

# AN IMPROVED METHOD FOR ESTIMATING TEMPERATURE RISE OF A BUSHING LOADED ABOVE NAMEPLATE RATING

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## ABSTRACT

We have developed an accurate but simple method to estimate the temperature rise (referred to as "rise" hereafter) of a bushing conductor under any load condition. This method consists of one equation and two predetermined rise profiles  $F_1(z)$  and  $F_2(z)$ .  $F_1(z)$  is the incremental rise profile at the rated current and  $F_2(z)$  is the normalized rise profile at zero current.  $F_1(z)$  and  $F_2(z)$  can be obtained from two base thermal tests. The proposed method allows us to estimate the rise profile of the bushing under any given load condition. Therefore the rise and the location of the hottest spot can be determined from this profile. We have successfully applied this method to various bushings, such as bushings with and without oil circulation, bottom-connected and draw-lead connected bushings, and some special bushings with two conductors. We examined this method with a thermal circuit model and verified that the thermal model supports the new method.

## I. INTRODUCTION

The standard IEEE Guide for Application of Power Apparatus Bushings, IEEE C57.19.100-1995<sup>(1)</sup> provides a simple equation

$$\Delta\theta_{HS} = K_1 * I^n + K_2 * \Delta\theta_0 \quad (1)$$

to estimate the hottest spot of the bushings.

Equation (1) is based on W. J. McNutt's paper<sup>[2]</sup> except for the value of the exponent  $n$ . The standard describes a method for calculating the thermal constants  $K_1$ ,  $K_2$  and  $n$  from thermal tests.

However, test results show that  $K_1$ ,  $K_2$  and  $n$  are not constant, but vary from test to test. The hottest spot rise obtained from this equation does not match well with actual thermal test results.

Thermal tests of bushings show that the location of the hottest spot of a bushing migrates with current and oil rise. Because of this migration,  $K_1$ ,  $K_2$  and  $n$ , which we determined based on the hottest-spot at rated load conditions with an overload test, cannot predict the hottest-spot for an arbitrary current and oil rise.

We have developed a simple equation which requires two predetermined rise profiles  $F_1(z)$  and  $F_2(z)$  to estimate the rise profile under non-standard load conditions. For each bushing,  $F_1(z)$  and  $F_2(z)$  are the base rise profiles which we obtain from two thermal tests: one at zero current and the other at the rated current.  $F_1(z)$  and  $F_2(z)$  replace the thermal constants  $K_1$  and  $K_2$  in equation (1). The exponent  $n$  in our equation is a constant equal to two, while  $n$  in the IEEE Standard is a variable. This method enables us to estimate the rise profile under any load condition and predict the hottest spot rise and its location accurately.

This paper will present the theory behind the simple estimation method, thermal test, actual thermal test results, and analysis. Also discussed is a comparison between the calculated results from an equivalent thermal model and the estimated results from the new method. The thermal model is used to show the accuracy of the simple estimation method. Hereafter, the results from the thermal test will be referred to as the "measured" results, those from the proposed simple estimation method as the "estimated" results and those from the thermal model as the "calculated" results.

## II. DEVELOPMENT OF THE THEORY

In a steady-state condition, the heat generated in a bushing without oil circulation transfers to the surface by thermal conduction, then to the surrounding air and oil through convec-

tion. As the convection mainly occurs within very thin boundary layers, we can view it as thermal conduction in these thin layers. Therefore, we can simulate the thermal characteristics of a bushing with a simple thermal conduction model with ohmic loss  $I^2R$  as the main heat source.

We can describe the thermal conduction equation for a bushing without oil circulation in a cylindrical coordinate system as

$$k_r(r,z) \frac{\partial^2 T(r,z)}{\partial r^2} + k_z(r,z) \frac{\partial^2 T(r,z)}{\partial z^2} = q(I,r,z) \quad (2)$$

where:

- $T(r,z)$  temperature profile under current  $I$
- $r$  radial coordinate from the bushing center line
- $z$  axial coordinate along the bushing centerline
- $k_r(r,z)$  radial thermal conductance at  $r,z$
- $k_z(r,z)$  axial thermal conductance at  $r,z$
- $q(I,r,z)$  heat generated under current  $I$  at  $r,z$
- $I$  current in per-unit referred to as pu.

In the standard, the temperature rise used is defined as the rise over the air ambient temperature. Because the bushing is long and slim, we can rewrite equation (2) in a rise format as

$$k_r(z) * (\Delta\theta(I,z) - \Delta\theta_0(z)) + k_z(z) * \frac{\partial^2 \Delta\theta(I,z)}{\partial z^2} = R(z) * I^2 \quad (3)$$

where:

- $\Delta\theta(I,z)$  rise profile of the conductor under current  $I$
- $\Delta\theta_0(z)$  rise of the surrounding medium at  $z$
- $k_r(z)$  radial thermal conductance from the conductor to the surrounding medium at  $z$
- $k_z(z)$  axial thermal conductance of the conductor at  $z$
- $R(z)$  electrical resistance of the conductor at  $z$ .

We can obtain the bushing rise profiles for a given load condition by solving (3) with the corresponding boundary and load conditions.

For a linear system, the solution of (3) is

$$\Delta\theta(I,z) = \Delta\theta_p(1,z) * I^2 + \Delta\theta_h(0,z) \quad (4)$$

where:

$\Delta\theta_h(0,z)$  the general solution of the corresponding homogeneous equation, which is the rise profile generated by temperature difference between the boundaries.

$\Delta\theta_p(1,z)$  a particular solution of the nonhomogeneous equation, which is the incremental rise profile generated by heat losses at one unit current.

As equation (4) shows, we must obtain  $\Delta\theta_h(0,z)$  and  $\Delta\theta_p(1,z)$  to solve the equation. However, as it is difficult to calculate these, we can determine them from two thermal tests. This is theoretically simple because  $\Delta\theta_h(0,z)$  is rise profile at zero current  $\Delta\theta(0,z)$ ; and  $\Delta\theta_p(1,z)$  is the difference between the rise profiles  $\Delta\theta(1,z)$  at the rated current and  $\Delta\theta(0,z)$  at zero current.

From this, we develop an equation to estimate the rise profiles of the conductor of a bushing as

$$\Delta\theta(I,z) = F_1(z) * I^2 + F_2(z) * \Delta\theta \quad (5)$$

where:

$$F_1(z) = \Delta\theta(1,z) - \Delta\theta(0,z) \quad (6)$$

$$F_2(z) = \Delta\theta(0,z) / \Delta\theta_0 \quad (7)$$

- $\Delta\theta(I,z)$  rise profile at current  $I$  pu and oil rise  $\Delta\theta$
- $F_1(z)$  incremental rise profile of the bushing, which is  $\Delta\theta_p(1,z)$  in equation (4)
- $F_2(z)$  normalized rise profile of the bushing with no current, which is a normalized  $\Delta\theta_h(0,z)$  in equation (4)
- $\Delta\theta(0,z)$  rise profile at zero current
- $\Delta\theta(1,z)$  rise profile at the rated current of 1 pu
- $\Delta\theta_0$  the rated oil rise
- $\Delta\theta$  actual oil rise

Equations (6) and (7) assume that the oil rise is precisely the rated value. However, in reality, it is not always possible to get the exact rated oil rise during the lab tests. Therefore, we use the following revised equations to obtain  $F_1(z)$  and  $F_2(z)$ .

$$F_2(z) = \Delta\theta'(0,z) / \Delta\theta' \quad (8)$$

$$F_1(z) = \Delta\theta'(1,z) - F_2(z) * \Delta\theta' \quad (9)$$

where:

- $\Delta\theta'(0,z)$  rise profile at zero current and the oil rise of  $\Delta\theta'$

$\Delta\theta(1,z)$  rise profile at the rated current of 1 pu and the oil rise of  $\Delta\theta'$

Even though equation (5) takes a similar form to equation (1), their meanings are quite different as stated below.

1. Equation (5) comes from the thermal differential equations but equation (1) is a mixture of thermal differential equation and a curve fitting technique.
2. Equation (1) estimates the hottest spot rise of a bushing under the assumption that the location of the hottest spot does not migrate with load conditions but equation (5) does not make this assumption.
3.  $F_1(z)$  and  $F_2(z)$  represent the base thermal characteristics of a bushing on its entire length, but  $K_1$  and  $K_2$  are determined at just one location along a bushing. The exponent  $n$  is equal to 2 in equation (5) because the heat generated in the conductor depends on  $I^2R$  according to the laws of physics. In equation (1), the value of  $n$  is chosen to make equation (1) best fit the thermal test results.
4. The new method we have developed requires only two thermal tests, while the old method requires at least three tests.
5. In the old method, the thermal constants cannot be uniquely determined due to the migration of the hottest spot.

### III. THERMAL TEST

To verify the new method, thermal tests were performed on various POC (paper-oil-capacitance) and PRC (paper-resin-capacitance) bushings with BIL from 110kV to 1550kV, the rated current from 400A to 6000A, and bushings with and without oil circulation. Most of the bushings we tested were bottom connected, others were draw lead cable, draw rod and special bushings.

All the bushings were prepared and tested according to the standard IEEE guide for Application of Power Apparatus Bushings, IEEE C57.19.100-1995.

Thermocouples were evenly spaced approximately 5"- 10" apart along the length of the bushing conductor and attached by pinching them into or making contact to the conductor with phosphor bronze thermocouple brushes. The bushing bottom end was immersed in an oil bath with the rated

minimum oil level. The bushing was connected to a high current power supply by copper buses. The current was adjusted and stabilized by a electronic device with feedback.

The temperature of the oil bath was measured with a thermocouple immersed approximately 2" below the oil surface and located 6" from the surface of the bushing. The ambient air temperature was determined by taking the average reading of three thermocouples located at heights corresponding to the mounting flange, midpoint, and top end of the bushing. The average temperature of these three locations was used as the ambient air temperature in calculating all temperature rises.

The thermal transients of the bushing were recorded by an OMEGA portable Datalogger at 0.5 hour time intervals. We maintained the same test condition for 8~40 hours or longer until reaching the steady-state temperature rise. For each bushing we took two rise profiles, one with zero current and the other with the rated current. Then  $F1(z)$  and  $F2(z)$  were determined by solving equations(6) and (7). Then we estimated the rise profiles of the bushings under different load conditions and compared them to the test results.

### IV. TEST RESULTS

This section shows the measured and estimated rise profiles to prove whether the simple estimation method is valid for various magnitudes of currents and oil rise. Furthermore, we also want to prove that this method is valid for different types of bushings, such as POC and PRC bushings, those with and without oil circulation, and those with drawlead cables and drawrods.

#### 1. At different magnitudes of currents

Figure 1 shows the measured and estimated rise profiles of a 350kV BIL 400/1200A bushing at various currents. This bushing is a PRC bushing with a copper conductor and without oil circulation. The bushing is 74 3/8" long. The rated minimum oil level is 21" from the flange mounting surface or 16.5" from the bushing oil end.

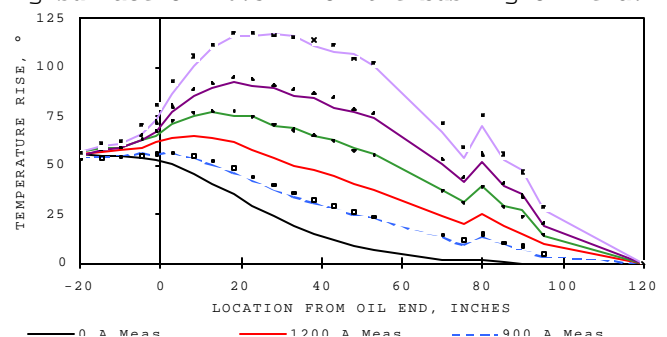


Figure 1

Measured and estimated rise profiles of a 350kV BIL 400/1200A PRC bushing at various currents

The estimated rise profiles of this bushing match the measured rise profiles very well from 0.75 pu to 1.75 pu current at rated oil rise. For a bushing without oil circulation, the hottest spot migrates towards the center of the bushing with increasing current. We found that the hottest spot is located above the real oil level when the current is high. Two or three peaks may appear in the rise profile. The peaks appearing near the ends of the bushing indicate quality of the bushing connection to the bus.

2. At different oil temperatures

Figure 2 shows the measured and estimated temperature rise profiles of a 550kV BIL 1200/1600A bushing at different oil rises. This bushing is a POC TBI bushing with an aluminum conductor and without oil circulation. The bushing is 100 7/8" long. The rated minimum oil level is 23" from the flange mounting surface or 20" from the bushing oil end.

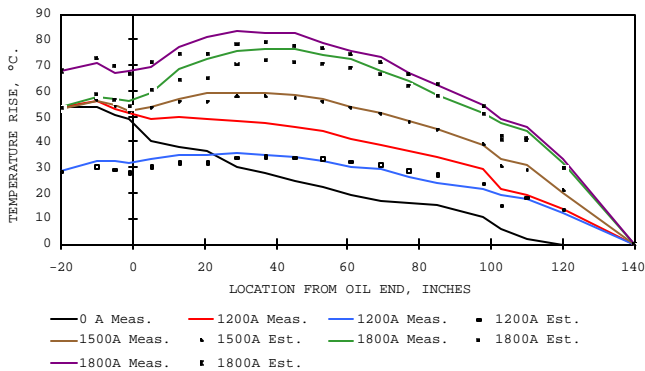


Figure 2

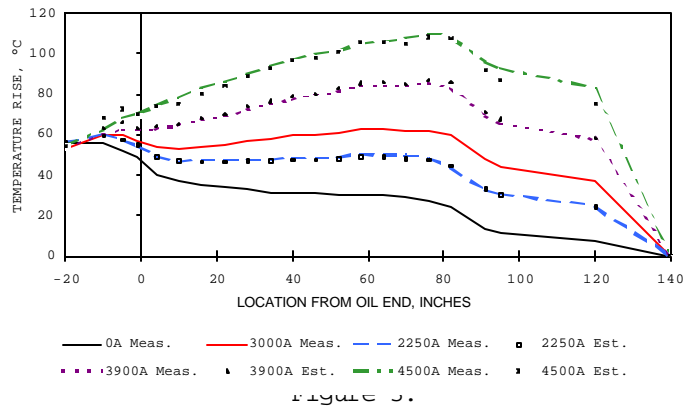
Measured and estimated rise profiles of a 550kV BIL 1200/1600A POC bushing without oil circulation at various oil rises

The estimated rise profiles of this bushing match the measured rise profiles very well for the oil rises from 30°C to 70°C. The hottest spot migrates with the oil rise in the opposite direction compared with that in different currents. When the oil rise increases, the hottest spot migrates toward the oil end of the bushing.

3. Bushing with oil circulation

Although equation (5) is based on the models without oil circulation, we have found that it is valid for bushings with oil circulation. The rise profiles of bushings with oil circulation are quite different from those without oil circulation. With an increase in current, the hottest spot of bushings with oil circulation migrates towards the top of the bushings rather than the center of the bushing.

Figure 3 shows the measured and estimated rise profiles of a 550kV BIL 3000A bushing with copper conductor and with oil circulation. The bushing is 91 1/16" long. The rated minimum oil level is 23" from the flange mounting surface or 20" from the bushing oil end.



Measured and estimated rise profiles of a 550kV BIL 3000A POC bushing with oil circulation at various load conditions

4. Bushing with a draw-rod

Tests show that we can use the new method for bushings with drawleads and drawrods.

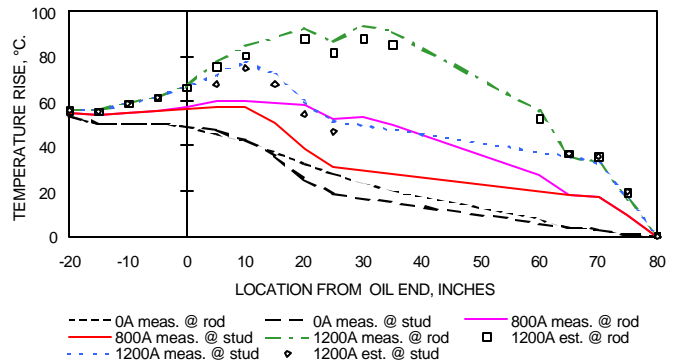


Figure 4

Measured and estimated rise profiles of a 350kV BIL 400A PRC drawlead bushing with  $\phi 1$ " drawrod

Figure 4 shows measured and estimated rise profiles of a 350kV BIL 400A PRC bushing with a drawrod. The temperature rise of the bushing

hollow stud and the drawrod were measured and recorded. The measured and estimated profiles match well on both the drawrod and the stud. The temperature rise of the drawlead or drawrod may be much higher than the rise of the bushing stud, so the capability of a drawlead bushing to handle the overload depends on the cable or rod used.

## V. THERMAL MODEL SIMULATION

Even though we have verified the simple estimation method by measurements, we want to determine the accuracy by using a more detailed thermal model. For this purpose, we have developed a thermal circuit model similar to an electric circuit consisting of daisy-chained  $\pi$  segments as shown in figure 5.

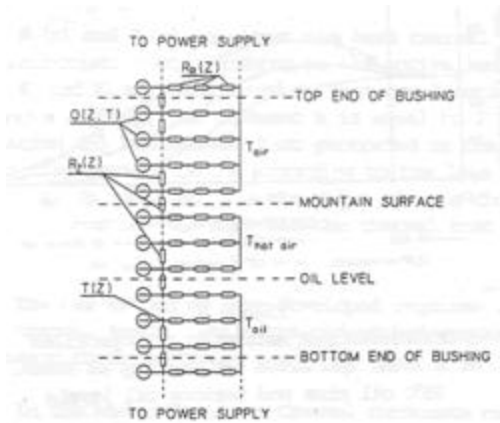


Figure 5

Thermal circuit model of a bushing without oil circulation

The model includes a bushing and connecting buses at the both ends. We have divided the bushing into 100 segments and the each connecting bus into 25 segments along their lengths. These segments are connected by 151 nodes. Each node consists of a heat source  $Q(Z, T)$ , two axial thermal resistors  $R_z(Z)$  and one set of radial thermal resistors  $R_r(Z)$ .

We calculate the heat source for each node from current, electrical resistance, temperature and skin effect. The thermal resistance of each thermal resistor is based on geometry, material, and the thermal transfer mechanism - conduction or convection. In this calculation, we use the following boundary conditions:

1. The top portion of the bushing above the flange mounting surface is in ambient air with uniform temperature.
2. The bottom portion of the bushing between the flange mounting surface and the oil level is considered to be in the hot air where the temperature is equal to the oil temperature.
3. The bottom portion of the bushing is immersed in the oil with uniform temperature.
4. There is no axial heat transfer at the ends of the buses.

The procedure for using this model to examine the new method is as follows:

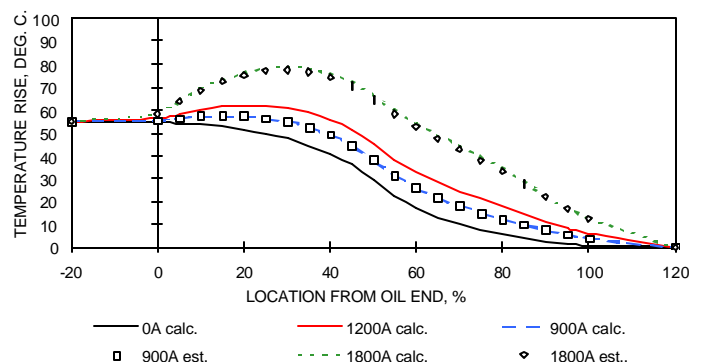
1. Calculate the rise profiles at zero current and the rated current from the thermal model and then obtain  $F_1(z)$  and  $F_2(z)$ .
2. Using the thermal model, calculate the rise profiles at various load conditions and use as the calculated profiles.
3. Use equation (3) with  $F_1(z)$  and  $F_2(z)$  to estimate the rise profiles at the same load conditions as procedure 2. These rise profiles are the estimated rise profiles.

## VI. CALCULATED RESULTS

This section shows the calculated and estimated rise profiles to prove whether the simple estimation method is valid for various magnitudes of current, oil rise and oil level for a bushing without oil circulation. The calculation is performed on a 350kV BIL 1200A POC bushing without oil circulation.

1. At different currents:

The results show that equation (3) could estimate the rise profiles at different current accurately if the conductor resistance did not change with temperature.



of a 350kV BIL 1200A PRC bushing at 1200A,  
21" oil level with various oil rises

Figure 6

Calculated and estimated rise profiles  
of a 350kV BIL 1200A PRC bushing at 55°C oil  
rise, 21" oil level and various currents

Because the resistance does change with temperature, we use an iterative method to calculate the rise profiles from the thermal model. Figure 6 shows the calculated rise profiles and the estimated rise profiles. The estimated profiles are slightly below the calculated profiles when overloaded and vice versa when underloaded, which is consistent with the thermal tests. From the thermal model, the deviation is about -0.5% at 125% current and about -3% at 150% current, and it may increase to -8% at 200% load.

2. At different oil temperature rises:

In the simple estimation method, we obtained  $F_1(z)$  and  $F_2(z)$  at the rated oil rise. However, because the general solution  $\Delta\Theta_h(0,z)$  and the particular solution  $\Delta\Theta_p(1,z)$  of equation (3) change with the oil rise,  $F_1(z)$  and  $F_2(z)$  must change with the oil rise. We can expect that the estimation based on  $F_1(z)$  and  $F_2(z)$  derived from the rated oil rise is no longer precise with the changing oil rise, and a deviation will occur.

Figure 7 presents comparison of the results from the calculation and estimation. The estimated rise profiles are below the calculated profiles when the oil rise is high and vice versa when the oil rise is low due to the changing resistance. The deviation is less than  $\pm 0.5\%$  in the range of 35°C. to 75°C oil rise at rated current. We consider this level of deviation negligible.

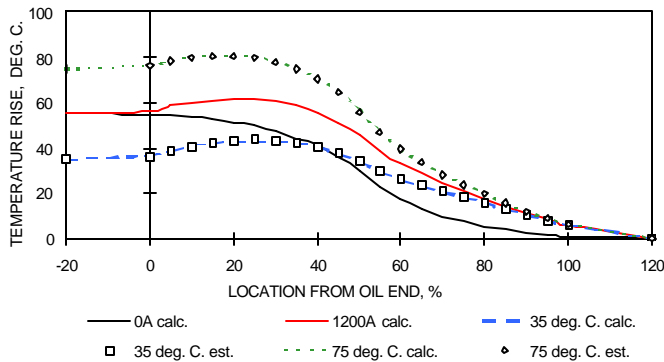


Figure 7

Calculated and estimated rise profiles

3. At different oil levels

Although the simple estimation method does not consider the oil level, it does have influence on the rise profile. The thermal calculation shows that when the bushing oil level is increased, the estimated rise profile is slightly higher than the calculated profile due to that the improved cooling from the higher oil level is not considered in the estimation.

The influence of the oil level is negligible when the bushing is working at the rated current, because the hottest spot at the rated current is located below the rated oil level. The calculation results show that the estimated hottest spot rise is only 1% higher than the calculated rise when the oil level is increased from the rated 21" below the mounting flange to 4.1".

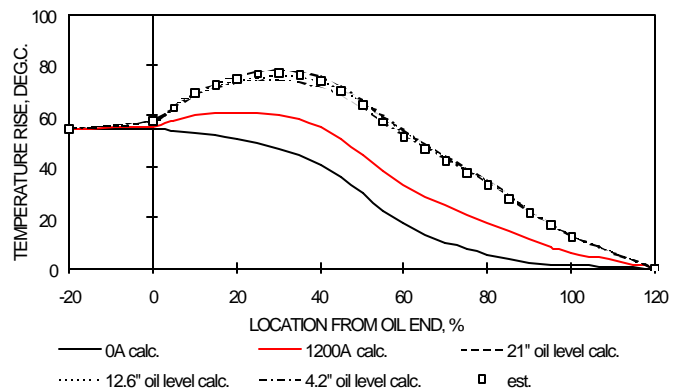


Figure 8

Calculated and estimated rise profiles  
of a 350kV BIL 1200A PRC bushing at 1800A,  
55°C oil rise and various oil levels

When the overload becomes greater, the influence of the oil level increases because the hottest spot migrates above the rated oil level. In a real application, the oil rise and the oil level go up at the same time. Their combining influence on the estimated rise cancel each other, therefore the deviation error of the estimated rise is less than if only one factor is considered in the estimate. For example, if the bushing is working at 1.5 pu, the estimated hottest spot rise is 77.3°C, the calculated hottest spot rise 78.7°C at rated oil level of 21" and 74.4°C at oil level of 4.1", respectively. Figure 7 compares the estimated rise profile to the calculated rise profiles. The resulting deviation between the estimated hottest spot rise and

the calculated rise is about 4% at  $1.0 \pm 0.5$  pu, which is consistent with the test results.

From the thermal model and the test results, we can expect that the accuracy of the estimated hottest spot rises is within 5% in the current range of  $1.0 \pm 0.5$  pu.

## VII. DISCUSSION

Because all the estimation is based on two profiles  $F_1(z)$  and  $F_2(z)$  deduced from two thermal tests, the accuracy of the thermal tests are extremely important in obtaining an accurate hottest spot temperature rise. Some factors influence the accuracy of the tests: bus connection conditions, the method and accuracy of temperature measurements, fluctuations of the ambient temperature and oil level, current fluctuations and current waveform distortion.

We obtain  $F_1(z)$  from the difference of the two base thermal tests. The connections from bushing to power supply influence the test results, especially for high current bushings. So it is very important to maintain very good connection during test.

Thermocouples were used to measure the conductor temperatures at several locations. The thermocouples making contact with the conductor are not electrically isolated from one another. There may be some stray coupling between the thermocouple circuit and the AC high current power supply. Our findings reveal a small erratic swing in the temperature readings immediately following the high current power supply switching off.

Thermally, a bushing with a large mass is an inertial system where the rise profiles lag the changes in the surrounding environment. The error resulting from the lagging effect can be reduced by averaging successive data after steady-state conditions are reached.

## VIII. CONCLUSION

The new method requires only two thermal tests and predicts the temperature rise along the entire bushing length accurately. From this profile we can determine the hottest spot temperature and its location. This method also enables us to calculate the overall average temperature of a bushing. The accuracy of the simple estimation method is about  $\pm 5\%$  if the load is within  $1.0 \pm 0.5$  pu.

This method is not limited to bushings without oil circulation. We have applied this method successfully to all types of bushings: from 110kV BIL to EHV, from low current to high current, POC and PRC, with and without oil circulation, and bottom connected and draw-lead/draw-rod connected. The test shows we can use this method for air-to-air bushings and special bushings with multiple conductors.

Besides accurately predicting the rise of a loaded bushing, this method provides a correction method for a test which is not run at the exact rated condition. This method can also be used to estimate the temperature rise of some extra high current bushings when the proper test facilities are not available.

We believe that our proposed method can help the IEEE standard committee improve the current standard and simplify the bushing thermal tests.

## ACKNOWLEDGMENT

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## BIOGRAPHY

He received BS in high voltage engineering in 1964, an MS in electrical measurements in 1967 and another MS in high voltage engineering in 1981 all from Tsinghua University, Beijing, China.

From 1968 to 1978 he works at Xi-an Power Rectifier Company in China and developed AC-DC and DC-AC energy conversion systems. From 1981 to 1985 he works at Electrical Engineering Institute of Chinese Academy of Sciences and developed high-voltage impulse generators, as well worked on high-voltage insulation projects.

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