT

Substation terminal equipment often limits the power flow through transmission circuits. The purpose of this project was to develop improved thermal models for substation terminal equipment to allow the use of infrared imaging technology as a means of both inspecting this equipment and making temperature measurements in substations. Better models may show that terminal equipment can be safely and reliably operated above its “nameplate” rating.

The advantages of infrared imaging are clear. Temperature measurements can be made in the field without requiring an outage, and it appears to be possible to take measurements on terminal equipment of multiple types at multiple locations at almost the same time. The problem observed in such measurements is that the normal power flow in terminal equipment is no more than 30% of the equipment rating and the equipment temperatures are therefore only a few degrees above air temperature.

For this project, some thermal model algorithms were derived from the technical literature. These models are more sophisticated than simple “ambient-adjusted” models but not so complex as to require detailed physical and electrical data from the utility user. Initial models for strain bus and bushings have been implemented in Version 1.0 of the Substation Terminal Loading (STLOAD) software, now available as an EPRI product. STLOAD draws heavily from the EPRI Power Transformer Loading (PTLOAD) software and allows for transient and cyclic rating calculations. The plotting and report tools used in PTLOAD are also available in STLOAD. STLOAD uses an expanded version of the EPRI thermal model library (TML4.DLL), which is common to PTLOAD and the Dynamic Thermal Circuit Rating (DTCR) software.

The terminal equipment models were also incorporated into Version 4.0 of the DTCR software. In this version of DTCR, entire transmission circuits, including lines, cables, transformers, and terminal equipment, can be dynamically rated.

GLOSSARY OF TERMS

Some terms and ideas are in wide use. Their definition here, greatly simplifies the writing of the technical brochure on "Selection of Rating Assumptions for Line Ratings". A glossary is included in this document.

Thermal ratings are determined according to the practices of transmission line engineers but ratings are applied in an operational environment in order to maintain safe operation. The system operator, therefore, greatly influences the sort of ratings that are to be calculated.

Absorptivity of Conductors and Equipment

A perfect black body absorber would have an absorptivity of 1.0. New aluminum conductors and terminal hardware have an absorptivity on the order of 0.2 to 0.3. Old aluminum and copper conductors have an absorptivity which approaches 0.9 depending on the environment. Absorptivity and emissivity are correlated and it is likely that both are high (near 1.0) or low (near 0.2)

Ambient Adjusted Thermal Ratings

One of the weather assumptions necessary to the calculation of substation terminal equipment is the ambient air temperature. Ambient-adjusted equipment ratings are calculated based on a real-time estimate of real-time substation air temperature. Other weather conditions are normally held constant.

Ampacity

The ampacity of equipment is that maximum constant current which will meet the design, security and safety criteria. In this report, ampacity has the same meaning as "steady-state thermal rating."

Annealing

The process wherein the tensile strength of copper or aluminium metal is reduced at sustained high temperatures (usually above 100°C).

Continuous or Normal Thermal Rating

In the simplest thermal rating system, a single thermal rating is specified. For example, the rating of a switch can be specified on the basis of a “nameplate rating” provided by the conductor manufacturer. This rating is used by operations personnel as a current limit for all lines that use this conductor, under all system conditions.

Dynamic Thermal Ratings

In this case, the line rating is calculated for real-time weather conditions. Since they are based on varying weather conditions, dynamic thermal ratings are valid for a rather short period of time (e.g. 15 minutes) unless “predicted” ratings are derived from field studies.

Electrical Clearance

The distance between energized bus conductors and other conductors, buildings, and earth. Minimum clearances are usually specified by regulations.

Emergency Thermal Rating

In most power systems, a second thermal rating, called an “emergency” thermal rating, is defined. The emergency rating of a line trap is normally higher than the continuous rating since the conductor is usually allowed to reach a higher temperature during emergencies but the number of hours per year, during which the higher rating can be used, is limited (e.g. 24 hours per year).

Emissivity of Conductor

A perfect black body radiator has an emissivity of 1.0. New aluminum metal hardware has an emissivity on the order of 0.2 to 0.3. Old aluminum and copper conductors have an emissivity which approaches 0.9 depending on the environment. Absorptivity and emissivity are correlated and it is likely that both are high (near 1.0) or low (near 0.2)

Long-time Emergency Rating

During a limited period of time after the loss of a major component of the power system (generator, EHV line, etc.), remaining circuits may experience higher than normal loads. During such infrequent emergencies, higher operating temperatures and/or accelerated aging of equipment may be allowed for limited periods of time (4 to 24 hours). These higher than normal equipment ratings are called long-time emergency ratings.

Rated Breaking Strength (“RBS”) of Strain Bus

A calculated value of composite tensile strength, which indicates the minimum test value for stranded bare conductor. Similar terms include Ultimate Tensile Strength (UTS) and Calculated Breaking Load (CBL).

Real-time Thermal Rating

This is the thermal rating calculated based on real-time weather data.

Seasonal Thermal Ratings

In regions where the difference between average daily air temperature in summer and winter varies by 10°C or more, seasonal ratings, both normal and emergency can be defined. Since the winter ratings are based on a lower air temperature, they are typically higher than summer ratings.

Short-time Emergency Rating

A thermal rating calculated for a short period of time

Solar Temperature

The solar temperature of substation bus is its temperature when it carries no electrical current. During the summer, the solar temperature of the bus conductor may exceed the air temperature by 5°C to 10°C depending on the wind conditions and the conductor emissivity and absorptivity.

Static Thermal Rating

A static thermal rating is normally based upon "worst-case" weather assumptions, and specified conductor parameter.

Steady-state Thermal Rating

A steady-state thermal rating is calculated based upon constant values of current and weather conditions.

Thermal Rating

The maximum electrical current which can be carried in substation terminal equipment under specified weather conditions (same meaning as ampacity).

Thermal Time Constant

Given an abrupt change in weather conditions or electrical current, from one steady value to a new steady value, the equipment temperature changes in an approximately exponential fashion. The thermal time constant is the time period during which 63% of the ultimate change in temperature occurs. The thermal time constant of substation terminal equipment typically ranges between 15 and 60 minutes.

Transient Thermal Rating

A transient thermal rating, valid for a short period of time (e.g. 15 minutes), is calculated for a step increase in equipment current. The calculation considers heat storage in the conductor and the resulting rating is a function of the pre-step current.

Uprating

The process by which the thermal rating of terminal equipment is increased.

"Worst-Case" Weather Conditions

Weather conditions which yield the maximum or near maximum value of equipment temperature for a given current.

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1

INTRODUCTION AND BACKGROUND

In comparison to overhead lines, underground cables, and power transformers, substation terminal equipment is usually much less expensive to replace, and since terminal equipment is within the utility substation boundaries, its replacement does not require public hearings or regulatory approval. Nonetheless, in many cases, the benefits of increasing the rating of lines, cables, and transformers may be limited by one or more breakers, line traps, or current transformers, and replacement of such equipment can be both time consuming and disruptive due to required circuit outages. Finally, just as with lines, cables, and transformers, when relatively modest increases in terminal equipment rating are required, more detailed knowledge of thermal behavior can often be obtained quite easily.

Substation terminal equipment consists of many different types and designs of power equipment. Included in this classification are line traps, oil circuit breakers, SF_6 circuit breakers, rigid tubular bus, line disconnects, current transformers, bolted connectors, and insulator bushings.

In a recent *Electra* article entitled "Dynamic Loading of Transmission Equipment – An Overview" (CIGRE 2002), representatives of Study Committee 23 concluded, "there is scope for implementing dynamic loading principles for a wide range of transmission assets." The need for increased power flow in substation terminal equipment is illustrated in Figure 1-1 taken from (New York Power Pool 1982). It shows that the thermal ratings of over 50% of the transmission circuits in New York State were determined by substation equipment.

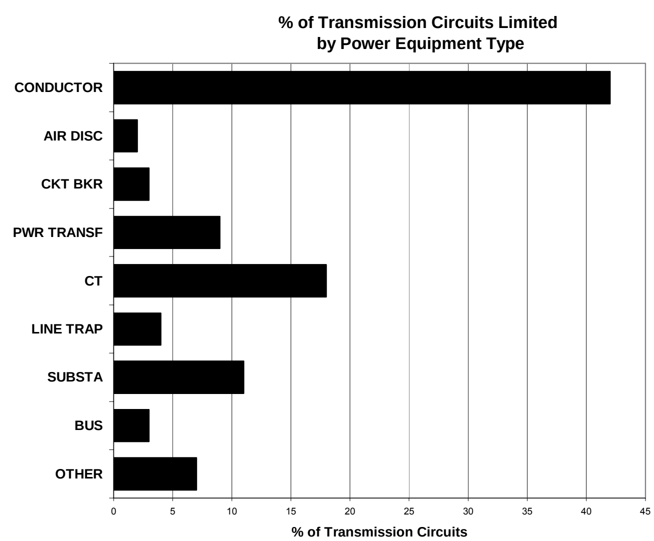


Figure 1-1
Thermally Limiting Transmission Circuit Equipment

The increase in circuit rating, resulting from applying the various methods of increasing power flow in overhead transmission lines, underground cable, and power transformers is often limited by terminal equipment, as shown in Figure 1-1.

Figure 1-2 illustrates the unexpected conclusion that relatively modest investments in terminal equipment (replacement of the CT in Circuit A) yields an increase in that circuit rating and a 50MW increase in the rating of the complex interface. As shown in the figure, a large increase in circuit rating is obtained for a very modest expenditure on terminal equipment rather than a relatively large investment in lines, cables, or transformers.

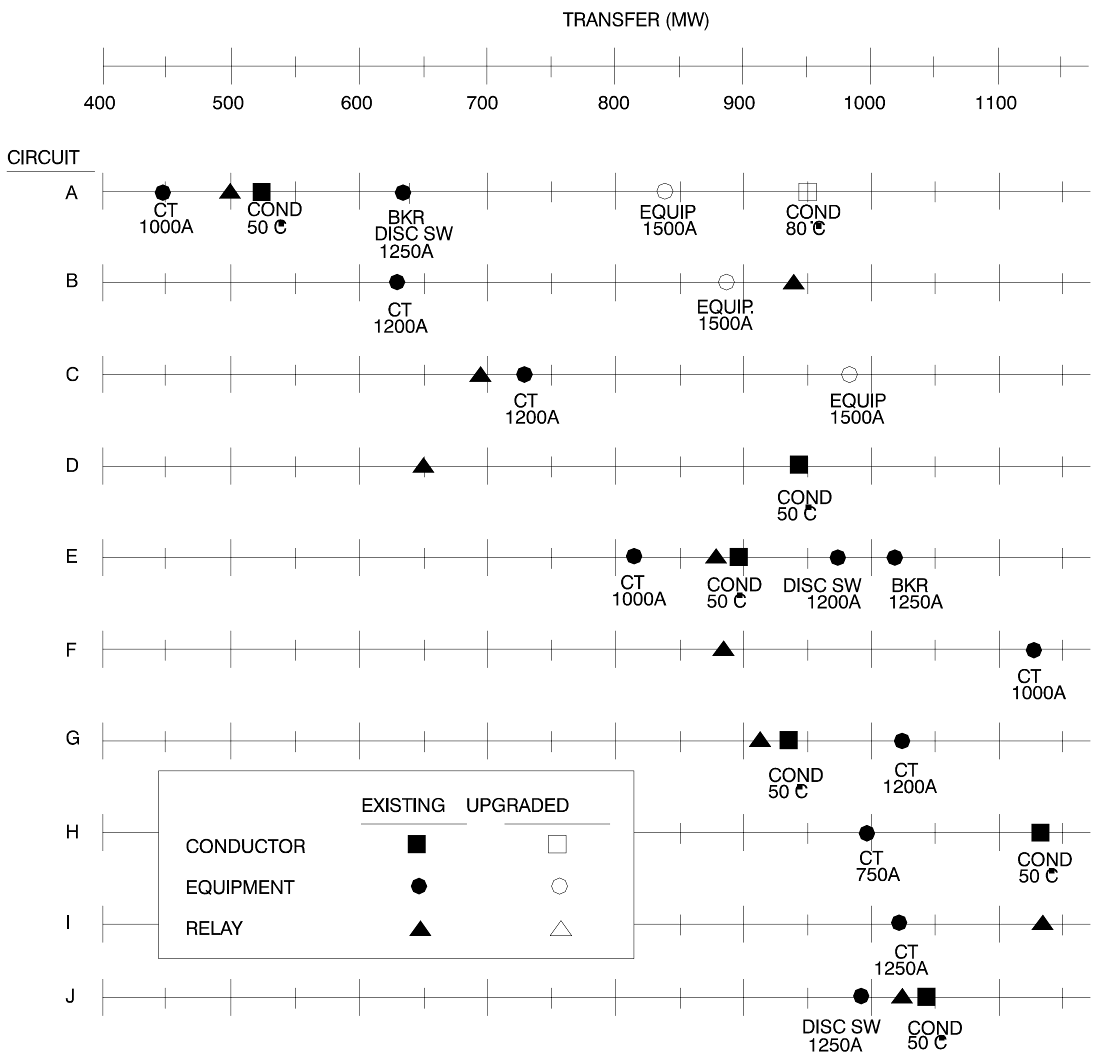


Figure 1-2
Diagram showing the limiting element for each of multiple circuits making up a complex power flow interface (diagram courtesy of N. Dag Reppen, NPC, Inc.)

This report summarizes the STLOAD project which was intended to study practical, rather simple methods of increasing the power flow through by replacing or increasing the rating of less capital-intensive equipment such as switches, bus, line traps, breakers, and power transformer auxiliary equipment. Because the substation equipment being uprated is generally less expensive to replace than lines, cables, and transformers, some of the more elaborate methods of monitoring are difficult or even impossible to justify economically. Also, because of the large number of switches, circuit breakers, etc., in any power system, and the variety of designs, both the thermal models that represent the equipment and requirement for weather monitoring must be kept simple.

2
SUBSTATION TERMINAL EQUIPMENT TYPES

Substation terminal equipment includes a wide variety of equipment types with varying opportunities for increased power flow. This report provides a broad overview of the types of equipment that might limit power circuit thermal ratings.

2.1 Equipment Rating Parameters

For each type of terminal equipment, the following issues are compared:

- Primary reasons for temperature and deterioration limits
- Type of thermal model used in rating calculations
- Consequences of over-temperature
- Degree of thermal interaction with other equipment
- Sensitivity to weather parameters
- Response to short-time emergency loads

The comparisons included here are not intended to be exhaustive, but rather to be an initial guide as to what can be expected to result from the various methods of increasing power flow.

2.1.1 Temperature and Deterioration Limits

Manufacturers of terminal equipment usually follow ANSI or IEEE or IEC standard recommendations with regard to maximum operating temperatures of substation terminal equipment. One clear exception is bus. While there are manufacturing standards for strain bus and tubular bus, temperature limits and thermal models are not typically included in the standards.

One obvious way to increase the rating of substation terminal equipment involves the use of higher than recommended equipment component temperatures, especially when this is done for limited periods of time and when such events occur infrequently. However, when the exceedence of normally recommended maximum equipment temperatures is to be allowed, the consequence of such events on the life and proper function of terminal equipment must be known.

2.1.2 Thermal Models

Thermal models for substation terminal equipment fall into one of two categories. The first category is similar to the power transformer "top oil" model. In this "ambient-adjusted" model, the temperature rise above ambient for critical components of the equipment (e.g., switch contact temperature), determined by reference to the appropriate standard, by a manufacturer test report (if available), or by field or laboratory measurement, is specified for a known current (typically the rated current of the equipment). This "reference" temperature rise is then adjusted for other currents according to an equation of the form:

$$\theta_2 = \theta_R \left(\frac{I_2}{I_R} \right)^{2n} \qquad \textbf{Eq. 2-1}$$

Where:

- θ_2 is the temperature rise to be calculated.
- θ_R is the "reference" temperature rise.
- I_2 is current for which the temperature rise is to be calculated.
- I_R is the "reference" current which causes θ_R..
- n is an exponent, generally close to 1.0.

The second category of thermal model consists of an actual heat balance similar to that used for overhead lines and underground cables. In this model, the temperature rise is calculated with a heat balance equation of the form:

$$I^2 R + q_s = q_r + q_c \qquad \textbf{Eq. 2-2}$$

Where:

- I is current in amps.
- R is the ac resistance of the component.
- q_s is the solar heat gain.
- q_r is the radiation heat loss.
- q_c is the convective heat loss.

With either sort of thermal model, heat storage in the equipment can be included in order to simulate transient thermal response to changes in current flow. Circuit breakers, CTs, and line traps are usually modeled with the "ambient adjusted" thermal model. Strain and tubular bus, bolted connectors are usually modeled with the heat balance approach. Switches and line traps can be modeled either way, but the heat balance approach usually requires too many dimensional and material parameters to be practical.

2.1.3 Determination of Equipment Thermal Parameters

As discussed in Section 5 of this report, the determination of other than default thermal parameters for substation terminal equipment is one of the most challenging parts of determining and increasing power flow through them. Unlike power transformers, for which certified heat run data is typically available, thermal test data from the manufacturer is seldom required by the utility and, if it was originally supplied, it may no longer be available for older equipment. For newer equipment, it should be possible to obtain documentation of a thermal design test. This documentation will contain measurements of the temperature rises above ambient of critical equipment parts at rated current. Thermal time constants and exponents are not typically available and must be determined by measurement or assumed.

2.1.4 Estimate and Consequences of Over-temperature

Unless one chooses to be extremely conservative, the magnitude and consequences of equipment over-temperature must be evaluated when rating substation equipment. For example, strain bus is seldom rated for still air conditions, because this would yield extremely low thermal ratings. But when strain bus is rated at 100°C on the basis of a 3-foot-per-second crosswind, then the temperature that it might obtain under still air conditions (the “temperature risk”) must be estimated, and the consequences of occasionally attaining such a temperature on bus strength and clearance evaluated.

2.1.5 Degree of Thermal Interaction With Other Equipment

Spacing of equipment in most substation designs is driven by electrical clearance considerations. At distances sufficient to meet these electrical clearance needs, there is little or no thermal interaction by means of convection or radiation. On the other hand, substation equipment is connected by electrical conductors that may conduct heat as well as current. The source of such heat may be either other electrically connected equipment or the conductor itself. Fortunately, the conduction of heat between equipment by means of typical bus conductors is unlikely to be significant. The impact of heat from conductors that are themselves hot, however, is a source of concern.

2.1.6 Sensitivity to Weather

The thermal rating of most substation equipment is sensitive to air temperature, solar heating, and wind speed and direction. Nonetheless, within the typical substation, because of the many equipment orientations and the degree of sheltering by other equipment and buildings, determination of reasonable values for solar heating, wind speed, and wind direction is very difficult. Air temperature, on the other hand, is easily determined for all equipment at a particular location. Therefore, with the possible exception of strain and rigid bus work, wind and solar effects are typically ignored.

2.1.7 Response to Short Time Emergency Overloads

In transmission power systems, normal power flows in most circuits are modest (i.e., less than 30% of the circuit thermal capacity). This occurs because the system must be capable of transmitting sudden increases in power flows due to the sudden loss (outage) of key components (e.g., generators and bulk transmission circuits). In order to limit the magnitude of such sudden "emergency" loads, the operator may intervene within a short period of time (e.g., 15 minutes) in order to reduce power flow levels to normal continuous ratings or below. In such situations, short-time emergency ratings of substation terminal equipment, may be useful.

Two factors determine the short-time emergency (STE) rating of substation terminal equipment (and other power equipment). These factors are the equipment's thermal time constant and its ability to withstand occasional high temperature events with an acceptable degree of deterioration. The thermal time constant is defined as that time, after a sudden increase in electrical current, after which the equipment temperature rise equals 63% of that which will ultimately occur if the new higher load continues indefinitely. An example of withstanding occasional high temperature exposure is the aging of free-standing current transformer insulation which may shorten the life but not cause short-term catastrophic failure.

2.1.8 Maximum Multiple of Nameplate Rating

For short-time and long-time emergency ratings, the thermal rating calculation formulas may allow for operation at many times the continuous "nameplate" rating but there may be perfectly good engineering reasons to limit these transient rating to a multiple of the nameplate rating. For example, this is done with power transformers, which are normally limited to 200% of nameplate regardless of the STE or long-time emergency (LTE) rating calculations.

2.2 Thermal Rating Parameter Comparison

Table 2-1
Summary of IPF Characteristics for Substation Terminal Equipment (Part I)

Substation Terminal Equipment Type	Temperature or Temp Rise Limits (°C)	Thermal Models	Consequence of Over-Temperature	Thermal Interaction With Other Equipment
Strain Bus	75 to 125 (cont.)	Heat balance	Loss of strength, sag clearance	Possible
Rigid Bus	75 to 125 (cont.)	Heat balance	Loss of strength	Possible
Switches (Air Disconnects)	70/93 rise normal 105/120 rise LTE	Ambient Adjusted	Contact damage, annealing of parts	None
Line Traps	90 to 115 rise (cont.)	Ambient Adjusted	Damage to Insulation or reduction in tensile strength of aluminum	None
Bushings	150 conductor temp	Adjusted for top oil of PT or OCB.	Reduction in insulation life, overpressure, gasket deterioration	Directly influenced by oil temp in OCB or PT
CTs - Bushing	120 hot spot	Adjusted for top oil of PT or OCB.	Decrease in insulation life	Can be directly influenced by oil temp in OCB or PT
CTs – Free-standing	45 rise oil 55 to 80 winding rise.	PT model, ambient adjusted	Decrease in insulation life	None
Circuit Breakers	90 (metal in oil) 80 (top oil)	Ambient Adjusted	Damage to contacts, annealing of parts	None
Current Limiting Reactors	55 or 80 rise	Ambient Adjusted	Damage to insulation	None

Table 2-2
Summary of IPF Characteristics for Substation Terminal Equipment (Part II)

Substation Terminal Equipment Type	Practical Sensitivity to Weather	Thermal Time Constant (min)	Sensitivity of Cont. Rating to Air Temp. (% change per °C)	Maximum Multiple of Nameplate
Strain Bus	Wind speed and direction, air temp, solar heating	5 to 15	0.6% to 0.8% 10% per fps wind	None
Rigid Bus	Wind speed and direction, air temp, solar heating	10 to 30	1.0% to 0.8% 10% per fps wind	None
Switches (Air Disconnects)	Air temp	30	0.8% for new 53°C rise 1.2% for older 30°C rise	200%
Line Traps	Air temp	15	0.2%	None
Bushings	Indirectly through transformer or breaker oil temperature	Adjusted for top oil of PT or OCB.	Reduction in insulation life	Directly influenced by oil temp in OCB or PT
CTs - Bushing	Air temp	15	Same as PT	Same as PT
CTs – Free-standing	Air temp	15	Similar to PTs with OA cooling.	
Circuit Breakers	Air temp	30	1%	200%
Current Limiting Reactors (Dry-type)	Air temp	15 to 30	0.8% for 55°C rise 0.4% for 80°C rise	200%

3
THERMAL MODELS FOR TERMINAL EQUIPMENT

As noted in the preceding section of this report, there are many types and designs of terminal equipment, and detailed thermal test data, particularly for older equipment, is unlikely to be available. As a result, simplicity is preferred in modeling terminal equipment.

3.1 Bus Conductors

Bus conductors in substations come in a wide variety of sizes and types. To keep things reasonably simple, three types of substation bus are recognized: rigid bus, strain bus, and jumpers:

- Rigid bus is normally tubular, functionally similar to copper or aluminum conduit or pipe, but some older rigid bus may be square or "L" shaped in cross-section.
- Strain bus is under tension (thus the name "strain"), and usually identical to stranded conductor used in overhead transmission lines. It usually is stranded aluminum wires with a steel wire core (i.e., ACSR).
- Jumpers are also made from stranded transmission conductor but are not under tension.

The three types of bus conductor are shown in Figure 3-1.

The thermal model for these bus types are similar to that of an overhead line (CIGRE 1997, IEEE 1993), consisting of a heat balance between Ohmic and solar heat input and convective and radiation heat losses.

The steady state temperature given a constant load, ambient temperature, and effective wind speed must be solved by iteration so as to satisfy the following heat balance equation:

$$I^2 R + q_s = q_r + q_c + q_{cond} \quad \text{Eq. 3-1}$$

Where:

- I is current in amps.
- R is the ac resistance at temperature T in ohms/meter.
- q_s is the solar heat gain (W/m).
- q_r is the radiation heat loss (W/m).

- q_c is the convective heat loss (W/m).
- q_{cond} is heat loss/gain due to conduction (W/m).

One difference between substation bus and overhead lines is that reflected solar heating is negligible for lines, but not for substation bus, where the conductor are somewhat closer to the ground.

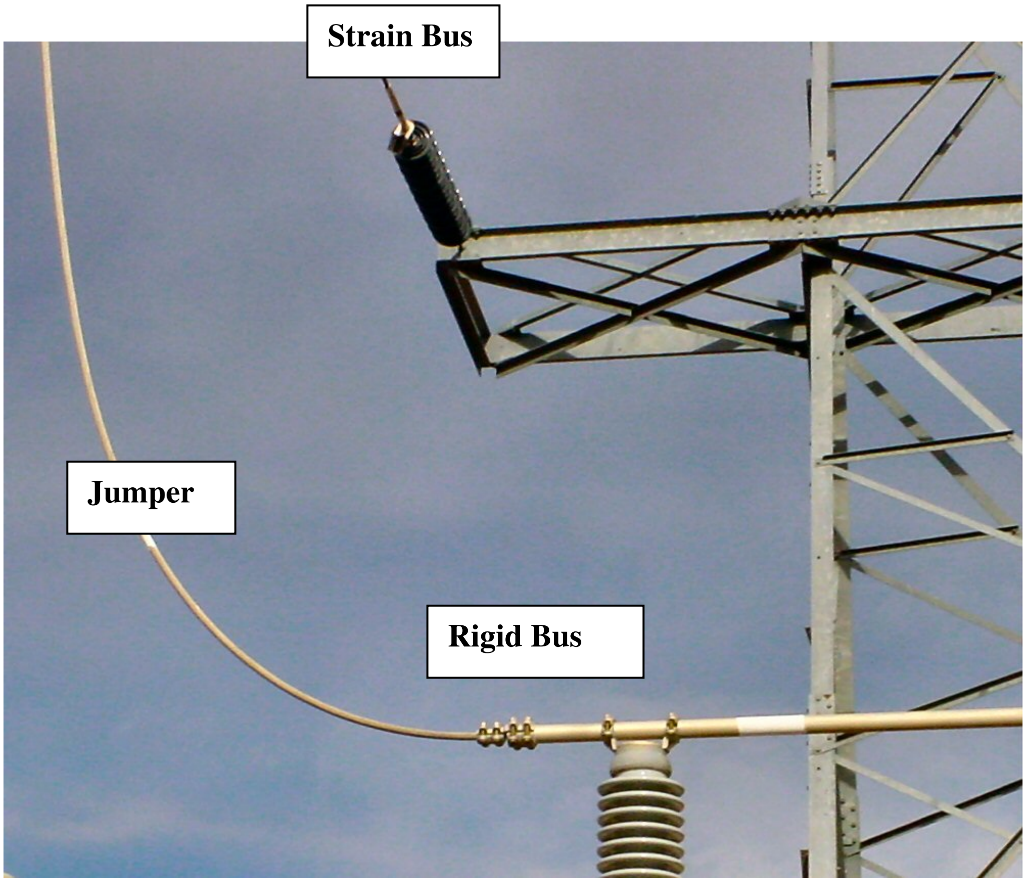


Figure 3-1
Three Types of Substation Bus Conductor.

There are other important thermal rating differences, even for the same conductor applied as substation strain bus and as a phase conductor in an overhead line. These differences include:

- The decrease in electrical clearance at high temperature is less likely to be a problem for substation bus where strain bus spans are short.
- The issue of loss in strength due to annealing is less likely to be a concern in bus applications since the increase in tension under ice and wind load is less than for lines.
- High electrical losses in bus are not a concern because of the short length involved.
- Inspection of connectors is much simpler in a substation than in a line, which might be 50 or more miles in length.

On the other hand, the temperature attained under high load conditions for both strain bus and line conductors is very sensitive to wind cooling (forced convection).

Given these observations, it seems reasonable that substation bus could be rated "less conservatively" than overhead lines.

Consider Drake ACSR used as both substation bus and as the phase conductor in a line. One end of the line terminates at the substation with the Drake bus conductor. Assume that both conductors are rated at 990 A for a conductor temperature of 100°C, wind speed 2 ft/sec perpendicular to the conductor, air temperature of 40°C, and full sun. If the wind drops to 0 ft/sec, the conductor temperature with full rated load would increase to 130°C. This is acceptable in both applications.

Now consider the impact of increasing the assumed wind speed from 2 ft/sec wind to 3 ft/sec. The risk associated with this change in the assumed rating conditions appears to be greater for the line than for the strain bus in the substation. Any possible deterioration in the physical conductor and associated hardware is easier to spot by a single trip to the substation. A line inspection is far more expensive, requiring more time and travel. Any permanent increase in sag is a genuine safety concern along the line not within the substation. Any loss in conductor strength is more likely to result in a high tension failure of the line during the next severe ice storm than in the shorter substation span.

Oddly enough, however, substation bus is normally rated more conservatively than lines in terms of weather assumptions. Thus, one simple approach to increasing power flow in substation bus might be the use of less conservative weather assumptions.

3.2 Switch (Air Disconnect)

ANSI standards (ANSI 1979) specify certain requirements for high-voltage air disconnect switches. The standards specify the rated current (thermal rating) of the switch and the weather conditions and equipment temperatures under which the rating is calculated. For example, modern switches, produced after 1971, with silver contacts, are rated for continuous operation at a temperature rise of 53°C, whereas those manufactured after 1971 are rated for continuous operation at a rise of 30°C. In both cases, the continuous rating is calculated for an air temperature of 40°C. A typical, rather simple switch design is shown in Figure 3-2.

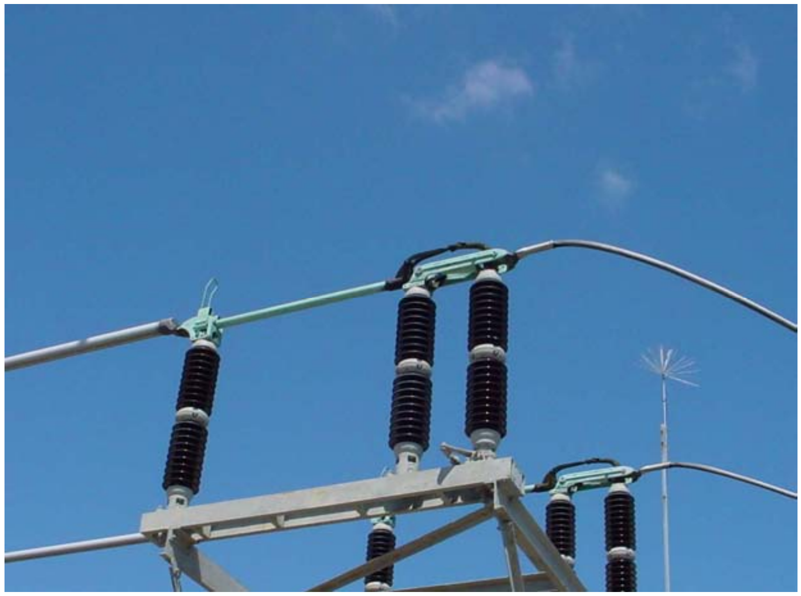


Figure 3-2
Typical Air Disconnect (switch).

The PJM Interconnection has published detailed rating data (PJM 1999) for air disconnects. The conclusions drawn in the PJM documents reflect the operating philosophy of PJM and should be considered by anyone utilizing the analysis. For example (New York Power Pool 1995), the NY Power Pool (presently NY ISO) utilizes limits of 93°C, 120°C, and 140°C in calculating the rating of pre-1971 air disconnects for normal continuous, long-time emergency (LTE) and short-time emergency (STE) ratings. The most recent PJM recommendations are 93°C, 115°C, and 125°C for the same ratings. The PJM standard also considers the temperature of conducting material joints, switch terminals with bolted connections, and flexible connectors.

The PJM discussion also considers annealing of copper and aluminum component parts as a factor in high-temperature limits, while the NY ISO discussion does not.

3.2.1 Simple Dynamic Rating Switch Model

The adjustment of steady-state switch rating, I_R, with air temperature, T_A, may be approximated as follows:

$$I_2 = I_R \cdot \left(\frac{T_R - T_A}{T_R - 40} \right)^{\frac{1}{2}} \qquad \text{Eq. 3-2}$$

Table 3-1 shows the variation of steady-state switch rating with air temperature, using this simple equation. Notice that the variation in the rating of the newer switches, having a higher allowable contact temperature rise over air temperature, is less. In any event, Table 3-1 indicates that the switch rating can be 5% to 20% higher on a cool day.

Table 3-1
Impact of Air Temperature on the Normal Rating of Air Disconnects

Ambient Temperature (°C)	Thermal Rating (53°C rise in silver contact temp) %Nameplate (after 1971)	Thermal Rating (30°C rise in silver contact temp) %Nameplate (before 1971)
45	95	91
40	100	100
35	105	108
30	109	115
25	113	122
20	117	129

The following, more general equations, are given in ANSI C37.30. They allow adjustment of manufacturer nameplate rating for both steady-state and transient loads. The critical contact temperature may also be tracked with these equations as load and air temperature vary over time.

$$I_2 = I_R \cdot \left(\frac{T_R - T_A}{T_R - 40} \right)^{\frac{1}{2n}} \quad \text{Eq. 3-3}$$

$$\theta_U = \theta_R \left(\frac{I_2}{I_R} \right)^{2n} \quad \text{Eq. 3-4}$$

$$\theta_2 = \theta_1 + (\theta_U - \theta_1)(1 - e^{-\Delta t/\tau}) \quad \text{Eq. 3-5}$$

$$T_2 = T_A + \theta_2 \quad \text{Eq. 3-6}$$

Where:

- θ_U is the ultimate contact temperature rise.
- θ_R is the rated contact temperature rise.
- I^2 is switch current at the present time step, t2.
- I_R is the rated switch current.
- n is an exponent, generally between 0.7 and 1.0 (default 0.8).
- θ_2 is the contact temperature rise at the present time step, t2.
- T_A is the ambient temperature.
- θ_1 is the contact temperature rise at the previous time step, t1.
- Δt is the time step.
- τ is the switch thermal time constant (default 30.0 min).

The switch rating can be determined by one of several "observable temperature" rises with different limiting temperatures. It seems likely that the switch contacts will most often be the limiting temperature. In addition, it must be assumed that the contacts are kept in good condition such that there is not an appreciable increase in contact resistance.

3.2.2 Thermodynamic Dynamic Rating Switch Models

As part of the development of the EPRI DTCR software, thermodynamic models of certain switches were developed (Coneybeer 1992) and verified through laboratory testing. For example, Figure 3-3, Figure 3-4, and Figure 3-5 show a comparison of contact temperature measured in a laboratory to temperature calculated with a thermodynamic switch model.

The thermodynamic switch model consists of modeling three switch segments separately—the contact segment, the bus bar segment, and the shunt. The model is basically a heat balance much like that used to model a bare overhead line. The detailed model had the advantage that it adjusted ratings for wind cooling, but it had a number of disadvantages, primarily consisting of the requirement for detailed geometrical dimensions and electrical and thermal parameters as illustrated by the following list:

- Outer and inner diameters of the bus segment.
- Contact material and surface emissivity/absorptivity.
- Switch rated current, contact temperature at rated current, and ratio of contact resistance to that of a new contact.
- Dimensions of contacts.
- Shunt material and emissivity/absorptivity.
- Shunt width and thickness.

Utility advisors on the project concluded that these requirements were onerous and impractical, given the number of switch designs being used in large utilities. In addition to these problems, the tests indicated that the switch contact temperature calculation was adequately modeled with the simpler ANSI/IEEE equations and with previously developed utility models (Bendo et al. 1979). This is illustrated in Figure 3-3.

In addition, the laboratory testing of an old weathered switch with contacts that were in poor condition showed that the ANSI/IEEE model (or presumably the Dynamp thermal model with default parameters) underestimated the contact temperature, as shown in Figure 3-5. The good agreement between the measured temperature and the EPRI Dynamp thermal model was accomplished by noting the poor condition of the switch contacts and adjusting the parameters accordingly—hardly a practical solution to a "bad" switch. In reality, this switch should have been de-rated or replaced if part of a heavily loaded power circuit.

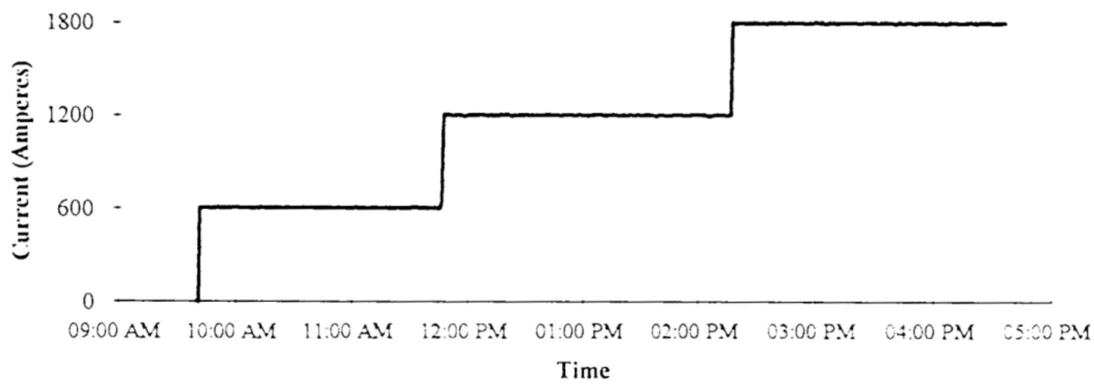


Figure 3-3
Laboratory Current Step-Sequence for Switch Tests.

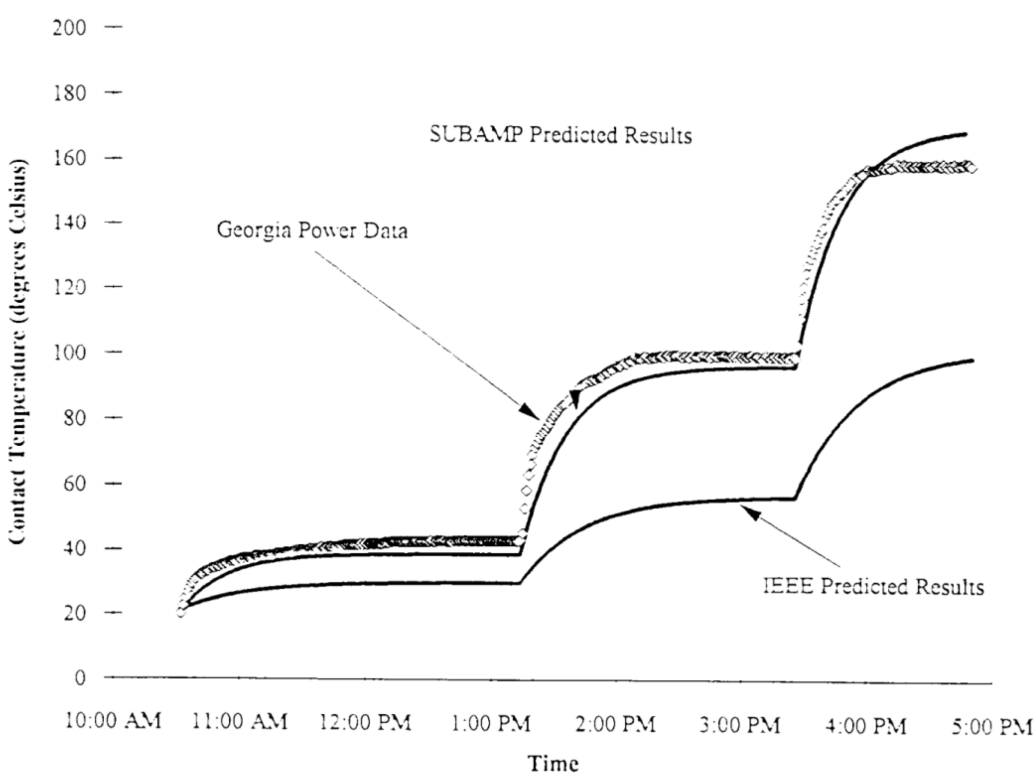


Figure 3-4
Comparison of laboratory measurements of contact segment temperature to IEEE/ANSI and EPRI Dynamp thermodynamic model with adjusted parameters.

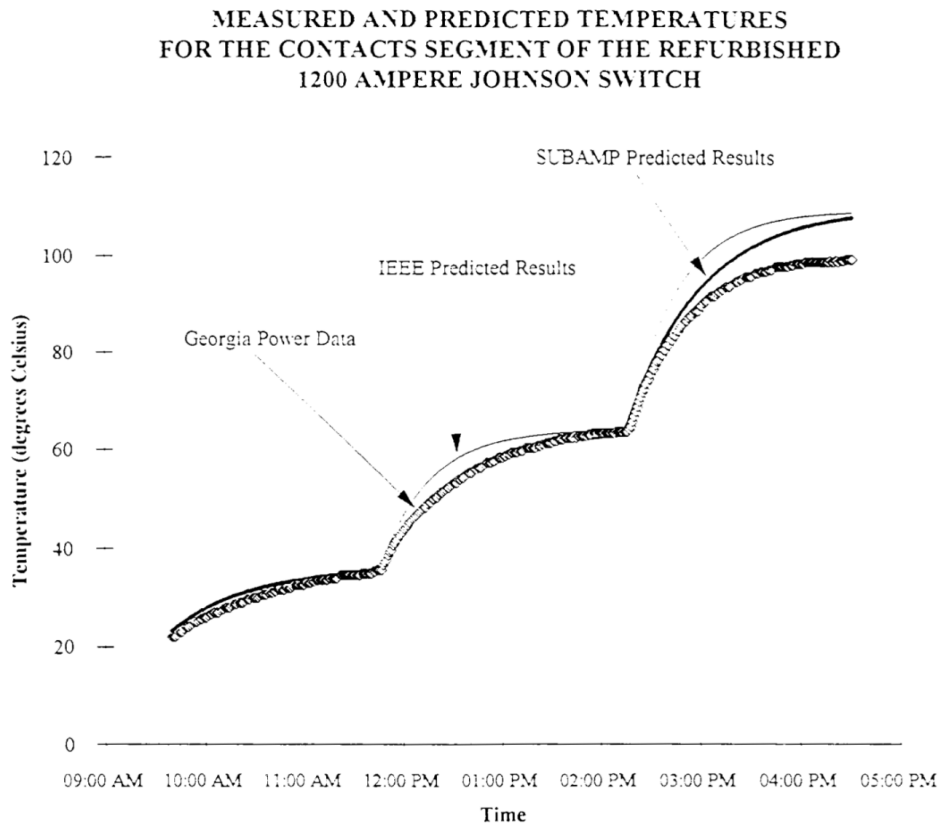


Figure 3-5
Comparison of laboratory test results to the ANSI/IEEE model and the EPRI Dynamp thermodynamic model.

3.2.3 Field Testing of Switches

Both as part of the original series of substation terminal tests and as part of more recent field measurements of switch temperature in operating substations, it was concluded that even in heavily loaded circuits, switch temperatures rarely reach levels that allow for meaningful measurements. The older DTCR tests concluded that the temperature rise due to solar heating was generally higher than the temperature rise due to electrical current.

The more recent tests utilized infrared (IR) imaging cameras and prepared (white painted) switch surfaces. It was found that this approach to measurement provides a noncontact measurement of temperature with an accuracy of within 1° to 2° C. The camera used was not unusual, but the experience of the operator was.

The primary impediment to field testing involves the relatively low current levels that most switches and other substation equipment experience. At a current equal to 30% of the switch's thermal rating, the temperature rise is only about 10% of the rated rise.

3.3 Air-core Reactor

Series-connected air-core reactors are governed by ANSI standards (ANSI 1996, 1965). The rating is limited by the hot-spot temperature rise of the conductor in contact with the insulation or encapsulation material. The limiting temperature varies depending upon the insulation material (as indicated by the temperature index). For specific limits, refer to Table 3-2. No thermal model is specifically outlined in the applicable standards. The following simple model should reflect a reasonable compromise between accuracy and efficiency.

$$\theta_U = \theta_R \left(\frac{I_2}{I_R} \right)^{2n} \qquad \textbf{Eq. 3-7}$$

$$\theta_2 = \theta_1 + (\theta_U - \theta_1)\left(1 - e^{-\Delta t/\tau}\right) \qquad \textbf{Eq. 3-8}$$

$$T_2 = T_A + \theta_2 \qquad \textbf{Eq. 3-9}$$

Where:

- θ_U is the ultimate winding hot spot temperature rise.
- θ_R is the rated winding hot spot temperature rise.
- I_2 is winding current at the present time step, t_2.
- I_R is the rated current.
- n is an exponent, generally between 0.7 and 1.0 (default 0.8).
- θ_2 is the winding hot spot temperature rise at the present time step, t_2.
- θ_1 is the winding hot spot temperature rise at the previous time step, t_1.
- Δt is the time step.
- τ is the winding thermal time constant (default 5.0 min).
- T_2 is the winding hot spot temperature at the present time step, t_2.
- T_A is the ambient temperature.

Table 3-2
Temperature Limits for Air-Core Reactors

Insulation Temperature Index (°C)	Average Winding Rise by Resistance (°C)	Hottest-spot Winding Temperature Rise (°C)
105	55	85
130	80	110
155	100	135
180	115	160
220	140	200

3.4 Oil Circuit Breaker

ANSI standard (ANSI 1998) gives an expression for allowable continuous current at different ambients. This expression can be rearranged to give the temperature rise as a function of the current as follows:

$$\theta_C = \theta_{C,R} \left(\frac{I}{I_R} \right)^{1.8} \quad \textbf{Eq. 3-10}$$

Equation 3-10 is for steady state. To calculate the temperature during transient loading periods, it is necessary to break the contact temperature rise over ambient into two components with different time constants: contact rise over oil and oil rise over ambient (ANSI 1979). This may cause some difficulty in application, as the rated contact rise over oil may not be available. In addition, an expression or some guidance needs to be developed in estimating the time constant.

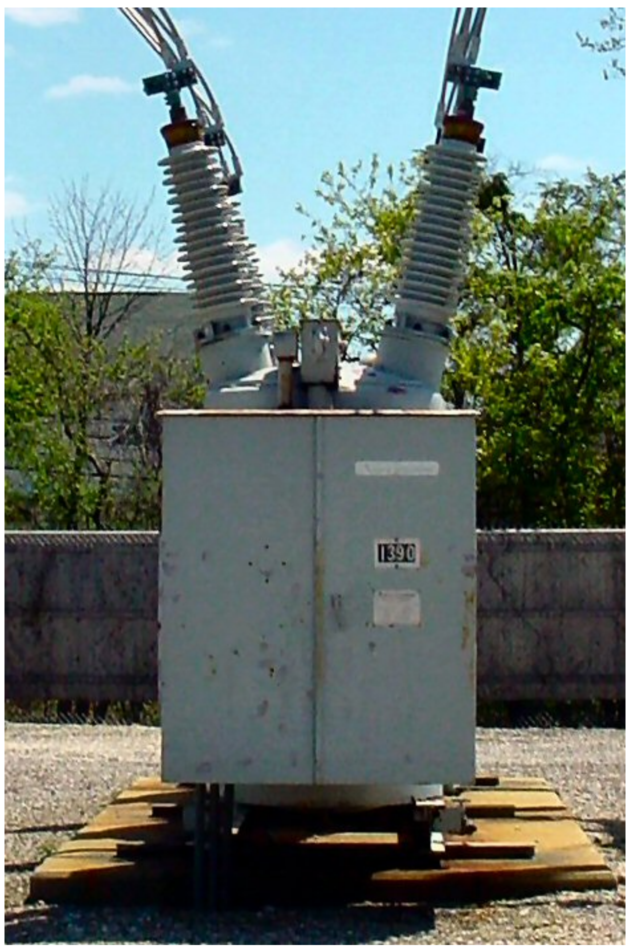


Figure 3-6
Oil Circuit Breaker

The transient formulation is as follows:

$$\theta_{O,U} = \theta_{O,R}\left(\frac{I_2}{I_R}\right)^m \quad \textbf{Eq. 3-11}$$

$$\theta_{O,2} = \theta_{O,1} + \left(\theta_{O,U} - \theta_{O,1}\right)\left(1 - e^{-\Delta t/\tau_O}\right) \quad \textbf{Eq. 3-12}$$

$$\theta_{HS,U} = \theta_{HS,R}\left(\frac{I_2}{I_R}\right)^n \quad \textbf{Eq. 3-13}$$

$$\theta_{HS,2} = \theta_{HS,1} + \left(\theta_{HS,U} - \theta_{HS,1}\right)\left(1 - e^{-\Delta t/\tau_W}\right) \quad \textbf{Eq. 3-14}$$

$$T_{HS,2} = T_A + \theta_{O,2} + \theta_{HS,2} \quad \textbf{Eq. 3-15}$$

Where:

- $\theta_{O,U}$ is the ultimate oil temperature rise.
- $\theta_{O,R}$ is the rated oil temperature rise.
- I_2 is current at the present time step, *t*2.
- I_R is the rated current.
- *m* is an exponent, generally between 1.5 and 2.0 (default 1.8).
- $\theta_{O,2}$ is the oil temperature rise at the present time step, *t*2.
- $\theta_{O,1}$ is the oil temperature rise at the previous time step, *t*1.
- Δt is the time step.
- τ_O is the oil thermal time constant.
- $\theta_{HS,U}$ is the ultimate hot spot temperature rise over oil.
- $\theta_{HS,R}$ is the rated hot spot rise over oil.
- *n* is an exponent, generally between 1.5 and 2.0 (default 1.8).
- $\theta_{HS,2}$ is the hot spot rise over oil at the present time step, *t*2.
- $\theta_{HS,1}$ is the hot spot rise over oil at the previous time step, *t*1.
- τ_W is the winding thermal time constant (default 5.0 min).
- $T_{HS,2}$ is hot spot temperature at the present time step, *t*2.
- T_A is the ambient temperature.

3.5 SF_6 Circuit Breaker

The equations given in (ANSI 1998) and (ANSI 1979) also apply to SF_6 breakers. However, whereas it is necessary to divide the contact temperature rise into two components for oil circuit breakers, it should be sufficient to consider only the temperature rise of the contacts over ambient for SF_6 breakers.

Figure 3-7
SF_6 Circuit Breaker

There should be no appreciable thermal capacitance between the contacts and the ambient air.

$$\theta_U = \theta_R \left(\frac{I_2}{I_R} \right)^{2n} \quad \textbf{Eq. 3-16}$$

$$\theta_2 = T_A + \theta_1 + \left(\theta_U - \theta_1 \right)\left(1 - e^{-\Delta t/\tau}\right) \quad \textbf{Eq. 3-17}$$

Where:

- θ_U is the ultimate contact temperature rise.
- θ_R is the rated contact temperature rise.

- I_2 is breaker current at the present time step, *t*2.
- I_R is the continuous current rating of the breaker.
- *n* is an exponent, generally between 0.7 and 1.0 (default 0.8).
- θ_2 is the contact temperature rise at the present time step, *t*2.
- T_A is the ambient temperature.
- θ_1 is the contact temperature rise at the previous time step, *t*1.
- Δt is the time step.
- τ is the breaker contact thermal time constant (default 5.0 min).

3.6 Bushings (Oil-immersed Equipment Only)

This model (ANSI 1995a) applies to capacitance graded (condenser) bushings with oil-impregnated paper or resin-impregnated paper. Draw-lead bushing applications are not considered, because the temperature rises will depend upon the size of the draw lead conductor and the amount of insulation on the draw lead.

Figure 3-8
Bushing

Note that use of this model requires tested values for K_1, K_2, and n.

The bushing model is as follows:

$$\theta_{TO,U} = \theta_{TO,R}\left(\frac{\left(I_2/I_{E,R}\right)^2 R+1}{R+1}\right)^m \quad \textbf{Eq. 3-18}$$

$$\theta_{TO,2} = \theta_{TO,1} + \left(\theta_{TO,U} - \theta_{TO,1}\right)\left(1-e^{-\Delta t/\tau_O}\right) \quad \textbf{Eq. 3-19}$$

Note: Equations 3-18 and 3-19 are for the calculation of the temperature of the oil in which the bushing is immersed, and are included for the sake of completeness. These equations are not necessary if the oil temperature is specified or monitored.

$$\theta_{HS,U} = K_1\left(I_2/I_{B,R}\right)^n \quad \textbf{Eq. 3-20}$$

$$\theta_{HS,2} = \theta_{HS,1} + \left(\theta_{HS,U} - \theta_{HS,1}\right)\left(1-e^{-\Delta t/\tau_b}\right) \quad \textbf{Eq. 3-21}$$

$$T_{HS,2} = T_A + K_2\theta_{TO,2} + \theta_{HS,2} \quad \textbf{Eq. 3-22}$$

Where:

- $\theta_{O,U}$ is the ultimate oil temperature rise.
- $\theta_{O,R}$ is the rated oil temperature rise.
- I_2 is current at the present time step, $t2$.
- $I_{E,R}$ is the rated current of the equipment (transformer, OCB, etc.).
- m is an exponent, generally between 0.7 and 1.0 (default 0.8).
- $\theta_{TO,2}$ is the oil temperature rise at the present time step, $t2$.
- $\theta_{TO,1}$ is the oil temperature rise at the previous time step, $t1$.
- Δt is the time step.
- τ_O is the oil thermal time constant.
- $\theta_{HS,U}$ is the ultimate bushing hot spot temperature rise over oil.
- K_1 is constant equal to the rated bushing hot spot rise over oil (15-32).
- $I_{B,R}$ is the rated bushing current.
- n is an exponent, generally between 1.6 and 2.0 (default 1.8).
- $\theta_{HS,2}$ is the bushing hot spot rise over oil at the present time step, $t2$.
- $\theta_{HS,1}$ is the bushing hot spot rise over oil at the previous time step, $t1$.

- τ_b is the bushing thermal time constant (default 5.0 min).
- $T_{HS,2}$ is bushing hot spot temperature at the present time step, *t*2.
- T_A is the ambient temperature.
- K_2 is a bushing-specific constant between 0.6 and 0.8.

3.7 Current Transformers

The rating of CTs can be complex. They are rated according to (ANSI 1993), but unlike other substation terminal equipment, the limits on current are a function of the tap selection and the secondary burden as well as the CT itself. No single set of rating factors can be specified for all applications, even in the same utility substation.

To develop continuous ratings, the continuous thermal current rating factor (CTRCF), defined in (ANSI 1993), must be used. The standard does not consider LTE or STE ratings, so these must be determined by nonstandard methods, which should be different for free-standing and for bushing-type CTs.

In general the rating of bushing-type CTs is considered equal to that of the circuit breaker or power transformer in which the CT is installed.

If the tap used on a bushing CT is less than its maximum ratio, additional thermal capacity beyond that of the CT set to its full winding tap position. The adjustment of thermal capacity for tap position can allow operation at currents above the rating for full tap position. For example, at the 50% tap position, the CT rating would be 140% of its full winding position rating.

The adjustment of a free-standing CT whose tap position rating is I_{tap}, and whose rated maximum temperature rise is θ_R, the rating for air temperature (θ_{air}), can be obtained in much the standard ambient adjustment method using the tap rating as a basis:

$$I = I_{tap} * \left[\frac{30 - \theta_R - \theta_{air}}{\theta_R} \right]^{\frac{1}{2}} \qquad \textbf{Eq. 3-23}$$

Noncontinuous ratings can be calculated based on the power transformer model loading guide with 55°C average winding rise and OA cooling mode parameters. The winding rise exponent of 2 is typically used to be conservative.

3.8 Line Traps

Line traps consist of an air-core inductance coil. They are described by reference (ANSI 1981), but the standard does not make rating adjustments terribly clear, and there is some disagreement between sources. Following the method and suggestions outlined in the PJM document on rating of line traps (PJM 1999), suitable temperature limits are a function of the manufacturer as shown in Table 3-3.

Table 3-3
PJM Recommended Temperature Limits for Line Traps

Line Trap Manufacturer	Limit of Rise for Rated Continuous Current (°C)	Normal Max Temperature (°C)	LTE (>24 hrs) Max Temperature (°C)	STE (<24 hrs) Max Temperature (°C)
GE Type CF (1954-1965)	90	130	145	160
Westinghouse Type M	110	150	165	180
Trench Type L	110	150	170	190
GE Type CF (after 1965)	115	155	170	190

The adjustment of line trap continuous rating for air temperature is obtained using the usual equation form with an exponent of 2.0 in (PJM 1999). Other sources use 1.8.

The calculation of an STE rating can be obtained using the temperature limits shown in Table 3-3 in an equation of the form similar to transient calculations with other substation terminal equipment. For a 2-hour STE rating with a GE Type CF, pre-1965 line trap, having a 30-minute thermal time constant, the STE rating is:

$$I_{STE} = \left(\frac{\frac{30}{1-0.0183} + 160 - 130}{90} \right) = 134\% \qquad \textbf{Eq. 3-24}$$

Because of the lack of a clear rating adjustment method in the ANSI standard, the engineer should review the various assumptions before doing such adjustments.

3.9 Other Types of Terminal Equipment

Other types of substation terminal equipment, while not specifically described here, are derived similarly. Two excellent articles on increased power flow for substation terminal equipment are noted as references (Cronin 1972, Conway et al. 1979).

4
UPRATING OF SUBSTATION TERMINAL EQUIPMENT

Overhead lines and underground cables are not considered in this report but are considered elsewhere. The replacement or physical modification of overhead or underground transmission lines is very expensive and can be extremely difficult to schedule given the need for reliable power service. Failure of lines and cables occurs outside of the restricted access of a substation and can result in legal and safety issues. Because of this, real-time monitoring and dynamic rating of lines and cables is relatively easy to justify even though the monitoring and communications can be expensive and complex.

Similarly, power transformers (the primary cost component of substations) and their replacement typically involve large capital outlays and extended service outages. Failure of transformers can occur in a number of ways, and cooling equipment can be complex. As with lines and cables, real-time monitoring of transformers and the development of dynamic thermal rating methods are often easily justified.

Substation terminal equipment considered here fall into one of four categories:

- Conductors that connect current-carrying (and non-current-carrying) equipment (strain bus, jumpers, rigid tubular bus, bolted and welded connectors).
- Air-insulated terminal equipment (line disconnects, free-standing current transformers, series reactors, and power line carrier [PLC] line traps).
- Oil-insulated equipment associated with a power transformer (load tap changers, transformer bushings).
- Oil circuit breakers and associated bushings.

None of the terminal equipment considered have associated forced cooling equipment (fans, circulating pumps for oil, etc.). All have much simpler failure modes than cables, lines, and power transformers. All are considerably less expensive to replace. As a result, as the comedian Rodney Dangerfield might have said, they don't get the same "respect."

There are several ways in which the rating of substation terminal equipment is unique. A large substation may have only a few power transformers and three or four lines connected to it, yet it may have tens or hundreds of line disconnects, bus segments, connectors, etc. Even a moderately short overhead line has miles of conductor that the public can stand under or ride under, whereas all of the substation equipment at a location is enclosed by a fence and warning signs. Imminent failures in power transformer windings, underground cables, and overhead conductor splices are not directly visible or measurable, but in many cases overheated terminal equipment can be detected with a simple infrared scan.

As shown previously, ANSI, IEEE, and IEC standards for substation terminal equipment usually allow the nameplate rating of the equipment to be adjusted for air temperatures other than 40°C. Numerous technical publications suggest that the equipment thermal rating can be further adjusted for heat storage capacity, and that the attainment of equipment temperatures higher than the continuous limits is acceptable for short periods of time.

In reference (Coneybeer 1992), basic thermodynamic methods are applied to switches, bus, and wave traps. The experiments (sponsored by EPRI) and resulting thermal algorithms account for solar heating and forced convection (wind) cooling. In these models, the terminal substation equipment is modeled by multiple, thermodynamically coupled components. While shown to be accurate, the dynamic rating algorithms based on this work required a great deal of detailed weather data, and equipment parameters and dimensions not readily available to the utility engineer.

Choosing practical thermal models for the various types, sizes, and designs of substation terminal equipment is a matter of maximizing accuracy while minimizing complexity. As discussed in the following, the complexity of thermal models and monitoring methods must be balanced against the cost and complexity of implementation, the practicality of maintenance procedures, and the consequences of equipment failure.

Increasing the thermal rating of terminal equipment can be accomplished by one or more of the following methods:

1. Accepting increased deterioration rates by using higher equipment temperature limits.
2. Using actual equipment temperature rise data from manufacturer or field tests rather than conservative estimates.
3. Adjusting the rating for actual weather conditions (e.g., air temperature) and pre-contingency circuit loading.

Unless detailed experimental data is available, the first of these methods can result in unexpected equipment failures. The use of manufacturer or field test data is discussed in Section 5.1. Adjusting ratings by monitoring weather conditions and circuit load is discussed in Section 4.1.

4.1 Monitoring and Communications

Communications is an essential part of dynamic thermal monitoring and rating of any power circuit components. Dynamic rating of overhead lines may require communication of measured data from multiple remote locations along the line route to a nearby substation, where the data is collated and communicated to an operations center by means of RTU channels. This process can be complex and require frequent maintenance visits to unprotected sites.

Dynamic rating of power transformers and terminal substation equipment is much simpler, since any equipment or weather monitoring equipment is kept within the secure boundaries of the substation, and the communications link to the utility operations center is near at hand.

Given the number of switches and other terminal substation equipment, the use of equipment monitors (e.g., a switch contact temperature monitor) is impractical and almost certainly uneconomical. On the other hand, a single weather station located in or near the substation is probably sufficient to dynamically rate all equipment in the station.

4.2 Maintenance and Inspection Procedures

An initial inspection and periodic inspection visits are crucial to reliable operation of dynamically rated terminal substation equipment, since it is not economic to monitor the equipment in real-time. In contrast to overhead lines, the inspection of most terminal equipment can be performed quickly and easily with infrared imaging equipment and a trip to the single substation location. Clearly, algorithms for the dynamic rating assume that the equipment is operating in excellent condition.

It may be very difficult to detect imminent failures of overhead lines (particularly full tension splices) or underground cables, but thermal problems in substation terminal equipment can usually be spotted before an unexpected outage can occur.

4.3 Reliability and Consequences of Failure

Substations are designed to be reliable with alternate configurations available if certain equipment should fail. Thus the consequences of failure of a single substation component may be less than for a critical line or cable.

Failures may occur as the result of metallic deterioration (e.g., switch contact plating), annealing (e.g., strain bus), or insulation aging (e.g., wave traps or free-standing CTs). The mechanism of failure depends on the type of terminal equipment.

In any event, the consequence of failure may be less for substation terminal equipment. Overhead lines and underground cables are placed in corridors that are not secured against public access. If either fails, the public or property may be harmed. Substation equipment is enclosed by fencing designed to limit access, and neither the public nor non-utility property is likely to be damaged in the event of a failure.

On the basis of this observation, certain dynamic rating calculation methods that yield higher thermal ratings in exchange for an increased (but low) probability of temperature limit exceedence may be justified. Such approaches can seldom be justified for overhead lines where the public safety may be directly involved.

5
LINE RATING PREDICTION—AN EXAMPLE CASE

Given the various thermal models for terminal equipment, the calculation of thermal ratings depends on having certain thermal parameters. There are three basic methods by which these thermal parameters can be found. In order of preference the methods are:

1. The manufacturer provides laboratory test data for the device, including transient behavior.
2. Laboratory tests or field measurements are performed to obtain thermal parameters.
3. Typical thermal parameters are selected from the technical literature or from the appropriate standards.

5.1 Manufacturer Test Report Data

Two examples of manufacturer test reports are included here. The first involves temperature measurements at rated load for an SF_6 circuit breaker. The second is for an air disconnect switch.

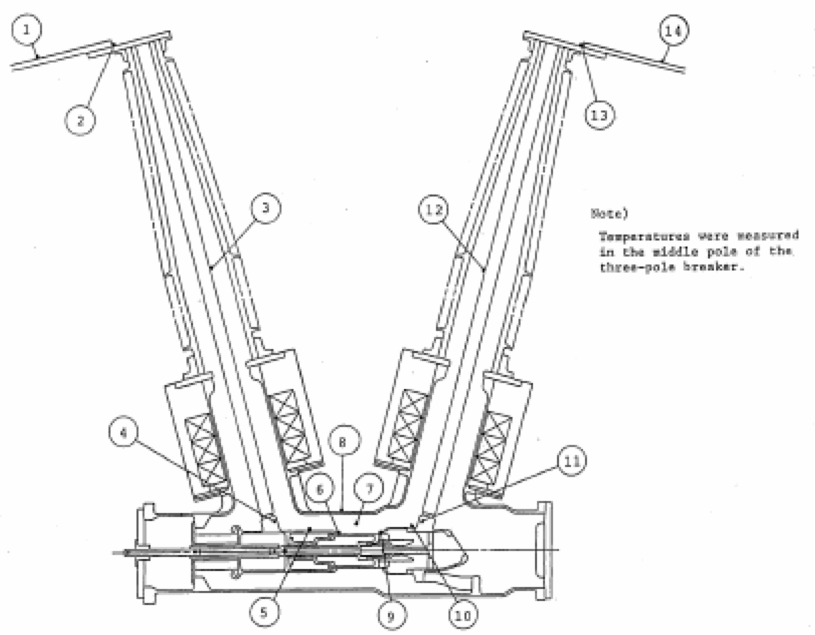


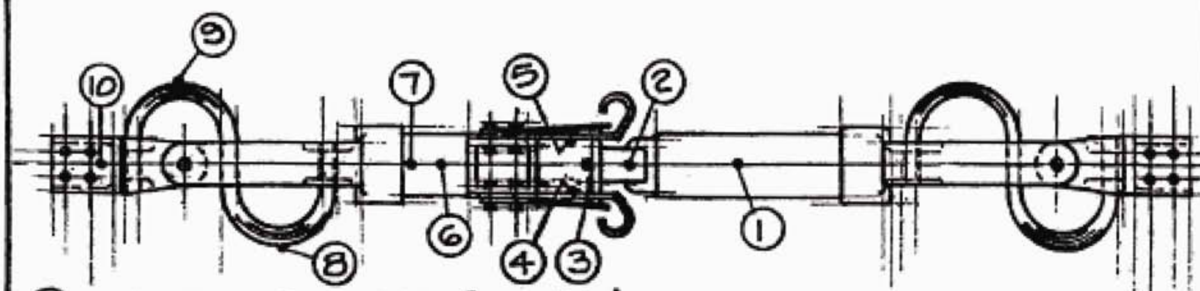
Figure 5-1
SF_6 Circuit Breaker With Measuring Locations for Laboratory Tests

With the SF_6 circuit breaker, the design margins for the various components vary somewhat, but are surprisingly large for most parts. For example, the 44°C temperature rise of the main contact is the highest measured for the various CB components, yet it is considerably less than the default rise of 65°C. The current in the circuit breaker would need to exceed the rated current by more than 20% before the main contact temperature rise reaches 65°C, but at this current level the bushing terminal would exceed its rise limit of 50°C. Considering all the measured temperature rises for all the circuit breaker components, the equipment could be operated at about 15% over nameplate without exceeding the normal ANSI limits.

Table 5-1
Steady-State Temperature Measurements for SF_6 Breaker

Location of TC Measurement	Measured Temperature Rise (°C)	Specified Maximum Temperature Rise (°C)
1 – Conductor for test	41	-
2 – Bushing terminal	38	50
3 – Bushing conductor	42	-
4 – Conductor junction	41	65
5 – Conductor junction	40	65
6 – Finger contact	42	65
7 – SF_6 gas	29	-
8 – Enclosure	22	70
9 – Main contact	44	65
10 - Conductor junction	40	65
11 - Conductor junction	41	65
12 - Bushing conductor	41	-
13 - Bushing terminal	38	50
14 - Conductor for test	40	-
Ambient temp	32	
Loading duration	12 hours	

For the air disconnect, the maximum temperature rise occurs for TC #1. Assuming an allowable temperature rise of 53°C, the measured rise of 42.5°C would allow for a switch load above nameplate of approximately 15%.



SWITCH CURRENT CARRYING PARTS WITH THERMOCOUPLE LOCATIONS.

THERMOCOUPLE READING

	1	2	3	4	5	6	7	8	9	10	11				
TOTAL TEMPERATURE	77.5	71.25	69.5	65	64	72	70	71.5	74.25	73.5	69.5				
TEMP. RISE DEGREES CELSIUS	42.5	36.25	34.5	30	29	37	35	36.5	39.25	38.5	34.5				

THERMOCOUPLE 12 = 35°C AMBIENT TEMPERATURE AT END TEST PERIOD

NOTES:
THERMOCOUPLES #5 & #4 INSIDE OF TOP FEMALE CONTACT SHOES
THERMOCOUPLE #3 AT TOP END OF MALE CONTACT

Figure 5-2
Laboratory Test Data for Switch at Rated Loading

6 CONCLUSIONS AND SUMMARY

In this report concerning increasing ratings for substation terminal equipment, certain methods of calculation are presented that allow safe, reliable operation of terminal equipment above its "nameplate" rating. Thus a 1200 A switch may be operated at more than 1200 A by considering actual air temperature (rather than 40^{o}C), the manufacturer's test data for temperature rise at rated load (rather than default ANSI values), and possible operation at higher than usual temperature limits. In addition, for emergency ratings, the limited duration emergency rating may be higher if the heat storage capacity of the switch is considered.

If air temperature at the substation and the electrical loading of the equipment are reported to SCADA/EMS in real-time, substation terminal equipment can be dynamically rated. This is particularly useful in increasing the circuit rating when overhead lines, power transformers, or underground cables, in series with the terminal equipment, are also dynamically rated.

Field verification of substation equipment thermal behavior is particularly important since the basic rating of the equipment and all methods of increasing the rating depend upon the equipment being in excellent condition. Field measurements made with infrared imaging cameras are an excellent way to affirm the thermal condition of substation equipment. Not only is it possible to use infrared imaging cameras to spot high temperatures and detect damaged equipment, but if small areas of the surface of bus, switches, etc. are prepared by painting, a high-quality camera in the hands of an experienced operator can be used to measure temperatures within a few degrees centigrade. Under high current load conditions, equipment temperature measurement can serve to verify the thermal models and parameter assumptions.

In summary, it is possible to operate substation terminal equipment at current levels exceeding "nameplate" by 5% to 15% in most cases without reducing reliability, but the condition of the equipment must be verified by periodic inspections.

7
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A
CIGRE PAPER

Dynamic Thermal Rating of Substation Terminal Equipment

by

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A.1 Abstract

Open transmission access and economic uncertainties are the reasons why many utilities around the world are operating their transmission equipment at much higher loads than in the past. While considerable attention has been paid to the dynamic thermal rating of overhead lines, power transformers, and underground cables [1], substation equipment has generally been ignored. This seems to have occurred because of the assumption of relatively low replacement cost for switches, buswork, etc..

The authors contend that the utilization of relatively simple dynamic rating algorithms, new simpler field temperature calibration methods, and the rising cost of outages required for equipment replacement, make the dynamic rating of substation equipment both practical and relatively cheap.

This work was initiated by EPRI to supplement and extend the prior efforts to develop and field test dynamic rating methods for lines, cables, and power transformers [2].

KEY WORDS: Substation Equipment - Overhead Line - Underground Cable - Power Transformer – Transmission - Dynamic Ratings - Thermal Time Constant - Annealing - Loss Of Insulation Life – Line Disconnects – Wave Traps – Circuit Breakers - Buswork

A.2 Introduction

Power transmission companies are undergoing a major transformation that requires the increased utilization of existing power equipment while maintaining system reliability. Those electric utilities that own and operate the existing transmission system must respond to the need for increased local transmission capacity with uncertain return on investment. As a result, the real-time monitoring and dynamic rating of power equipment [1] is becoming an important tool in

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assuring the public safety and maintaining system reliability while allowing increased power flows with minimum capital investment.

In a recent Electra article entitled "Dynamic Loading of Transmission Equipment – An Overview" [3], representatives of Study Committee 23 concluded, "there is scope for implementing dynamic loading principles for a wide range of transmission assets." The need for dynamic modeling of substation equipment is illustrated in the following Figure taken from [4]. It shows that the thermal rating of over 50% of the transmission circuits in the state of New York state are thermally limited by substation equipment (see Figure 1).

The dynamic rating of overhead lines has been studied extensively. Real-time monitoring devices have been developed and tested leading to the practical implementation of dynamic line ratings at many locations [5], [6]. Similarly, underground cables and power transformers have also been studied extensively, monitoring devices developed and tested, and improved thermal models proposed and tested. This generally successful attempt to increase the utilization of major power equipment whose replacement requires large capital investment and long outage periods is relatively easy to justify economically.

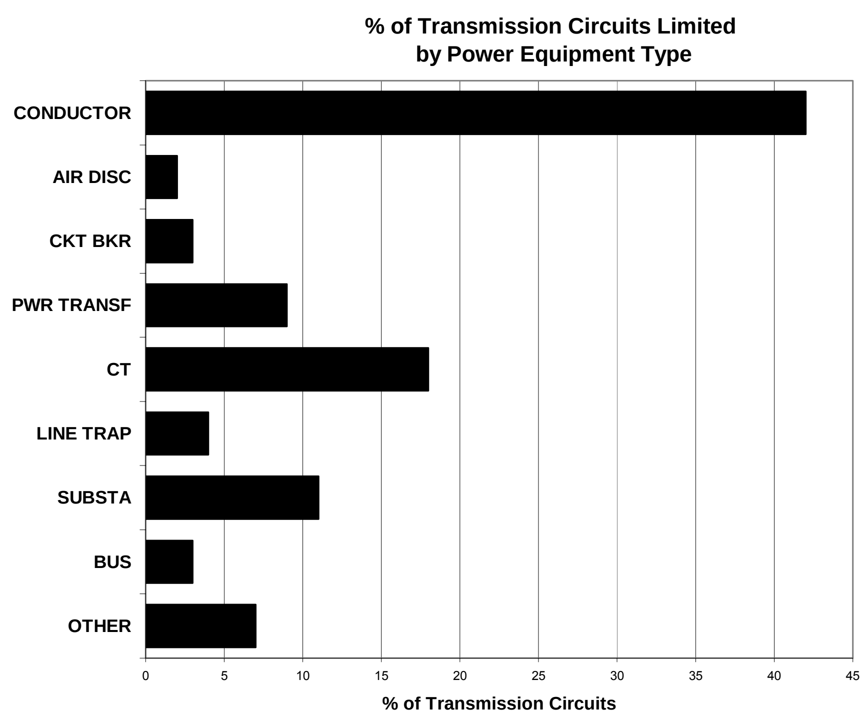

Figure A-1
Thermally Limiting Transmission Circuit Equipment

This paper investigates the practicality of dynamically rating and monitoring less capital-intensive substation equipment such as switches, bus, line traps, breakers, and power transformer auxiliary equipment. Because the equipment being dynamically rated is generally less expensive to replace, some of the dynamic rating methods involving relatively expensive monitoring equipment, that have been applied to lines, cables, and transformers are difficult or even impossible to justify economically for substation equipment. Also, because of the large number of switches, circuit breakers, etc., in any power system, and the variety of designs, thermal models and weather monitoring must be kept simple.

Also, in keeping with the emphasis on simplicity and low cost for dynamic rating of substation equipment, simple and low cost methods of field temperature measurement are considered. Future evaluation of experimental methods will need to be incorporated into practical thermal models that provide estimates of safe current loading limits.

This paper will address the following questions:

- What is the temperature response of substation equipment at currents above "nameplate"?
- What is the impact of high temperature operation on substation equipment life?
- What are the risks involved in postponing the replacement of existing substation equipment?
- What types of temperature sensors can be used to measure critical temperatures in such equipment?
- Are special inspection or maintenance methods necessary for substation equipment while running at higher ratings?

A.3 Dynamic Thermal Circuit Rating Technology

In 1993, EPRI initiated a project to develop and field test software, which would allow the "real-time thermal monitoring of transmission circuits" [1]. Thermal models for underground cable, overhead lines, power transformers, and substation equipment such as line traps, circuit breakers, bus, switches, and current transformers were studied. The resulting thermal models were incorporated into the DTCR (Dynamic Thermal Circuit Rating) and PTLOAD (Power Transformer LOADing) programs, intended for use by operators and substation engineers, respectively.

Since that initial project, the EPRI software has gone through several fundamental revisions and extensions involving the improved modeling of overhead lines and underground cables and power transformers but the simple "ambient adjusted" thermal models for substation equipment (e.g. switches, substation bus, cable jumpers, circuit breakers, wavetraps, current transformers, and connectors) have not been revised.

Though DTCR can calculate dynamic ratings of lines, cables, and transformers accurately, the calculation of dynamic ratings of other substation equipment is presently rather limited. The consequences of high temperature operation of substation equipment are not clearly understood and suitable thermal parameters for older substation equipment are seldom available.

This paper will report the initial results and future plans for research involving the high temperature operation of substation equipment other than power transformers.

A.4 Dynamic Rating Issues—Substation Terminal Equipment

Substation equipment considered in this paper excludes power transformers. Power transformers are the primary cost component of substations. Their replacement typically involves large capital outlays and extended service outages. Failure of transformers can occur in a number of ways and cooling equipment can be complex. Because of this, real-time monitoring of transformer physical and thermal state is often justified and is often combined with dynamic rating calculations to allow increased asset utilization.

Terminal substation equipment (air disconnects, circuit breakers, bus, bushings, current transformers, and wave traps) are functionally and physically simpler, none have associated forced cooling equipment, all have much simpler and generally more obvious failure modes, and all are considerably less expensive to replace. Finally, while even a large substation may have only a few power transformers, it usually has many switches, bus segments, connectors, etc.

In those situations where terminal substation equipment limits the increase in power flow that could otherwise be obtained by dynamically rating a power transformer, line or cable, the dynamic rating of the terminal equipment is a sensible option. This is particularly true in those cases where the economic losses associated with the circuit outage needed for the replacement are high.

Nonetheless, since the replacement cost of terminal substation equipment is modest, and since the numbers of such equipments is large, any process of monitoring and/or dynamically rating terminal substation equipment must be correspondingly modest.

ANSI, IEEE and IEC standards [7], [8], [9], [10] for substation equipment usually allow the nameplate rating of the equipment to be adjusted for air temperatures below 40°C. Numerous technical publications suggest that the equipment thermal rating can be further adjusted for heat storage capacity and that the attainment of equipment temperatures higher than the continuous limits is acceptable for short periods of time [11,12,13].

In reference [14], basic thermodynamic methods are applied to switches, bus, and wave traps. The experiments and resulting thermal algorithms account for solar heating and forced convection (wind) cooling. In these models, the terminal substation equipment is modeled by multiple, thermodynamically coupled components. While shown to be accurate, the dynamic rating algorithms based on this work required a great deal of detailed weather data, and equipment parameters and dimensions not readily available to the utility engineer.

The choice of a practical dynamic thermal model for the various types, sizes and designs of substation terminal equipment is a matter of maximizing accuracy without requiring excessive complexity in monitoring or characterizing the equipment. As discussed in the following, the complexity of dynamic thermal models and monitoring methods must be balanced against the cost and complexity of implementation, the practicality of maintenance procedures, the consequences of equipment failure.

A.4.1 Monitoring and Communications

Communications is an essential part of dynamic thermal monitoring and rating of any power circuit components. Dynamic rating of overhead lines may require communication of measured data from multiple remote locations along the line route to a nearby substation where the data is collated and communicated to operations center by means of RTU channels. This process can be complex and require frequent maintenance visits to unprotected sites.

Dynamic rating of power transformers and terminal substation equipment is much simpler since any equipment or weather monitoring equipment is kept within the secure boundaries of the substation and the communications link to the utility operations center is near at hand.

Given the number of switches and other terminal substation equipment, the use of equipment monitors (e.g. a switch contact temperature monitor) is impractical and almost certainly uneconomical. On the other hand a single weather station located in or near the substation is probably sufficient to dynamically rate all equipment in the station.

A.4.2 Maintenance and Inspection Procedures

An initial inspection and periodic inspection visits are crucial to reliable operation of dynamically rated terminal substation equipment since it is not economic to monitor the equipment in real-time. In contrast to overhead lines, the inspection of most terminal equipment can be performed quickly and easily with infrared imaging equipment and a trip to the single substation location. Clearly, algorithms for the dynamic rating assume that the equipment is operating in excellent condition.

It may be very difficult to detect imminent failures of overhead lines (particularly full tension splices) or underground cables but thermal problems in substation terminal equipment can usually be spotted before an unexpected outage can occur.

A.4.3 Reliability and Consequences of Failure

Substations are designed to be reliable with alternate configurations available if certain equipment should fail. Thus the consequences of failure of a single substation component may be less than for a critical line or cable.

Failures may occur as the result of metallic deterioration (e.g. switch contact plating), annealing (e.g. strain bus), or insulation aging (e.g. wave traps or free-standing CTs). The mechanism of failure depends on the type of terminal equipment.

In any event, the consequence of failure may be less for substation terminal equipment. Overhead lines and underground cables are placed in corridors that are not secured against public access. If either fails, the public or property may be harmed. Substation equipment is enclosed by fencing designed to limit access and neither the public nor non-utility property is likely to be damaged in the event of a failure.

On the basis of this observation, certain dynamic rating calculation methods that yield higher thermal ratings in exchange for an increased (but low) probability of temperature limit exceedence may be justified. Such approaches can seldom be justified for overhead lines where the public safety may be directly involved.

A.5 Special Thermal Issues

Clearly, not all types of substation terminal equipment have the same failure modes or the same thermal change rates in response to changes in weather and current levels. There are, however, certain common issues that involve almost all types

A.5.1 Heat Storage

In comparison to bare overhead line conductors, the cooling rates of substation terminal equipment is normally lower and the mass per unit length is normally higher so thermal time constants are higher. Where overhead line thermal time constants may be 5 to 10 minutes, switches and bus may be somewhat longer (e.g. 15 minutes for switches and 30 minutes for circuit breakers). As a result, the increase in transient ("short time emergency") or dynamic ratings for substation terminal equipment ratings may show a larger increase over continuous ratings than are seen for overhead lines.

A.5.2 Mutual Heating

Power equipment operating temperatures may be limited either to protect critical components from thermal damage or to limit the heating of electrically connected equipment. One of the goals of this work is to characterize the problem of mutual heating of electrically connected equipment. Lines, operated at high temperature levels may cause heating of its substation terminal equipment

A.5.3 Contact Resistance

In many locations within the substation, contact resistance of bolted connectors, compression connectors, and line disconnect contacts are a matter of concern. It is probably impractical to consider contact resistances in the dynamic rating calculation but it is relatively easy to see such problems with infrared inspections.

A.6 Thermal Models for Substation Equipment

In comparison to thermal models for overhead line conductors and underground cables, thermal models for substation equipment can be quite complex because they typically consist of multiple different component parts and because the heat flow is typically three not two dimensional. In research at the Georgia Institute of Technology, Coneybeer [14] developed a complex model for a particular type of 1200 ampere line disconnect switch. Separate models were developed for bus connections, contacts, and flexible shunt straps. The effects of wind and air temperature were included for each of the switch components. The emissivity of each switch component as well as the dimensions of each were required as input to the calculation.

As noted previously, the use of such complex dynamic thermal models is not usually justified for substation terminal equipment. As an alternative, simpler non-thermodynamic models, based upon manufacturer test data adjusted for air temperature and including heat storage effects is probably adequate and appropriate.

Consider the following simple model for a continuous rating calculation of a switch where the manufacturer test data indicates that the 1200 amp nameplate rating is based upon a critical equipment temperature of 70°C and an air temperature of 40°C.

$$TMAX_{SS} = 1200 * \sqrt{\frac{70 - 25}{70 - 40}} = 1470 \text{ AMPS}$$

The calculated increase in continuous rating is based upon a constant monitored real-time air temperature of 25°C. Using models such as this, all of the switches of this same design in the substation can be given the higher continuous rating as long as the air temperature remains at 25°C.

A.6.1 Dynamic Emergency Ratings

Depending upon engineering judgment, manufacturer recommendations and the advice of applicable equipment standards, it may be possible to allow the substation terminal equipment to go to a critical equipment temperature 105°C for a limited period of time, perhaps 30 minutes or several hours.

The dynamic emergency rating of the same equipment can then be increased as follows:

$$I_{LTE} = 1200 * \sqrt{\frac{105 - 25}{70 - 40}} = 1960 \text{AMPS}$$

A.6.2 Line (Wave) Traps

Line traps present an unusually complicated thermal modeling problem. In older models, the AC and DC resistance ratio far exceeds that of bus or overhead conductor because of coupling between adjacent turns of the trap coil but certain designs exhibit ratios that are far lower than those found on older designs. Certain designs allow free movement of air between the windings, others do not. End caps are used on some traps to prevent access by animals; these caps greatly alter the thermal characteristics of the coils. Line traps may be mounted either vertically or horizontally, which greatly alters the convection cooling characteristics.

The increase in dynamic rating of line traps is generally less than that of bus and switches.

A.6.3 Current Transformers

Normal ratings for CTs can be found using the methods of ANSI Standard C57.13 according to the CT current rating factor (CTCRF), which varies from 1.0.

LTE and STE ratings can be calculated using equations and parameters essentially similar to those for the OA rating of power transformers.

LTE and STE ratings of bushing type CTs will normally be as great as the rating of the circuit breaker or power transformer to which they are attached though the manufacturer should be consulted to assure that no damage is done to the parent unit.

A.6.4 Circuit Breakers

Ratings of circuit breakers are essentially calculated by the ambient adjusted methods. The equation for the normal continuous, steady state rating of a circuit breaker is:

$$I_{SS} = I_{NP} * \left[\frac{TMAX_{SS} - TA}{TMAX_{NP} - TA_{NP}} \right]^{\frac{1}{1.8}}$$

LTE and STE ratings can also be calculated with the ambient adjusted rating model by noting that the maximum allowable temperature of contacts is similar to those of air disconnect switches (105°C) and that the time constant of the circuit breaker should be taken as 1/2 hour unless otherwise determined.

A.7 Dynamic Rating of Substation Terminal Equipment

The dynamic rating of substation terminal equipment by means of ambient adjustment of manufacturer ratings meets the need for simplicity and low cost. The concept is straightforward. Substation equipment is tested indoors at relatively high air temperature in order to come up with the nameplate rating. Furthermore, the rating is specified for a constant electrical load. Therefore, the nameplate rating can be adjusted both for air temperatures below the test temperature and for sudden limited duration electrical loads.

The simple equations for ambient adjustment of ratings can be extended to consider heat storage if a thermal time constant can be determined either by test or estimate. Short time emergency ratings are a function of the maximum allowable critical equipment temperature for short times, the thermal time constant and the initial equipment temperature at the onset of the increased load. The simple ambient adjusted model can be modified to allow tracking of equipment temperature and dynamic estimates of short time emergency ratings.

A.7.1 Air Temperature Variation

Air temperature is usually quite consistent over modest distances. While this of course depends on terrain, the variation in air temperature within the typical substation or over distances of as much as a few miles is quite small. For example, consider Figure A-2, which compares air temperature between two locations approximately 2 km apart over a week.

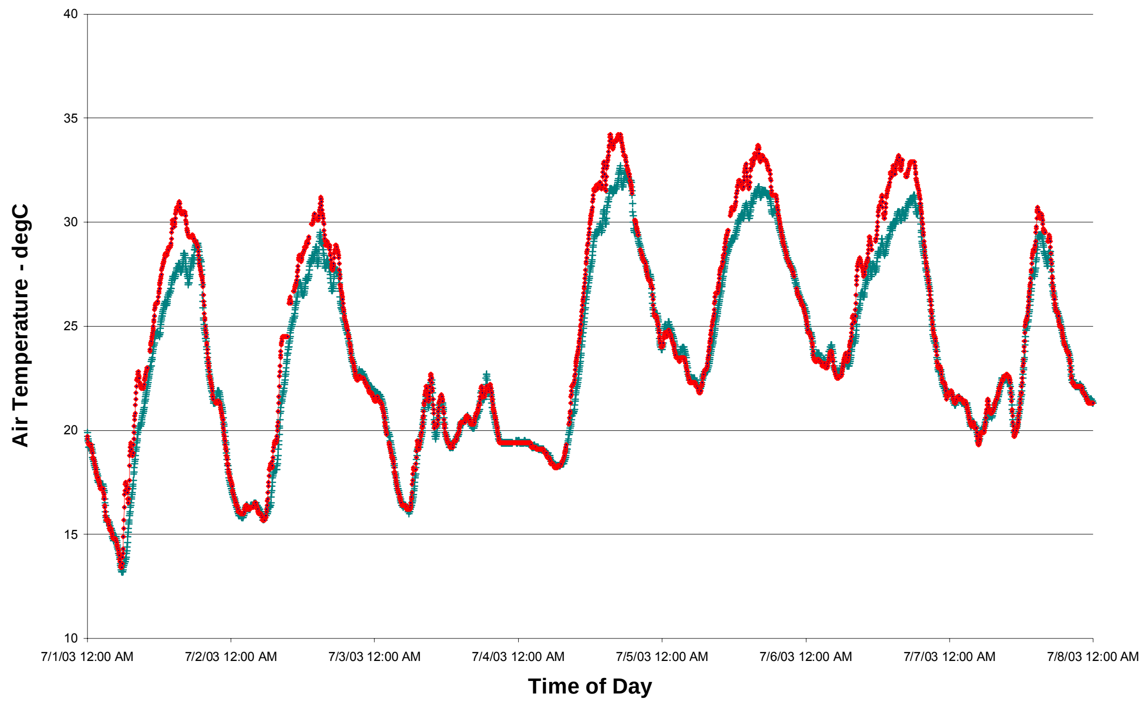

Figure A-2
Comparison of Air Temperature at Two Locations Approximately 2 km Apart.

In addition to being reasonably consistent between nearby locations, air temperature is both quite consistent and predictable in daily variation as shown in Figure A-3.

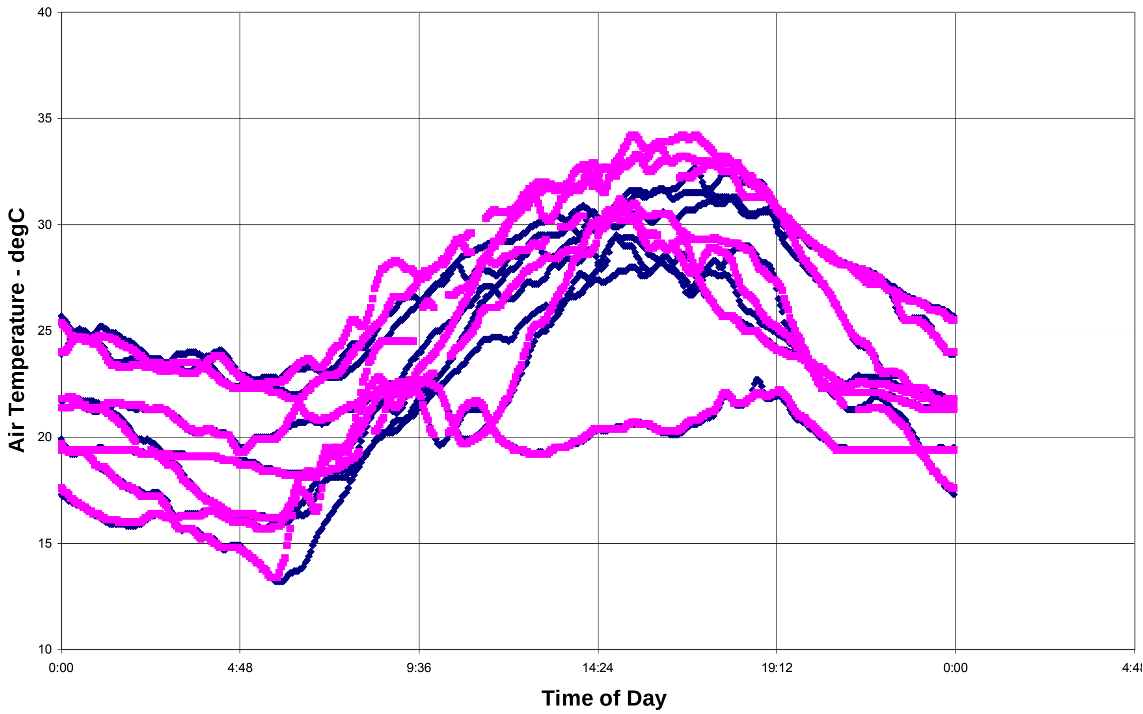

Figure A-3
Examples of Daily Variation in Air Temperature Over a One Week Period.

These characteristics of air temperature, consistency over moderate distances and chronological predictability, make this variable attractive as the basis for the dynamic rating of substation terminal equipment. A single simple air temperature monitor within or in the vicinity of the substation can be used in conjunction with relatively simple thermal models to dynamically rate all of the terminal equipment in the substation.

A.8 Field and Laboratory Measurements

Certain types of thermal measurements are required in dynamically rating substation equipment.

- Manufacturer's heat run testing allows a more accurate estimate of the critical equipment component temperature at the nameplate current rating. In general, the use of actual manufacturer's test data yields somewhat higher ratings even at the "nameplate rating" test air temperature.
- Manufacturer's test data does not normally include transient load response data. If transient ratings are to be calculated, such information must be obtained by laboratory testing of typical equipment or by field measurements. In the laboratory, temperatures can be monitored with thermocouples and step current changes can be applied in a controlled fashion. This does not, however, give a realistic estimate of the equipment temperature field conditions.
- Field test data can be obtained through the use of infrared imaging equipment and limited outages required to prepare equipment surfaces with a paint of controlled emissivity.

A.9 Conclusions

Because of the relative modest costs of replacement, the successful dynamic thermal rating of substation equipment requires relatively simple thermal models that can be used with low cost monitoring and communication links. Furthermore, high maintenance cost and any increase in present failure rates must be avoided.

This paper suggests a generic, simple thermal model that can be customized for various types and designs of substation equipment. The model is a straightforward extension of the ambient adjustment methods allowed in most equipment standards.

Required environmental monitoring is limited to real-time air temperature in the vicinity of the rated substation equipment. The single air temperature monitor can be located within or adjacent to the substation wherein the substation equipment resides. If an air temperature monitor associated with the dynamic rating of nearby lines or power transformers is already available, that data may be used after some simple field measurements.

Because of the variety of substation designs and types and the frequent lack of laboratory heat run data (particularly regarding transient thermal behavior), field tests of substation equipment may be required. A relatively simple method involving the use of infrared imaging devices is suggested and is presently being evaluated.

The dynamic rating of substation equipment can often be justified both economically and technically, particularly in those situations where the equipment would otherwise limit the increase in dynamic rating that can be obtained with overhead lines, power transformers, or underground cables.

A.10 References

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A.11 Biographies

Dr. Rambabu (Ram) Adapa is working at the Electric Power Research Institute (EPRI), Palo Alto, California, USA as the Technical Manager, Increased Power Flow, in the Transmission & Substations area of Power Delivery & Markets Sector. Prior to this position until June 2001, he was Manager, International Technical Liaison for Power Delivery. Until December 1999, he was the Product Line Leader for Transmission, Substations, and Grid Operations. Also, Dr. Adapa was a Channel Director for the newly created EPRI subsidiary company, ElectricWindow (an e-commerce company) during late 1990s. Previously, Dr. Adapa worked as Manager of Power System Planning, in the Grid Operations and Planning Business Area at EPRI. Prior to joining EPRI in 1989, he was a Staff Engineer in the Systems Engineering Department of McGraw-Edison Power Systems (presently known as Cooper Power Systems), Franksville, Wisconsin. Dr. Adapa is a Senior Member of the IEEE Power Engineering Society; member of several IEEE working groups and CIGRE task forces. Dr. Adapa received the 2001 IEEE Regional Outstanding Engineer award for Region 6 for his outstanding contributions to the Power Engineering Profession and to the IEEE Power Engineering Activities in Region 6. He is a Registered Professional Engineer in the State of Wisconsin. He is an individual Member of CIGRE.

Dr. Dale A. Douglass is a Principal Engineer of Power Delivery Consultants, Inc. based in Niskayuna, New York. He has over 30 years of experience in transmission power delivery, having worked with Power Technologies, Inc., Kaiser Aluminium, and Bell Laboratories in addition to PDC. He is presently the convenor of CIGRE Working Group B2-12 on Electrical

Aspects of Transmission Lines and Vice Chairman of IEEE's Towers, Poles, and Conductors Subcommittee. He has been involved in studies of overhead line sag-tension, high temperature operation, dynamic rating of lines, cables, and substation equipment, and both current and voltage upgrading of overhead lines. In 1996 he was elected a Fellow of the Institute of Electrical and Electronic Engineers.

B
REPORT FROM SNELL INFRARED ON MEASUREMENTS PERFORMED AT PSNM AND CNP

The acrobat files “EPRI_Infrared_PSNM” and “EPRI_Infrared_CPE” give some idea of the form and quality of infrared measurements of substation terminal equipment. A few simple conclusions can be made from these initial measurements.

- The ability to see both visual and infrared pictures side by side simplifies understanding of the measurements.
- Certain temperature measurements require surface preparation (painting) to control emissivity. This is necessary for infrared temperature measurement accuracy on surfaces such as tubular aluminum bus. Painting was done with a hot stick and roller at PS NM.
- A major challenge in doing such field measurements will be finding terminal equipment with high enough electrical loads to see equipment temperatures well above ambient.
- With the hand-held camera, it is possible to take and record a series of shots, fast enough to estimate temperature change with time if a load change can be arranged.
- We found a switch operating at 200oF with a load of 25% nameplate. This emphasizes the need to perform an infrared scan prior to trying to increase ratings of terminal equipment.
- We will try to arrange laboratory measurements where we can verify the imaging camera temperature accuracy by comparison to thermocouple measurements.

C
USE OF HEAT RUN DATA IN STLOAD

Thermal models in STLOAD fall into two broad categories: 1) detailed thermodynamic models and 2) empirical models. The detailed thermodynamic models are used in devices with simple and, more importantly, known geometries. This is limited to overhead line conductors and lengths of substation bus conductor. More complex equipment, including switches, circuit breakers and line traps, must use an empirically-based model. For these devices, the exact geometry and dimensions are rarely known and most often cannot be measured. Even if the geometry were known, the complex geometry would make application of heat transfer correlations extremely difficult.

These empirical models are all of similar form. A benchmark temperature rise (above the surrounding ambient medium) is given at a specified load level (usually the nameplate rating). This known temperature rise is then related to arbitrary load levels by the ratio of losses (heat generated) raised to some exponent, as illustrated in the following equation:

$$\Delta\theta_1 = \Delta\theta_R \left(\frac{I_1}{I_R}\right)^n \qquad \textbf{Eq. C-1}$$

Where,

- $\Delta\theta_R$ is the temperature rise at rated load
- I_R is the rated load current
- $\Delta\theta_1$ is the temperature rise at a given load, I_1
- n is an exponent between 1.2 and 2.0

The above equation gives the temperature rise of a component above the surrounding medium at steady state. The temperature at any time, t, can be determined by equating the heat input to the sum of the change in heat storage and the heat loss:

Heat generated = Change in heat storage + Heat loss

$$Q_{gen} = mC_p \frac{d\theta}{dt} + K\Delta\theta^x \qquad \textbf{Eq. C-2}$$

Traditionally, transient temperatures have been calculated by approximating an instant of time as a step-change in load and calculating the temperature at the end of the time step as follows:

$$\Delta\theta = \Delta\theta_i + \left(\Delta\theta_u - \Delta\theta_i\right)\left(1 - e^{\frac{-\Delta t}{\tau}}\right) \qquad \textbf{Eq. C-3}$$

Where,

$\Delta\theta$ is the calculated temperature at time $t+\Delta t$
$\Delta\theta_i$ is the initial temperature at time t
$\Delta\theta_u$ is the ultimate steady-state temperature
Δt is the time step
τ is the time constant

Therefore, for any piece of equipment (except for bus), the following must be measured, derived or estimated:

- Temperature rise at rated load (or some known load)
- Exponent that relates temperature rise to load
- Thermal time constant

For components that are immersed in oil, the above information must be given for both the component rise over oil and the oil rise over air.

The temperature rise at rated load must either be measured during a factory type test on a similar piece of equipment or it must be estimated using knowledge of the applicable standards that the equipment was designed to. Often, if the manufacturer is still in business, a test report giving at least the temperature rise at rated load can be obtained. Often, a diligent manufacturer will also have measured temperature rise at an additional load level or load levels.

With some substation equipment, such as circuit breakers or switches, temperature rises may be measured and reported for several components. Some of these components will have different allowable temperature rises, given the material and application. The question then becomes what temperature rise should be used. In the simplest case, where all components have the same allowable temperatures, the temperature rise of the component with the highest reported temperature rise is used.

C.1 Derivation of Exponent

There are three experimental situations to model as shown in the following.

C.1.1 Single Measured (or estimated) Temperature

In this simple case, the exponent cannot be derived from the measured value, since we only have a single data point. Therefore, the value must be estimated by a combination of experience with similar equipment where the temperature rise was measured at more than one load level and knowledge of the heat transfer mechanisms present. From the heat transfer correlations for the three mechanisms of heat transfer of importance, the following range of exponents can be derived for each mechanism over the temperature range of interest:

Mechanism	Exponent (Losses)	Exponent (Current)
Radiation	0.883-0.895	1.77-1.79
Forced Convection	1.0	2.0
Natural Convection	0.75-0.8	1.5-1.6

The combined exponent for a given component depends upon the relative proportions of each mechanism present. Since wind speeds are highly variable in a substation environment and the exact determination of heat transfer for a given wind speed is extremely difficult for anything more than a simple geometry, the contributions of forced convection are neglected. This isn't a gross error, however, since the components of interest generally do not have a large surface area exposed to the wind. Given that forced convection is a small portion of the total heat transfer, the remaining mechanisms are dominant. Therefore, exponents tend to be in the range of 0.75 to 0.9. If the exponent is unknown, selecting a value of 0.9 is appropriate.

Example 1

ITE 230kV 1600A Type TTR-49 switch manufactured in 1960

Looking at the measured temperature rises (Appendix A), the highest temperature rise of is 29.5C. For the exponent, a value of 1.8 is used, as suggested above.

C.1.2 Measured Temperatures at Two Load Points

Given two temperature rises at two different load levels, the exponent can be estimated by:

$$n = \frac{\log\left(\frac{\Delta\theta_1}{\Delta\theta_2}\right)}{\log\left(\frac{I_1^{\,2}}{I_2^{\,2}}\right)} \qquad \textbf{Eq. C-4}$$

Example 2

ABB Type 145PM63 145kV 2000A & 3000A SF6 circuit breaker manufacturer in 1992

Highest component temperature rise was 27.6C at 2000A and 47.0C at 3000A. Using the above equation, the exponent is:

$$n = \frac{\log\left(\frac{47.0}{27.6}\right)}{\log\left(\frac{3000}{2000}\right)} = 1.3$$

C.1.3 Measured Temperatures at Three or More Load Points

When three or more load points are present, the equation given above will yield slightly different exponents for each pair of temperatures, given errors in measurement and the small inaccuracies in modeling. Therefore, it is best to use a form of regression fit to select the exponent that gives the best fit to all available points. This is easily accomplished using a spreadsheet software package, widely available today. At the time of this writing, Microsoft Excel XP is a commonly available package, and will be used here to demonstrate this process. However, the procedure should be similar for other packages. The general procedure (in Excel) is as follows:

1. Plot temperature rise vs. per unit load for each available data point.
2. Right-click on data points in chart and select “Add Trendline”.
3. For the “Trend/Regression type” select “Power”.
4. Click on the “Options” tab and select the option labeled “Display equation on chart”.
5. Click “OK” to generate the trendline. The equation will be displayed on the chart, for example “$y = 42.512x^{1.5094}$”. The exponent in this equation is the best-fit exponent for all of the available data points. In the example given, the exponent would be 1.5.

C.1.4 Derivation of Time Constant

The derivation of the thermal time constants requires continuous temperature measurement over a step change in load current. The thermal time constant is the length of time it takes to reach 63.2% of the ultimate steady-state temperature rise minus the initial steady-state temperature rise.

Example:

$t_i = 36C$
$t_f = 64C$
$0.623 * (64C – 36C) + 36C = 53C$

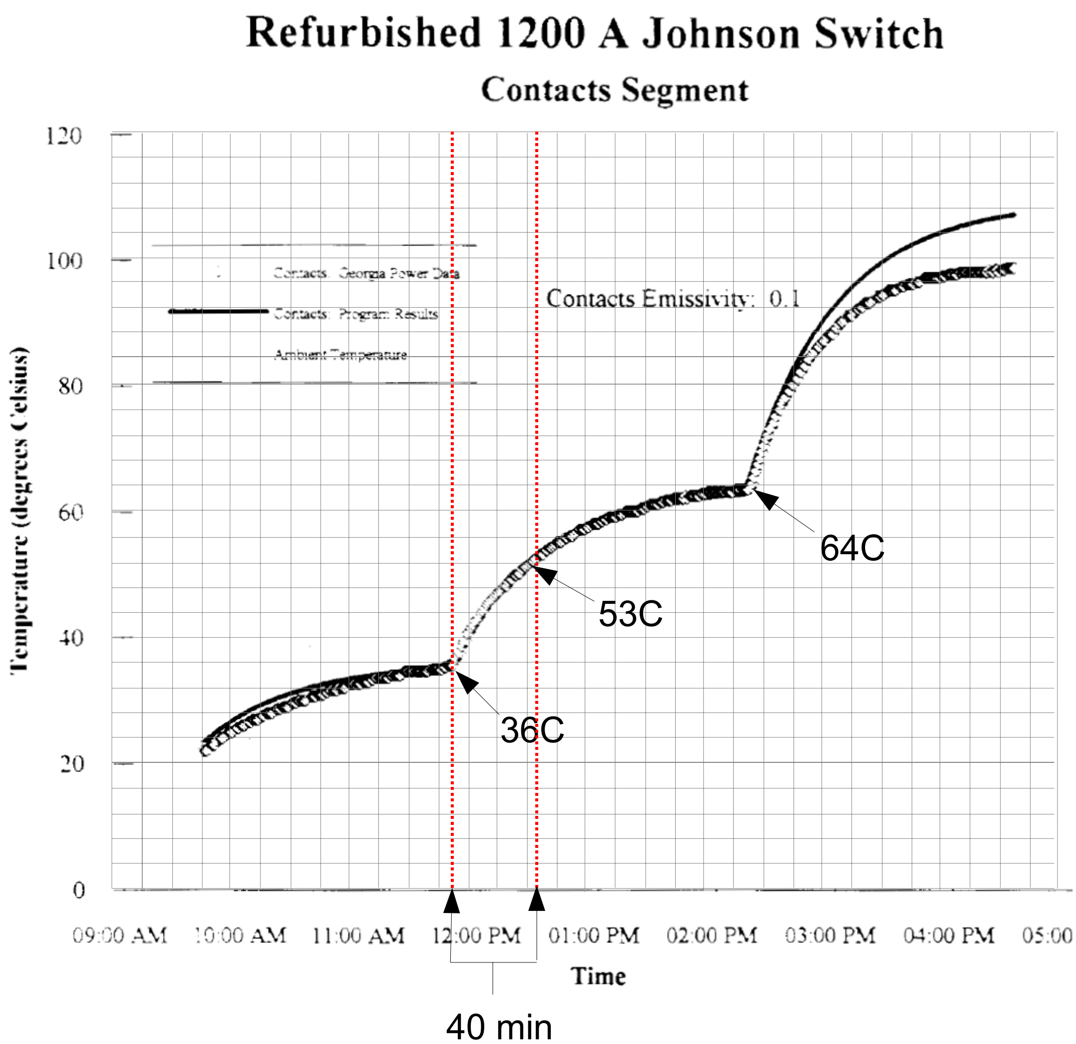


Figure C-1
Transient Heat Run Tests for a 1200 A Switch

From the plot of temperatures, the time constant for this switch is approximately 40 minutes.

C.2 Switch (Air Disconnect)

ANSI Standards [9] specify certain requirements for high voltage air disconnect switches. The standards specify the rated current (thermal rating) of the switch and the weather conditions and equipment temperatures under which the rating is calculated. For example, modern switches, produced after 1971, with silver contacts, are rated for continuous operation at a temperature rise of 53°C whereas those manufactured after 1971 are rated for continuous operation at a rise of 30°C. In both cases, the continuous rating is calculated for an air temperature of 40°C. A typical rather simple switch design is shown in Figure C-2.

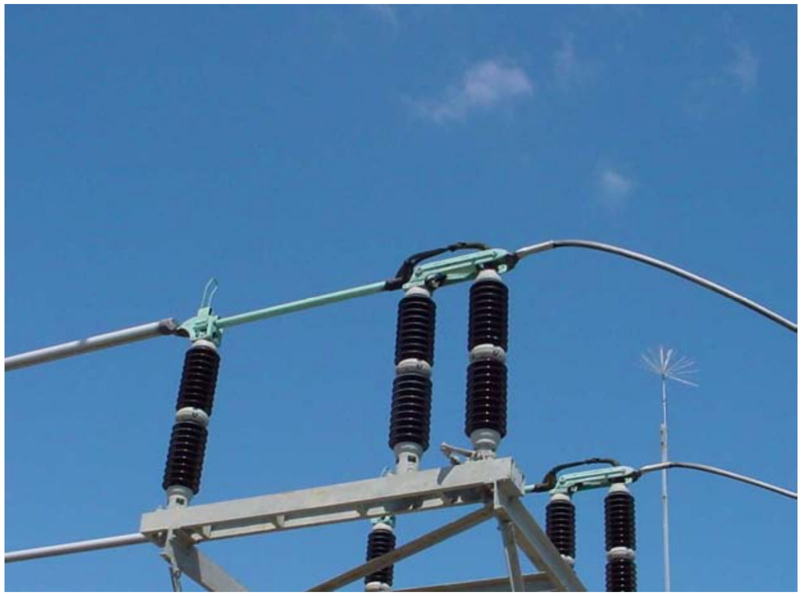


Figure C-2
Typical Air Disconnect (switch)

PJM has published detailed rating data [10] for air disconnects. The conclusions drawn in the PJM documents reflect the operating philosophy of PJM and should be considered by anyone utilizing the analysis that they present. For example [11], the NY Power Pool (presently NY ISO) utilizes limits of 93°C, 120°C, and 140°C in calculating the rating of pre-1971 air disconnects for normal continuous, long time emergency and short time emergency ratings. The most recent PJM recommendations are 93°C, 115°C, and 125°C for the same ratings. The PJM standard also considers the temperature of conducting material joints, switch terminals with bolted connections, and flexible connectors.

The PJM discussion also considers annealing of copper and aluminum component parts as a factor in high temperature limits while the NY ISO discussion does not.

Table C-1
Limits on Temperature Rise and Maximum Temperature for Air Disconnects

Switch Part	Limit of Temperature Rise at Rate Load (deg C)	Maximum Allowable Temperature (deg C)
Contacts in air		
Copper or copper alloy	33	75
Copper or copper alloy to silver or silver alloy, or equivalent	43	90
Silver, silver alloy or equivalent	53	105
Other	per manufacturer	per manufacturer
Conducting mechanical joints		
Copper or aluminum	43	90
Silver, silver alloy or equivalent	53	105
Other	per manufacturer	per manufacturer
Switch terminals with bolted connections	43	90
Welded or brazed joints or equivalent	53	105
Other current-carrying parts		
Copper or copper alloy castings	53	105
Hard-drawn copper parts	37	80
Heat-treated aluminum alloy parts	53	105
Woven-wire flexible connectors	33	75
Other materials	per manufacturer	per manufacturer
Insulator caps and pins and bushing caps	57	110
Current-carrying parts in contact with insulating materials		
Insulation class 90C	37	80
Insulation class 105C	47	95
Insulation class 130C	63	120
Insulation class 155C	80	145
Insulation class 180C	97	170
Insulation class 220C	123	210
Oil	43	90
SF6	307	350
Switches built in accordance with C37.30-1962	30	70

NOTES (Table C-1)

For switches, the temperature that is used in the rating calculations should be the temperature rise of the part that comes closest to the limit of temperature rise at rated load given in the second column of the table above. Specifically, the measured temperature rise that is the largest percent of the limit for that part is the temperature rise that is used in the calculations.

Emergencies less than 24 hrs, add 20C to maximum temperature.

Emergencies greater than 24 hrs, add 10C to maximum temperature.

Limit rating to 200%. (old PJM 180%)

PJM suggests exponent of 1.8 in old guide and 2.0 in new guide.

Time constant is approx. 30 minutes. (agrees with PJM)

C37.30-1992, C37.30-1997 & C37.30-1962 by reference. 1992 is a revision of 1971 standard.

C.3 Circuit Breakers

Table C-2
Temperature Rises and Limits for Circuit Breakers

	Part	Rated Temperature Rise
Material used as insulation and metal parts in contact with insulation of these classes	O	50 (<1999 40)
	A	65 (55)
	B	90 (80)
	F	115 (105)
	H	140 (130)
	C	180
	Oil	50
Contacts	Bare copper and bare-copper alloy	
	in air	35
	in SF6	65
	in oil	40
	Silver-coated or nickel-coated	
	in air	65
	in SF6	65
	in oil	50
	Tin-coated	
	in air	65
	in SF6	65
	in oil	50
	Contacts in breakers manufactured before 1964	
	in air	35
	in SF6	35
	in oil	30
Connections, bolted or the equivalent	Bare-copper, bare-copper alloy, bare-aluminum or bare-aluminum alloy	
	in air	50
	in SF6	75
	in oil	60
	Silver-coated or nickel-coated	
	in air	75
	in SF6	75
	in oil	60
	Tin-coated	
	in air	65
	in SF6	65
	in oil	60
All other contacts or connections made of bare metals or coated with other materials		per manufacturer
Terminals for the connection to external conductors by screws or bolts	Bare-copper or bare-copper alloy	50
	Silver-coated, nickel-coated or tin-coated	65
	Other coatings	per manufacturer
Metal parts acting as springs		avoid impairing temper

NOTES (Table C-2)
SF6 are relatively straightforward. The rated temperature rise can be used. For oil breakers, the oil rise is uncertain.
Time constant roughly 0.5hr (w/ oil)
Rating does not exceed 200%.
Exponents between 1.6 and 2.0, with 1.8 typical.
For emergencies <= 4hrs, add 15C to max temp.
For emergencies > 4hrs, <= 8hrs add 10C to max temp.
Must reduce to 95% cont. rating for minimum 2hrs following emergency
Inspect after emergency
C37.04-1979 & C37.04-1999

C.4 Line Traps

Line traps consist of an air-core inductance coil. They are described by reference [22] but the standard does not make rating adjustments terribly clear and there is some disagreement between sources. Following the method and suggestions outlined in the PJM document on rating of line traps [23], suitable temperature limits are a function of the manufacturer as shown in the following table:

Table C-3
PJM Recommended Temperature Limits for Line Traps.

Line Trap Manufacturer	Limit of rise for rated continuous current – deg C	Normal Max Temperature – deg C	LTE (>24 hrs) Max temperature – deg C	STE (<24 hrs) Max temperature – deg C
GE Type CF (1954-1965)	90	130	145	160
Westinghouse Type M	110	150	165	180
Trench Type L	110	150	170	190
GE Type CF (after 1965)	115	155	170	190

The adjustment of line trap continuous rating for air temperature is obtained using the usual equation form with an exponent of 2.0 in [23]. Other sources use 1.8.

C.5 Current Transformers

The rating of CTs can be complex. They are rated according to [21] but, unlike other substation terminal equipment, the limits on current are a function of the tap selection and the secondary burden as well as the CT itself. No single set of rating factors can be specified for all applications even in the same utility substation.

To develop continuous ratings, the continuous thermal current rating factor (RF), defined in [21] must be used. The standard does not consider LTE or STE ratings so these must be determined by non-standard methods which should be different for free-standing and for bushing-type CTs.

In general the rating of bushing-type CTs is considered equal to that of the circuit breaker or power transformer in which the CT is installed.

If the tap used on a bushing CT is less than its maximum ratio, additional thermal capacity is available beyond that of the CT set to its full winding tap position. The adjustment of thermal capacity for tap position can allow operation at currents above the rating for full tap position. For example, at the 50% tap position, the CT rating would be 140% of its full winding position rating.

$$Itap = Itap_r \times \left(\frac{I_r}{Itap_r} \right)^{1/n} \times RF$$

Itap is then used as the rated load that corresponds with the given temperature rise.

Table C-4
Average and Hot-Spot Temperature Rise for Instrument Transformers

	30C Ambient		55C Ambient	
Type of instrument transformer	Avg. winding rise by resistance	Hottest-spot winding rise	Avg. winding rise by resistance	Hottest-spot winding rise
55C	55	65	30	40
65C*	65	80	40	55
80C	80	110	55	85

* The 65C insulation class was introduced as a part of the standard in 1993.

Bushing CTs that are applied internal to circuit breaker or power transformers are limited by the allowable temperature rises specified in C37.04 and C57.12.00 respectively. For circuit breakers, the allowable temperature rise of the CT winding is the same as those given above for a 30C ambient. For power transformer, the CT winding hot spot rise would be limited to 65C for a 55C rise power transformer or 80C for a 65C rise power transformer

D
LABORATORY VERIFICATION OF INFRARED TEMPERATURE MEASUREMENTS

This report includes both measurements and analysis considering two issues that are important to the substation field measurements of terminal equipment temperatures. The first issue is the accuracy of temperature measurements made with high quality infrared imaging measurements made by a trained technician and the second is the likely variation in temperature along substation bus and jumpers.

Measurements made by PDC and the Snell Infrared technician, Shane Brooker, at PLP's test facility in Cleveland, Ohio, indicate that infrared measurements of temperature on properly prepared power equipment surfaces are within 2 degrees C of measurements made with conventional thermocouples over the anticipated range of 35C to 90 C. It appears that infrared temperature measurements made with a painted surface are more reliable than those made with insulating tape.

Limited measurements, and a new analytical model developed by PDC, show that heat flow over jumpers is quite low. For a 1.1 inch diameter jumper in still air, connected to an object at 150°C, the jumper temperature drops to within a few degrees of air temperature within no more than 3 feet. The analytical model can be applied to any size jumper.

D.1 Acknowledgment

The tests described and analyzed in this document were performed as part of the EPRI project EP-P13579/C6702 "Improved Thermal Modeling Tools for Substation Equipment". Dr. Ram Adapa of EPRI is the project manager.

The laboratory tests were performed with the full cooperation of Mr. John Olenik of Preformed Line Products in their laboratories in Cleveland, Ohio. Permission for the testing and use of facilities at PLP was also arranged by Mr. Robert Whapham of PLP. The authors wish to thank PLP for the use of their laboratory and for the time that they took to help us.

D.2 Test Goals

The primary purpose of these laboratory tests was to assess the accuracy of infrared temperature measurement with properly prepared (painted) power equipment surfaces. A secondary purpose was to briefly study the variation of temperature along non-current carrying conductors.

D.3 Introduction

Laboratory testing of power equipment is time consuming and expensive. It has several advantages, however: (1) the ability to make measurements of temperature with thermocouples at any location without concern for operating voltage; (2) a controlled thermal environment free of rain and wind effects; (3) the ability to control the electrical loading to study transient effects.

Field testing of substation terminal equipment is fast and inexpensive. It also has several advantages: (1) easy access to all types of utility terminal equipment, not just spare equipment; (2) measurements of actual operating equipment showing the full range of conditions found in the field; (3) able to study interconnected equipment. In field testing, temperature measurements can be made with infrared or with fiberoptic probes. Infrared imaging devices are utterly safe (non-contact) and are already in common use to assess the condition of substation terminal equipment.

These laboratory tests were performed to link laboratory temperature measurement technology using thermocouples to field measurements using an infrared imaging camera. Effects of surface preparation, distance, and sighting angle were studied.

D.4 Equipment & Test Setup

Infrared temperature measurements were performed with a FLIR PM695 infrared camera. This camera uses a Focal Point Array with a longwave spectral response in the 8-12μm range. This camera has a stated accuracy of +/-2C. This accuracy assumes ideal conditions and a known surface emissivity.

Figure D-1
Laboratory Test Layout Showing Camera and Target.

This test took place at Preformed Line Products' test lab in Cleveland, OH. PLP has a short test span used to test various pieces of line hardware at elevated temperatures. The span is enclosed in a building and current is circulated by two paralleled arc welding rigs, giving the capability to elevate the line temperature to 250°C under relatively controlled conditions.

The conductor used on the test span was a fairly new (ie. shiny) Drake conductor, with a diameter of roughly 1.1". In addition, a standard suspension clamp was placed on the conductor. Thermocouples were embedded at various locations on the conductor. A Fluke handheld thermocouple reader was also used to provide for spot measurements.

Several different materials were used to provide known emissivity targets on the line conductor and certain attached hardware. These materials included:

- *Rustoleum Professional flat white (7590) enamel spray paint*
- *3M brand electrical tape, both black and white*
- *adhesive-backed cotton*

D.5 Tests & Results

Four different series of tests were performed, with the general goals of evaluating the accuracy and precision of IR camera measurements and determining operating limits of distance and angle from target.

D.5.1 Test #1 – Comparison of Emissivity Control Surfaces

The first series of tests was focused on evaluating the accuracy of the camera measurements on stranded conductor, using several different materials as targets, over a range of temperatures. These materials included flat white enamel spray paint, black electrical tape and white electrical tape.

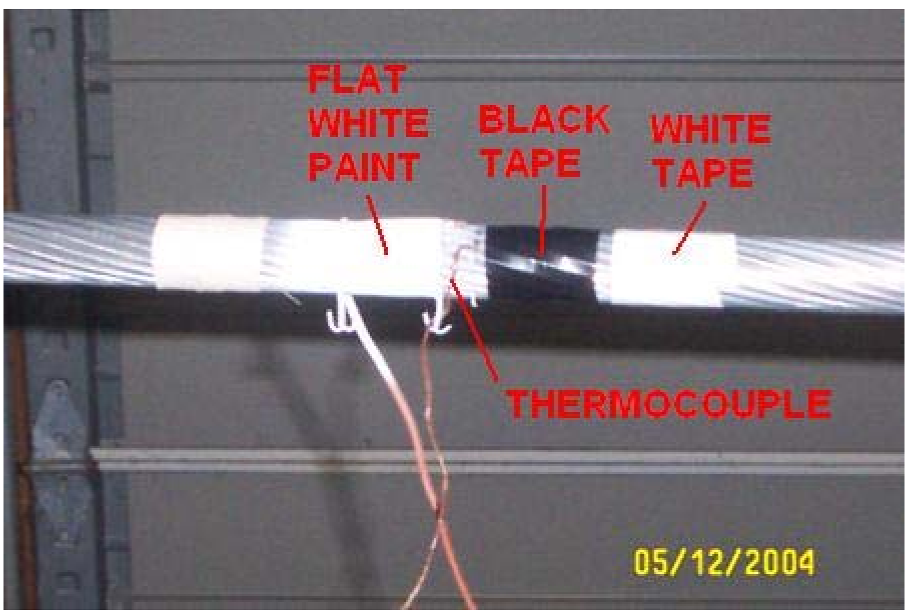


Figure D-2
Infrared Target Showing Paint and Tapes

For this test, a 12º lens was used. The ambient temperature was approx. 32C with a 38% relative humidity. The distance to the target was a short 2.1m. This test was performed with doors closed to minimize the effects of air movement. The emissivity for all targets was assumed to be 0.93. This number was selected by experience, in lieu of exact measured emissivity.

In order to evaluate the accuracy of the temperature over a regime of temperature, the temperature of the conductor was measured at one minute intervals as the line was heated from ambient temperature to a final steady-state temperature. This gave a range of measurements from approx. 30C-90C. In addition, this allowed demonstration of the capabilities of the method to measure transient temperature changes. The results of this test are summarized in Figure D-3.

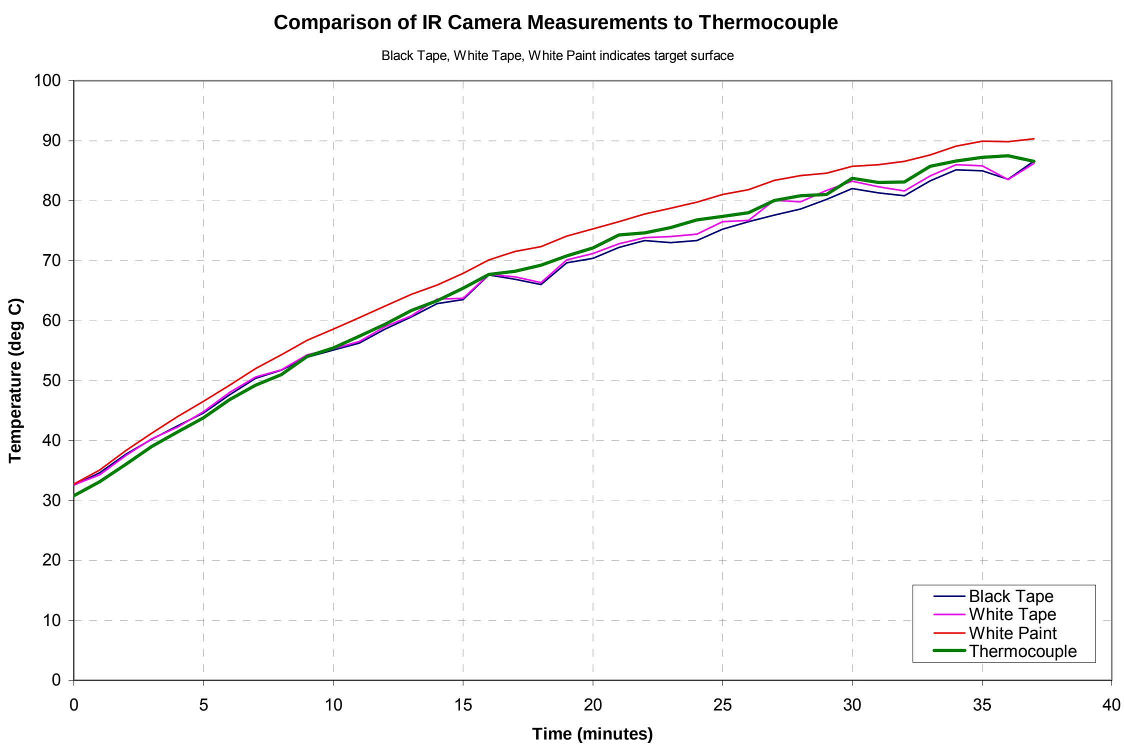


Figure D-3
Plot of Temperatures for Different Emissivity Control Materials.

Qualitatively, the camera measurements match the thermocouple measurements quite well. As shown in Table D-1, the errors for each target material were within 4°C, and often within 2°C. The range of errors was greatest for white and black electrical tape, however the average magnitude of error was smallest for these two materials. Flat white paint provided more precise values, with a standard deviation of 0.54, with slightly decreased accuracy.

Table D-1
Error analysis for Emissivity Control Materials.

	Range of Error	Average Error Magnitude	Standard Deviation
Black Electrical Tape	-3.9 -> 1.7	1.53	1.50
White Electrical Tape	-4.0 -> 1.8	1.10	1.28
Flat White Paint	1.9 -> 3.8	2.85	0.54

The errors for each emissivity control target materials is shown in Figure D-4, Figure D-5, and Figure D-6 in the form of histograms. Examining these plots yields the conclusion that flat white latex provides more precise results, however the average error is 2.85C. The errors for white latex appear to be offset by roughly 3C. This is likely due to the assumed emissivity of 0.93. If a slightly lower emissivity were used, the range of errors for flat white paint would be centered about zero, providing accuracies well within 2C.

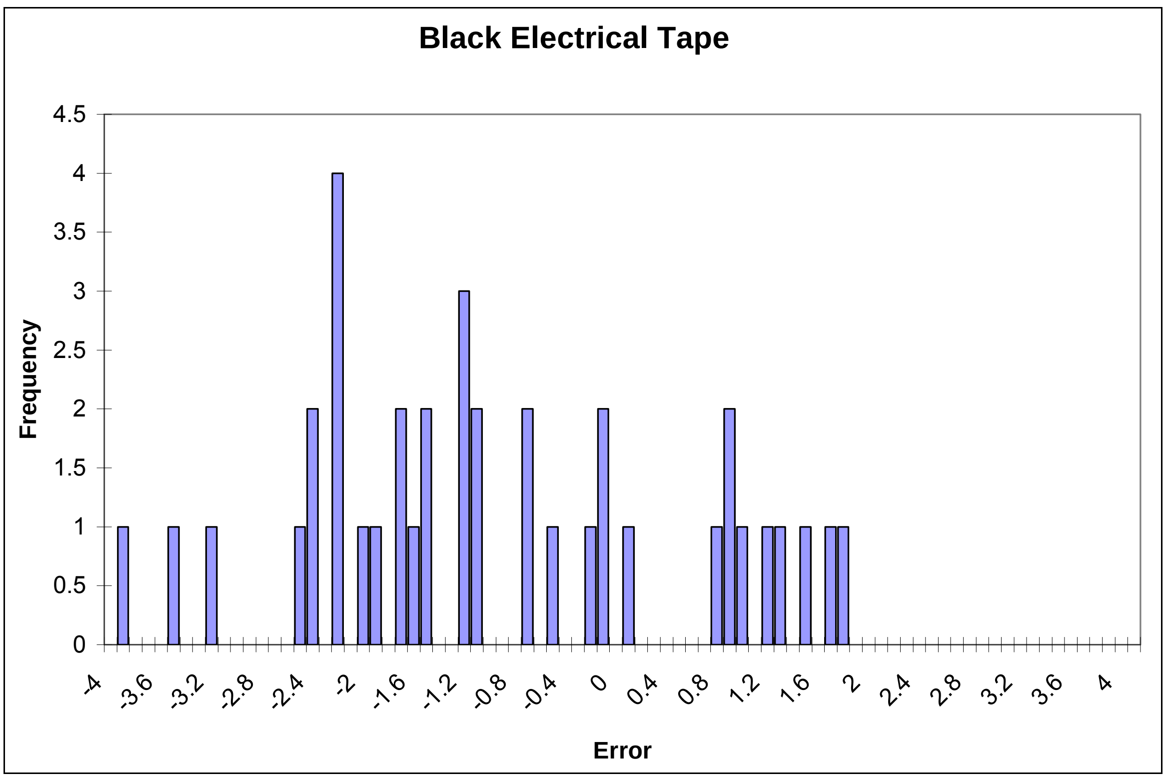


Figure D-4
Error Histogram for White Electrical Tape.

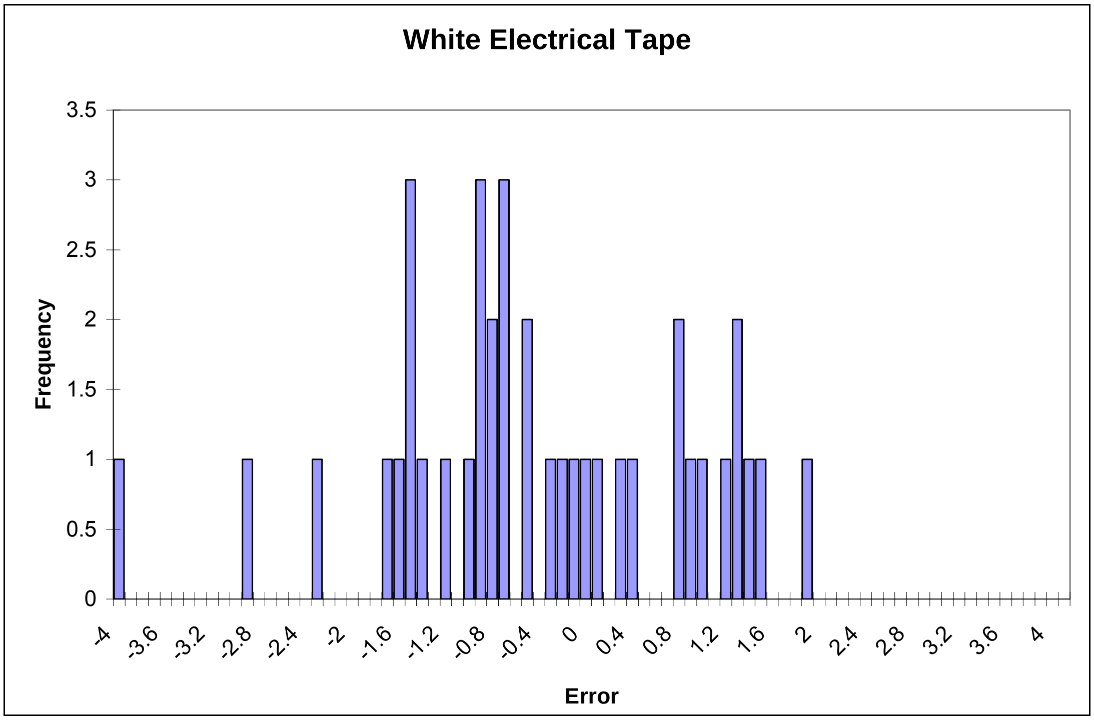


Figure D-5
Error Histogram for White Electrical Tape

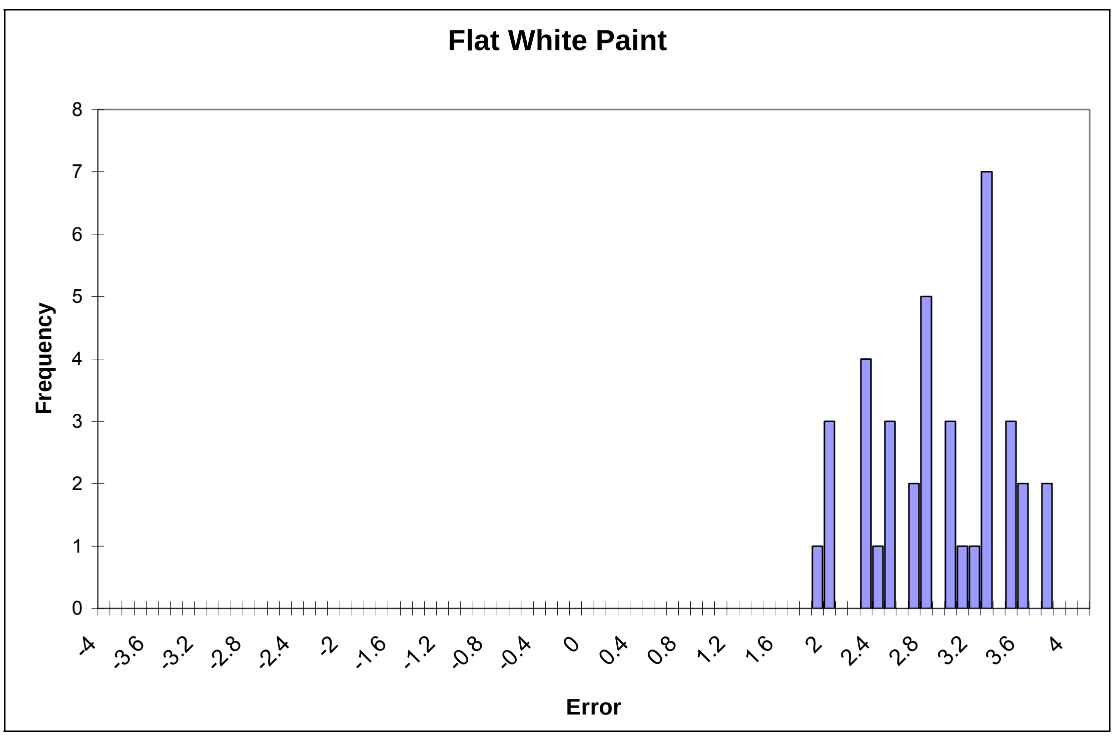


Figure D-6
Error Histogram for White Painted Surface.

D.5.2 Test #2 – Temperature Measurements on Suspension Clamp

Following the first test on stranded conductor, measurements were taken on a suspension clamp, to examine accuracy on a different type of surface. A 2” white circle was sprayed on the surface of the clamp. A thermocouple was then clamped to the surface using a wire wrap.

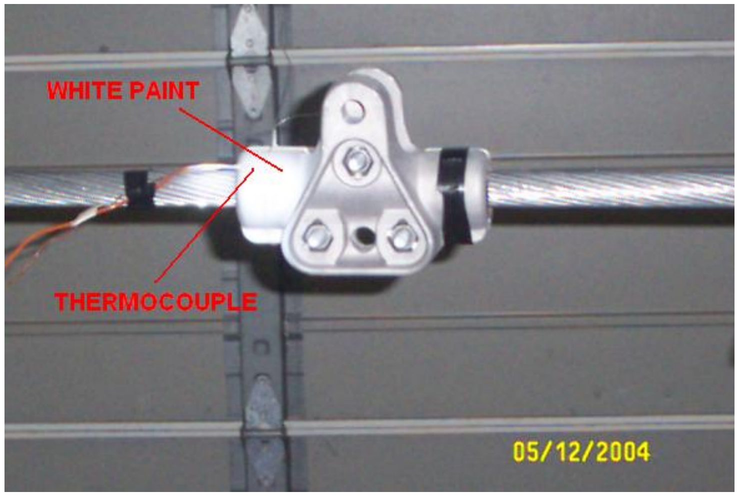


Figure D-7
Suspension Clamp IR Target.

For this test, a 12º lens was used. The ambient temperature was approx. 32°C with a 38% relative humidity. The distance to the target was a short 1.8m. This test was performed with doors closed to minimize the effects of air movement. The emissivity for all targets was again assumed to be 0.93.

Table D-2
Comparison for IR and TC on Suspension Clamp

Measurement	Thermocouple	Camera	Error
1	56.5	59.9	3.4
2	56.6	60.2	3.6
3	56.6	60.3	3.7
4	56.8	60.6	3.8
5	56.5	60.6	4.1
6	56.2	60.8	4.6
7	n/a	61.2	
8	n/a	61.5	
9	n/a	61.6	
10	59.1	62	2.9
11	n/a	62	
12	n/a	62.4	
13	59.7	62.5	2.8
14	59.9	63	3.1
		Average	3.56

The conductor was heated to a steady-state temperature of approx. 85°C. A series of measurements were then taken at steady-state. These measurements are summarized in Table D-2. Thermocouple measurements were not available for all points. The average error was 3.5°C, slightly higher than for stranded conductor. Some of this error, however, is not due to the camera measurements, but the thermocouple placement. It is difficult to get an accurate thermocouple reading on a surface such as this. This contact must be sufficient to permit rapid thermal conduction, but any fixture for the thermocouple must not affect the temperature of the test object.

D.5.3 Test #3 – Influence of Camera Angle and Distance on Accuracy

The goal of the third series of measurements was to establish the limits of camera distance and angle from the test object. To accomplish this, a series of measurements were taken of a 1" flat white paint target on the stranded conductor at distances ranging from 10'-75' and angles from 0º-45º. For each distance or angle, measurements were taken at 30 second intervals for 2 minutes, and the results averaged. The target is shown in Figure D-8.

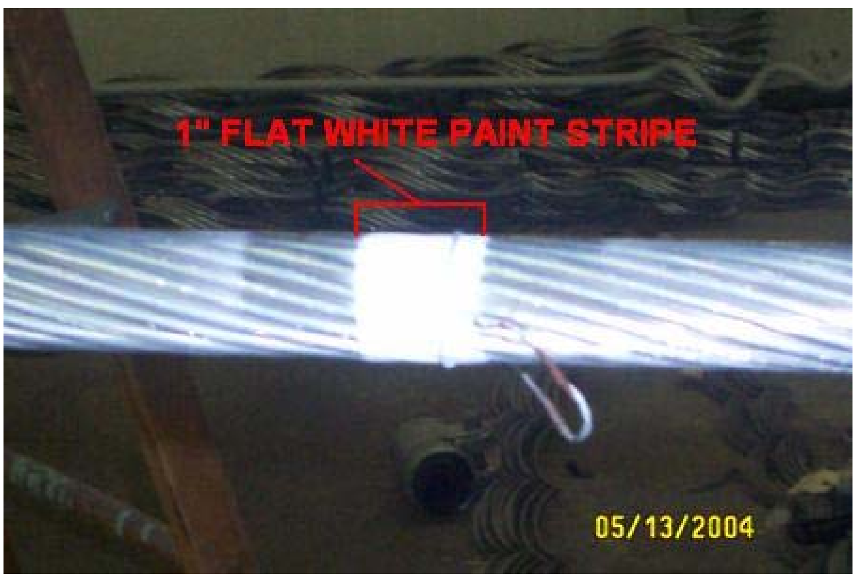


Figure D-8
Painted Target for Distance and Angle Tests

For this test, a 12º lens was used. The ambient temperature was approx. 30C with a 46% relative humidity. The distance to the target was variable. This test was performed with doors closed to minimize the effects of air movement. The emissivity for all targets was assumed to be 0.93.

In order to get up to 50 feet from the target, the imaging camera was taken outside of the room through a sliding door as shown in Figure D-9.

Figure D-9
IR Measurements of Target at a Distance.

The results of the distance portion of this test are shown in Table D-3. It is quite apparent that the accuracy drops sharply after 50'. Therefore, the maximum distance between the camera and test object should be 50' to maintain accuracy. Note that this is for a 12º lens. A 7º lens should yield accurate results up to approx 75'. A wider 45º lens would give a wider field of view, but should be limited to short distances of 20' or less.

Table D-3
IR Error vs Distance

Distance	Avg. Error
10'	2.22
20'	0.34
30'	0.28
40'	2.66
50'	3.1
75'	13.35

The accuracy of the camera is also affected by the angle of the camera to the surface plane of the test object. The camera should be perpendicular to the tangential surface plane of the test object to give the most reliable measurements. However, tests on the painted, stranded conductor showed no appreciable drop in accuracy for angles of incidence up to 45 degrees as shown in Table D-4.

Table D-4
IR Error vs Angle for Stranded Conductor

Angle	Avg. Error
0 deg	0.34
15 deg	0.16
30 deg	0.6
45 deg	0.98

Since the stranded conductor is a complex geometry with multiple facets at different angles, it was felt that the above test may be misleading. To provide a more meaningful test of accuracy versus angle, measurements were taken at various angles using the flat surface of the suspension clamp as a target. The tests were performed up to 30 deg, as obstructions between the camera and the suspension clamp prevented measurement at higher angles. The results are shown in Table D-5.

Table D-5
IR Error vs. Angle for Smooth Clamp Surface

Angle	Avg. Error
0 deg	1.88
15 deg	1.64
30 deg	1.94

Again, no appreciable decrease in accuracy is seen. However, it is still recommended that measurements be made as close to perpendicular as possible and not more than 30 deg from perpendicular.

D.5.4 Test #4 – Temperature Variation in Jumpers

The final test was not directly intended to evaluate the performance of the camera. Time allowed for an experiment to investigate the conduction of heat along an unloaded “jumper” or cable that might connect devices such as surge arrestors or PTs. To simulate this, a 3-bolt “T” clamp was fastened to the conductor (Drake) with a 2’ length of Drake conductor extending downward from the clamp. The large “jumper” conductor is probably unrealistic, but was the only available material at the time. A photo of the configuration is shown below. Note that the conductors are sprayed with flat white paint.

Figure D-10
Pigtail Temperature Gradient Test.

This same view now in infrared:

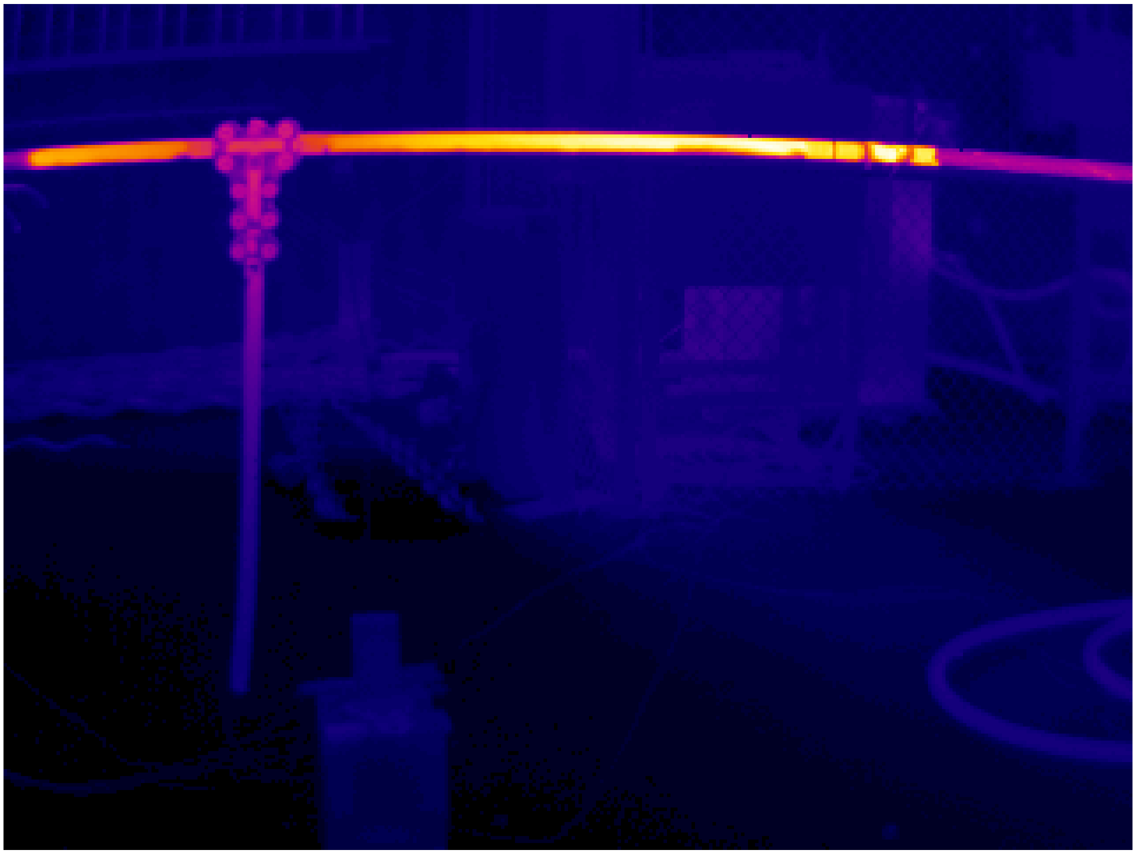


Figure D-11
IR Image of Pigtail Test

The peak conductor temperature was approx. 150C. The temperature of the conductor near the clamp was 90C. The temperature of the bottom of the jumper conductor increased only 3.2C above ambient to 36.7C. The temperature at the top of the jumper conductor was 60C.

D.6 Bus Conductor/Jumper Temperature Calculations

As shown in Test #4, the temperature of a bus jumper carrying no current drops off with surprising suddenness. This variation in axial temperature (i.e. temperature along the conductor) can be modeled as shown in Figure D-12.

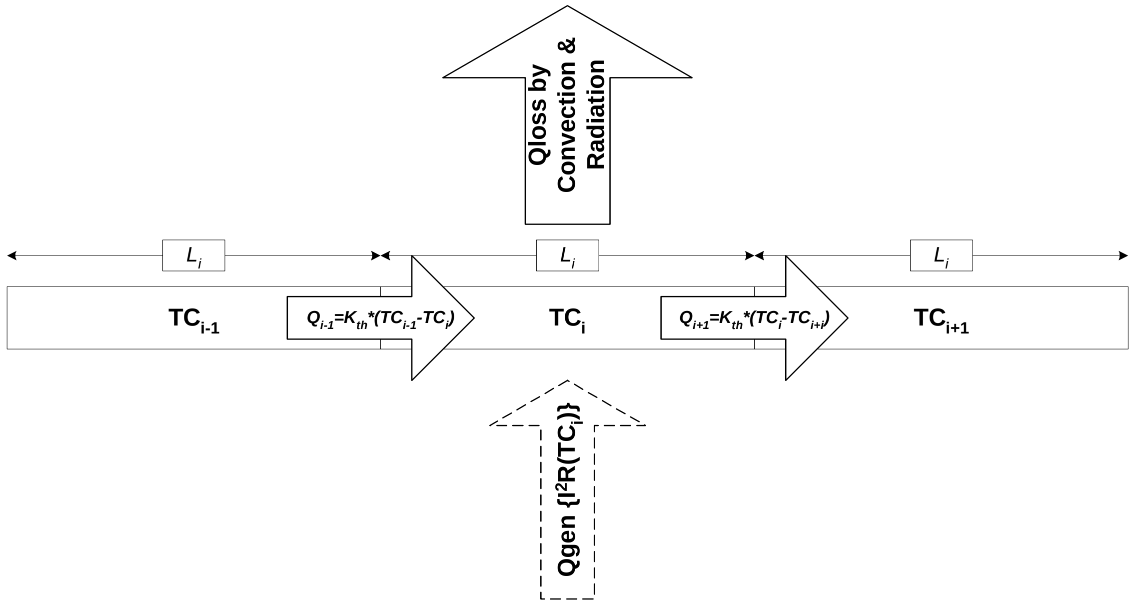


Figure D-12
Calculation Model for Axial Temperature Variation of Bus Conductor

In this mathematical model, the jumper conductor is modeled as a series of short lengths, each L_i meters long and each short segment is assumed to have an average temperature, TC_i, where *i* is the segment number. In each segment, the heat balance is given by the equation:

$$I^2 \cdot R_C(TC_i) + Q_{i-1} = Q_{i+1} + Q_R + Q_C$$

Where:

- I = current in segment (amperes)
- $R_C(TC_i)$ = Resistance of segment
- Q_{i-1} = Heat conducted into ith segment from i-1th segment
- Q_{i+1} = Heat conducted from the ith segment into the i+1th segment.
- Q_R and Q_C are heat lost from ith segment by radiation and convection, respectively..

The heat loss terms are defined by the normal IEEE 738 formulas and the resistance is simply that published for the bus conductor. The conduction terms, however, need to be defined here:

$$Q_{i-1} = \frac{TC_{i-1} - TC_i}{R_{th}}$$

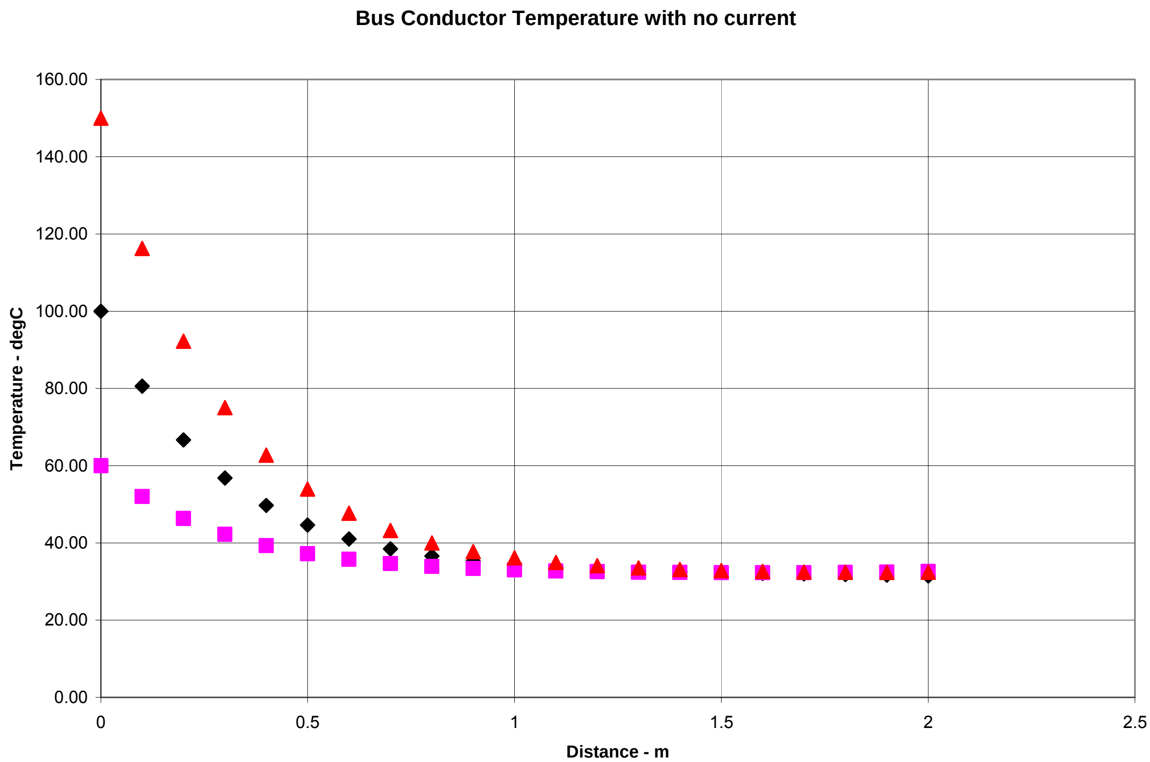
Where Rth = the bus conductor's thermal resistance:

$$R_{th} = \frac{L_i}{Area * \sigma_{th}}$$

Consider the case where a bus conductor which carries no current hot at one end. The heat which is conducted into the bus segment is lost to convection and radiation along the pigtail.

$$Q_{i-1} = Q_{i+1} + Q_R + Q_C$$
$$Q_{i-1} = \frac{TC_{i-1} - TC_i}{R_{th}} = \frac{TC_i - TC_{i+1}}{R_{th}} + (Q_R + Q_C)$$

The equation has a unique solution (i.e. series of segment temperatures, TCi) for each starting point temperature. The following plots of conductor temperature as a function of distance from the hot end can be obtained from the solution.



The theoretical model predicts that the temperature of 60C at the hot end will decrease to 36°C in 2 ft (0.6 m). This agrees with the experimental measurements where the temperature of the 2 ft length of bus conductor .decreased to approximately 37°C at the end of the 2 ft length.

D.7 Recommendations & Conclusions

- When used properly, infrared camera measurements provide a reliable and sufficiently accurate means of non-contact temperature measurement for our planned field measurements.
- Preparation of the target surface with a known, high emissivity covering is critical.
- Flat white paint provides the best target. The assumed emissivity of 0.93 should be decreased to a value preferably based upon experimental measurement.

- Electrical tape may provide a suitable substitute for paint if paint is not possible. However, electrical tape gives less precise results and does not adhere well. In addition, there is some evidence that emissivity may change with temperature.
- Using a 12 deg lens, the maximum distance between the camera and test object is 50'. A 7 deg lens may increase the range up to 75'.
- Measurements should be taken as close to perpendicular to the test object as possible. Angles up to 30 deg from perpendicular may be permissible.
- The analytical model for axial temperature variation in jumpers or bus is consistent with the limited measurement results.
- Jumpers and bus conductors appear to be poor axial heat conductors and the heat transmitted by non-current-carrying jumpers more than 3 feet in length can typically be neglected.

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