ESTIMATING THE TEMPERATURE RISE OF LOAD BREAK SWITCH CONTACTS IN ENCLOSED MV SWITCHGEAR

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ABSTRACT

MV switchgear experiences a rise in temperature during normal operation due to ohmic losses in conductors and contacts. If the temperature rise is too high, the switching device may be degraded. The focus of this paper is to find a value for the total heat transfer coefficient that may be applied to estimate the temperature of critical parts (open/close contact) of the load break switch in an enclosed MV switchgear, relative to the surrounding air (inside the enclosure) for future design.

The values for the total heat transfer coefficient (including all transfer mechanisms) showed a relatively strong dependence on the surface emissivity and the actual design of the switch, but was less dependent on temperature changes within the relevant temperature range.

Based on our findings, it is reasonable to assume that the total heat transfer coefficients may be applied in a first approximation of the temperature rise of a load break switch contacts relative to the surrounding air inside an enclosure. Further refinement could be obtained by taking the actual design of the switch into consideration, especially details influencing the emissivity and design elements influencing the heat conduction to adjacent conductor parts.

INTRODUCTION

MV switchgear experiences a rise in temperature during normal operation due to ohmic losses in conductors and contacts. If the temperature rise is too high, the switching device may be degraded.

Originally, switching devices were mounted in an open environment with good cooling conditions. However, since the late 1960s, there has been a growing trend towards developing metal-enclosed and more compact switchgear. Despite the restricted cooling of the these switchgear, SF_6-filled equipment normally bring limited thermal challenges due to the excellent thermal properties of the SF_6 gas. Unfortunately, SF_6 suffers from a high level of global warming potential (GWP), so it is preferable to replace the gas with more climate-friendly gases such as air. The alternative gases have poorer thermal properties compared with SF_6, and since keeping the switchgear's design compact is desirable, an optimized thermal design is required to limit the temperature rise. The most critical parts are the electrical contacts. The international standard IEC 62271-1 [1] specifies a maximum temperature rise of 75 K for bolted connections and 65 K for movable contacts (open/close and sliding/rotating).

MV switchgear consists of different switching devices (circuit breakers, load break switches (LBS), grounding switches, disconnectors), busbars, and fuses. This paper focuses on the LBS placed serially within the main current path. The scope of our work is to develop a practical design tool that can be applied to estimate the temperature rise of the LBS contacts in future air-filled switchgear designs. We suggest an approach where the temperature rise is determined in two steps:

1. The temperature rise of the air inside a sealed MV switchgear is estimated by applying a method based on the empirical approach described by the IEC TR 60890 [2].

2. The over-temperature (relative to the air inside the switchgear) of the contacts is determined by applying empirically determined heat transfer coefficients.

The first step is outlined in Ref [3] and [4]. In this paper, we focus on the second step of the method. The total heat transfer coefficient applicable for the relevant temperature range is calculated based on experimental data. The sensitivity of the coefficient is explored when different parameters are changed, such as the emissivity, the temperature range, and the LBS design.

THEORY

Total heat transfer coefficient

The heat generated by the current carrying parts and the load break switch (LBS) due to the ohmic losses (P_{LBS}) is transferred to the surroundings. The major part of the ohmic losses are found in the LBS and a total heat transfer coefficient (h_{tot}) for the switch may be defined by

$$
\begin{aligned}
P_{LBS} &= R_{LBS} I^2 && (1)\\
&= h_{tot} A_{LBS} (T_{LBS} - T_{air}) && (2)
\end{aligned}
$$

where R_{LBS} is the total resistance of the LBS at load conditions, I is the current through the switch, A_{LBS} is the heat exchange surface area of the LBS, T_{LBS} is the temperature of the LBS and T_{air} the temperature of the air surrounding it.

Equation (2) does not take into account the different mechanisms of heat transfer, and a more detailed power balance is needed in order to investigate and distinguish between the different contributions. Some of the heat generated in the LBS is lost by radiation to the enclosure walls (P_{rad}), some is lost by conduction to adjacent conductors (P_{cond}), and some is transferred to the surrounding air by means of convection (P_{conv}):

$$R_{LBS} I^2 = P_{rad} + P_{cond} + P_{conv} \quad (3)$$

A number of approximations and simplifications are made when defining a total heat transfer coefficient as in Equation (2). As the LBS is located inside an enclosure, the reference temperature for radiation and convection is not the same as would be the case for an open installation. In addition, the radiation depends on the temperature raised to the 4th power, and the contribution from conduction does not directly depend on the air temperature or surface area of the LBS. However, we expect the convection to be the dominant mechanism, and that the total heat transfer coefficient, h_{tot}, may be applied as a first approximation for estimating the temperature rise.

Radiation

The power radiated from the LBS to the enclosure walls is given by

$$P_{rad} = \varepsilon \sigma A_{LBS} (T_{LBS}^4 - T_{wall}^4) f \quad (4)$$

where ε is the average emissivity of the LBS, σ is Stefan Bolzmann's constant, T_{wall} is the average wall temperature, and f is a geometric factor included to account for the fact that some of the radiation exchange is with other hot surfaces.

Conduction

If the LBS is the hottest area along the current path, there will be some thermal conduction towards cooler conductor parts adjacent to the LBS. The conducted power upwards ($P_{cond,up}$) towards the busbar and downwards ($P_{cond,down}$) towards the cable connection is given by

$$P_{cond} = P_{cond,up} + P_{cond,down} \quad (5)$$

$$
\begin{aligned}
P_{cond,up} &= \frac{\lambda_{bus}}{s_{bus}} A_{bus}^{cc} (T_{LBS} - T_{bus}) && (6)\\
P_{cond,down} &= \frac{\lambda_{cable}}{s_{cable}} A_{cable}^{cc} (T_{LBS} - T_{cable}) && (7)
\end{aligned}
$$

where λ_{bus} and A_{bus}^{cc} are the heat conductivity and cross-sectional area of the conductor connecting the LBS to the busbar, T_{bus} is the temperature of the conductor a distance s_{bus} from the LBS. λ_{cable}, A_{cable}^{cc}, T_{cable}, and s_{cable} are the corresponding symbols for the conductor connecting the LBS to the cables/bushings, see Figure 1.

Convection

The heat exchange by convection, from the LBS to the surrounding air inside the enclosure, is given by

$$P_{conv} = h_{conv} A_{LBS} (T_{LBS} - T_{air}) \quad (8)$$

where h_{conv} is the convective heat transfer coefficient, which depends weakly on the temperature [5].

EXPERIMENTS

The experiments were performed on two different MV switchgears with the same rated current of 630 A. For both switchgears, two of the modules were equipped with load break cable switches (LBS). The other modules were electrically disconnected, and the current passed from one cable module via the busbars through the second cable module, see Figure 1. This is the current path through the switchgear during normal conditions in a common cable ring distribution system. The switchgear was filled with air and closed, but not sealed, i.e. the pressure inside was the same as the atmospheric pressure outside the enclosure. Commercial switchgear is typically overpressurized and has thus somewhat better thermal properties. The enclosure had no ventilation openings, and no air circulation from outside was possible during the measurements.

Thermal testing was carried out with a three-phase current, at a frequency of 50 Hz, supplied from a high current injector test equipment (Hilkar type AK23). Relevant temperatures were measured when the equipment had reached steady-state conditions (< 1 °C/hour).

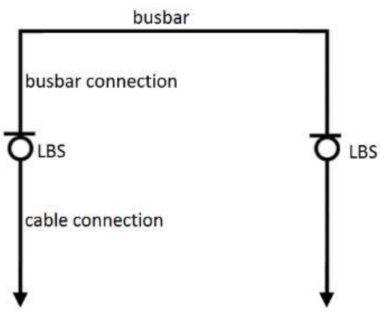

Figure 1: Current path for one of the three phases of the tested switchgears.

Two different switchgears were studied. The first was a (non-commercial) 3-module prototype (volume 0.405 m^3), equipped with a puffer-type load break switch. The second was a 4-module commercial switchgear (volume 0.540 m^3), equipped with a knife blade switch.

Puffer switch

The LBS in the 3-module switchgear, was a puffer switch, as shown schematically in Figure 2. It was equipped with a tulip-type of open/close contact and a linear sliding contact to provide electrical connection during contact movement. All conductors of the puffer switch were made of copper, some silver-plated and some bare copper.

The pressure cylinder and the crankcase enclosing the current path, see Figure 2 (a), affects the heat exchange since the radiation and convection from the heat source (current path) is restricted, while the total surface area for heat exchange with the surrounding air, is increased. Measurements were taken on a stripped version of the switch in order to simplify the conditions for the heat transfer, see Figure 2 (b), i.e. including the current path only and removing elements necessary for the switch to function properly, such as the pressure cylinder and the crankcase. Previously published results have shown that the temperatures of the LBS did not change significantly when removing these elements [6].

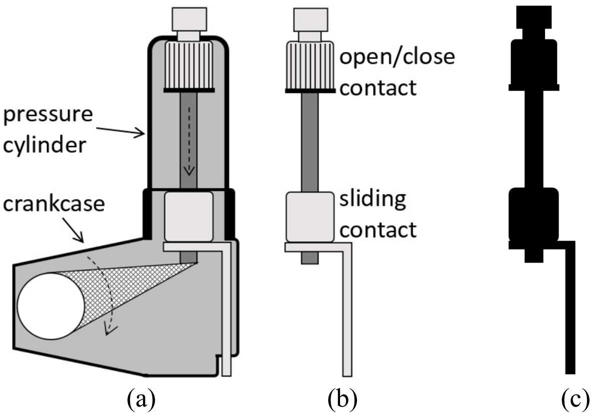

Figure 2: Puffer-type LBS. (a) Complete switch. (b) Stripped switch (used for Case 1 and 2). (c) Black-painted stripped switch (used for Case 3).

Influence of temperature range

Equations (4-6) show that the different transport mechanisms have different temperature dependencies, implying that the application of a total coefficient in Equation (2) may only be valid within a relatively narrow temperature range. The stripped puffer switch was tested with the 630 A rated current (Case 1) and 500 A (Case 2) in order to study the influence of temperature range. The different test conditions are summarized in Table 1.

Influence of radiation

Based on measurements taken with a thermographic camera, an average emissivity 0.23 was found for the stripped puffer switch shown in Figure 2 (b).

Previously published results [6] have shown that radiation can be important, and in order to study the influence of radiation on the total heat transfer coefficient in Case 3, the stripped puffer switch was covered with a matte finish black paint, as illustrated in Figure 2 (c). The emissivity then increased to 0.97.

Table 1: Load break switch (LBS) type, surface area (A_{LBS}), emissivity (ε), geometric factor, resistance (R_{LBS}), and test current (I) for the different test cases.

Case	LBS type	A_{LBS} [m^2]	ε [-]	f [-]	R_{LBS} [µΩ]	I [A]
1	Stripped puffer	0.027	0.23	0.7	56	630
2	Stripped puffer	0.027	0.23	0.7	52	500
3	Stripped puffer	0.027	0.97	0.7	56	630
4	Knife blade	0.025	0.17	0.8	32	630

Knife blade

The 4-module switchgear was equipped with a knife-type LBS. The open/close contact is defined by the two rotating, spring-loaded knife blades and a stationary single flat contact. The electrical connection to the knife blades are secured by a rotating spring-loaded contact, see Figure 3. An electrically insulating lever and chain transfers the rotational motion of the operating shaft to the knife blades. The lever partially encloses the middle of the knife blades. When determining the surface area (A_{LBS}) for heat exchange of this switch, we exclude surfaces upwards and downwards towards the insulating material, the inner surfaces of the knife blades and half the knife surface covered by the insulating lever. All conductor pieces were silver-plated copper conductors with an emissivity of 0.17.

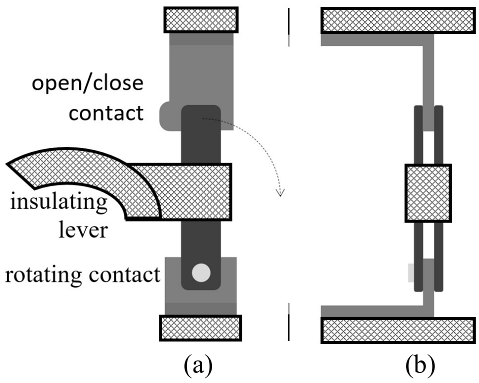

Figure 3: Knife blade-type LBS (used for Case 4). Areas with pattern filling illustrate insulating material. (a) Front view. (b) Side view.

Temperature measurements

In order to estimate the heat transfer coefficients defined in Equations (3-8), some simplifications are made regarding the temperature measurement points. For the temperature of the switches (T_{LBS}), we choose the point where the highest maximum temperature is expected in both types of switches. From practical experience, we know that this is the open/close contact, which also have the lowest permissible limit according to the standard (IEC 62271-1). Consequently, the measured temperature here will also be the limiting factor of the thermal design of the switch. The movable contacts have a relatively high level of contact resistance compared to other parts, and are normally the critical elements in the thermal design.

The temperature of the enclosure walls (T_{wall}) is needed in order to calculate the radiative power according to Equation (4). As the emissivity is small for all cases (except Case 3), the contribution from radiation is modest, and it is assumed that the wall temperature can be estimated by a single measuring point, chosen to be at the middle of the back wall, away from the electrical bushings and operating mechanism.

The temperature of the air inside the enclosure (T_{air}) is measured at the height corresponding to the where the switches are located. Measurements of the temperature drop across a limited distance above and below the LBS were taken in order to perform estimations of the heat conduction according to Equation (6) and (7). The input from bulk resistance and heat transfer from the relevant surfaces between the measuring points, was neglected.

RESULTS

Temperature measurements

The results of the temperature measurements are listed in Table 2 together with the total power dissipated in the LBS during load conditions (P_{LBS}), calculated from Equation (1).

Table 2: Power dissipated in the LBS during load conditions (P_{LBS}) and temperatures measured at the LBS (T_{LBS}), the air surrounding it (T_{air}), and the enclosure wall (T_{wall}).

Case	P_{LBS} [W]	T_{LBS} [K]	T_{air} [K]	T_{wall} [K]
1	22	372	325	310
2	13	344	314	302
3	22	363	327	309
4	13	369	326	312

Heat transfer coefficients for the LBS

Based on the values from Table 2, the total heat transfer coefficients for the LBS were calculated according to Equation (2), see Table 3. The uncertainty is at least ±15 %, based on the assumptions and estimates made.

Table 3: Calculated total heat transfer coefficient (h_{tot}) and convective heat transfer coefficient (h_{conv}).

Case	h_{tot} [W/(m^{2}K)]	h_{conv} [W/(m^{2}K)]
1	17	11
2	16	9.8
3	23	9.7
4	14	11

The radiated power was estimated for all cases, based on Equation (4) and values given in Table 1 and 2. Values around 10-15 % of the total LBS power, were found for all cases with a low level of emissivity (0.2). For Case 3 with a high level of emissivity, the percentage of power lost by radiation increased to around 40 %. The percentages of the LBS power lost by radiation for all cases, are illustrated with the yellow parts of the bar diagram in Figure 4.

The conductive power was estimated by Equations (6) and (7) for all cases based on temperatures measured above and below the LBS. The values found were around 20-30 % of the total LBS power, see Figure 4. The exception was Case 4, in which a temperature drop was only recorded downwards from the LBS, and the conductive contribution is reduced to about 10 %.

Based on the calculated contribution from radiation and conduction, the convective power was found by applying Equation (3). Based on these results, the convective heat transfer coefficients, h_{conv}, were calculated by applying Equation (8). The values are relatively consistent (10-11 W/(m^{2}K)), see Table 3, however the uncertainty is probably even higher than for h_{tot}. The values are in the upper range compared to values typically found in literature for free convection (typically 5-10 W/(m^{2}K)) for large surfaces in air. This may be reasonable, as we expect a more effective cooling of the small conductor surfaces.

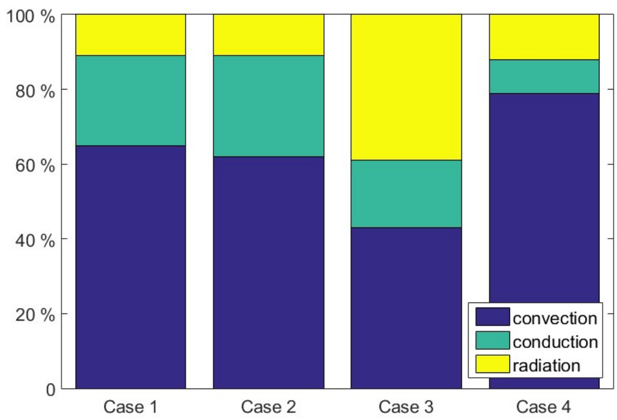

Figure 4: A comparison of the contribution from the different heat transfer mechanisms for all 4 cases.

DISCUSSION

The focus of the paper was to find a value for the total heat transfer coefficient, and see whether this can be applied when making an estimate for the temperature rise of critical parts (o/c contact) of the LBS in an enclosed MV switchgear for future designs. The following discussion uses Case 1 (stripped puffer switch) with a total heat transfer coefficient, h_{tot}, of 17 W/(m^{2}K) as the reference case.

Sensitivity to temperature range

Case 2 was performed with a reduced load current, and by comparing the results for Case 1 and 2, we see that h_{tot} depends only modestly on the temperature as long as the temperature are within the relevant range for this equipment (and the emissivity is low). The small reduction with reduced current and temperature, might be due to reduced radiation losses when the temperature is reduced.

Sensitivity to radiation

Case 3 was performed with a black painted LBS in order to increase the emissivity. By comparing the results for Case 1 and 3, we see that the total heat transfer coefficient is sensitive to the emissivity, as expected. The coefficient increases by 35 % when the emissivity increases from 0.23 to 0.97.

Different LBS design

When testing a different LBS design in Case 4 (knife blade switch), h_{tot} was 18 % lower compared to Case 1. This is partly explained by lower radiation (emissivity) for Case 4, but more important is the reduced contribution found from conduction in this case. This illustrates that the contribution from conduction is highly dependent on the surrounding construction, and construction elements that can function as heat sinks, as well as non-metallic materials that may restrict the heat transport by conduction, have to be considered.

Average for complete current path

The results presented above are found by focusing on the load break switch only, and a dependency on conduction was found. By estimating the average value of the total heat transfer coefficient along the complete current path, conduction is assumed to play a minor role as it can only occur through the bushings and mechanical supports of the current carrying parts. A value of 9 W/(m^{2}K) was then found for both switchgear. This value is closer to h_{tot} found for Case 4 compared to Case 1, as expected due to the low contribution from conduction in this case.

CONCLUSIONS

10-15 % of the power dissipated in the LBS was lost by radiation (for all cases with a low emissivity), while the conductive losses was in the range of 10-30 %, dependent on the construction.

A total heat transfer coefficient of about 17 (W/m^{2}K) was found for the stripped puffer switch. This value was found to be sensitive to the emissivity, but almost insensitive to the temperature changes within the relevant range. When changing the construction and the design of the LBS, the total heat transfer coefficient was reduced to about 14 W/(m^{2}K), partly due to restricted heat transport by conduction.

Based on this experience, it is reasonable to assume that the total heat transfer coefficients may be used in a first approximation when the temperature rise of a LBS contacts, relative to the surrounding air (in an enclosure), has to be estimated. As a next step, the actual design should be studied and the contribution from conduction estimated. It should be noted that the experiments (Case 1-3) were conducted on a stripped puffer switch. The pressure cylinder and crankcase affect heat transport and proper adjustments should be made to account for this.

ACKNOWLEDGEMENT

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