Technical Physics, 2026, Vol. 71, No. 2

12

Calculation of high-current contact heating by short-circuit current

© R.V. Kolesnik, M.A. Pavleino, M.S. Safonov, A.V. Khrestin

St Petersburg University, The Faculty of Physics,
198504 Peterhof, St. Petersburg, Russia
e-mail: s.pavleino@yandex.ru

Received May 14, 2025
Revised July 17, 2025
Accepted August 4, 2025

Heating of contacts closed by short-circuit currents with various waveforms to temperatures exceeding the material recrystallization temperature was calculated. The influence of aperiodic current component on the contact heating behavior was analyzed. Methods for building simplified computational models were proposed to considerably reduce the resource intensity of problems being solved while preserving the acceptable accuracy of results.

Keywords: power grid, fault, short circuit, contact, heating.

DOI: 10.61011/TP.2026.02.62890.118-25

Introduction

In case of power grid failure, short-circuit (SC) currents flow via current-carrying systems of electrical equipment during several tens of periods until tripping and contact closing occur [1,2]. It is the contact region where most significant overheating of structures occurs because contacts are characterized by the presence of additional resistance compared with homogeneous regions of current-carrying systems and are high heat release regions [3–5]. Therefore increased focus is made on contact heating in case of emergency.

Short-circuit current can have various waveforms. Depending on the fault initiation phase, current can contain an aperiodic component, which can considerably, up to two times, increase the maximum current in the first half-period [6,7]. This current is called the initial short-circuit current. Aperiodic component decays quite quickly, during several periods, and current becomes equal to the steady-state short-circuit current $I_{Short\,circuit}$. Heating of contacts by currents with the maximum aperiodic component $I_1(t)$ and without the maximum aperiodic component $I_2(t)$ are considered (see, for example, Figure 1, *a*, *b*).

In electrical engineering, heat impact of short-circuit current on conductors and current-carrying systems of electrical equipment is generally quantitatively estimated using the Joule integral [6], which is determined as integral from squared flowing current in the range from the fault start time ($t = 0$) to the fault end time ($t = \tau$):

$$B_\tau = \int_0^\tau I^2(t)dt.$$

Currents flowing during a longer time or greater in magnitude are characterized by higher Joule integrals. They lead to more significant heating. This also refers to heat impact by currents with the same duration, but different waveform, when the difference is in the presence or absence of aperiodic component. For example, current shown in Figure $2, a, b$ have the same steady-state value, but the Joule integral is higher by 10 % for $I_1(t)$ than for $I_2(t)$ due to the presence of aperiodic component. So, the short-circuit current with aperiodic component will lead to somewhat higher heating of homogeneous conductors that the sinewave current. For contacts, there can be a different case.

1. Influence of contact spot blooming on contact heating by short-circuit currents

Contact heating during fault current flow is significantly affected by the contact spot (CS) blooming effect. This was demonstrated by experimental studies and computer simulation results [8–11]. We discuss this issue in more detail by performing a series of numerical calculations.

Calculations are conducted for contacts in the form of coaxial cylinders made of cold-worked copper M1 and connected by one round contact spot. This is achieved by selecting the shape of cylinder contact surfaces. One of them is flat, the other has a truncated cone shape. One cylinder is rigidly fixed, and a contact pressure force of 1000 N along the axis of symmetry is applied to the other one. With such force, the CS radius before current passage is equal to 0.62 mm. Cylinder radius is 10 mm, cylinder height is 100 mm. Ambient air temperature is 293K.

The essence of the computation scheme is as follows. Contacts are brought in touch by applying an external force. Mechanical contact problem is initially solved to determine the initial CS size. Full current flow calculation time is broken into small intervals dT.

Three problems are successively solved at each time segment:

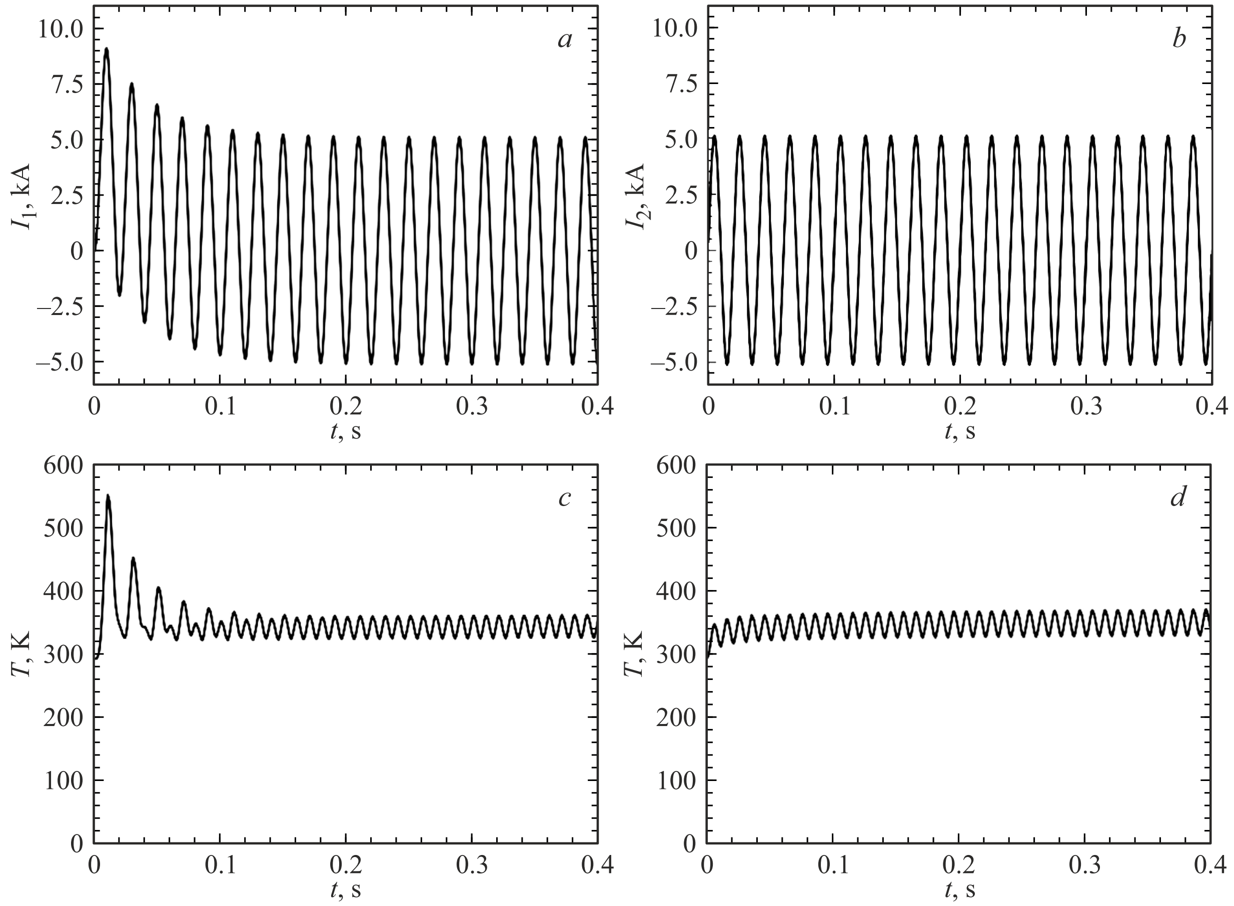

Figure 1. Time dependence of currents I_1 (a) and I_2 (b) and of CS temperature — (c), (d). $I_{Short\,circuit} = 5\,\mathrm{kA}$ case.

— current passage through contacts connected by CS with a known size where current density distribution is determined;

— heating by current with a known current density distribution (from the previous problem);

— mechanical contact problem with a known temperature distribution (from the previous problem) to determine the CS size changed by heating.

For details of the solution procedure and material properties, see [12]. The problem in such setting is called the initial problem, unlike approximate solution methods that will be discussed below.

Heating behavior, besides the current magnitude and waveform, is determined by the dependence of contact resistance on time $R_c(t)$. For bulk contacts with round-shaped spots, Rc can be calculated using the Holm equation [13]: $R_c = \rho/2a$, where ρ is the resistivity of material, a is the CS radius.

Variation of this resistance during short-circuit current passage is induced by resistivity and spot size variation during heating. If the spot temperature is lower than the material recrystallization (softening) temperature T_s, then the spot size increases negligibly. The contact spot blooming effect becomes significant when heating to a temperature higher than the material recrystallization temperature.

Consider the question of how the current magnitude and waveform (with and without aperiodic component) affect heating. Comparison will use the mean CS temperature at the end of short-circuit current pulse. Fault current duration is set to 0.4 s, which corresponds to commercial frequency current periods. During this time, aperiodic component, if any, decays, and the mean CS temperature for period almost stops changing.

We distinguish three typical cases, which differ in heating level in the first half-period with respect to the material softening temperature. In our case, $T_p = 600\,\mathrm{K}$. The CS temperature is hereinafter defined as the maximum spot surface temperature. Current with different waveforms $I_1(t)$ and $I_2(t)$ will be grouped in pairs provided that the steady-state short-circuit current $I_{Short\,circuit}$ is the same for each pair. $I_{Short\,circuit}$ is defined as a peak value.

The first pair of currents corresponds to $I_{Short\,circuit} = 5\,\mathrm{kA}$ (Figure $1, a, b$). Current level was chosen so that T_s was not reached even if there was a current surge in the first half-period. CS radius in both cases remains almost unchanged throughout the heating period.

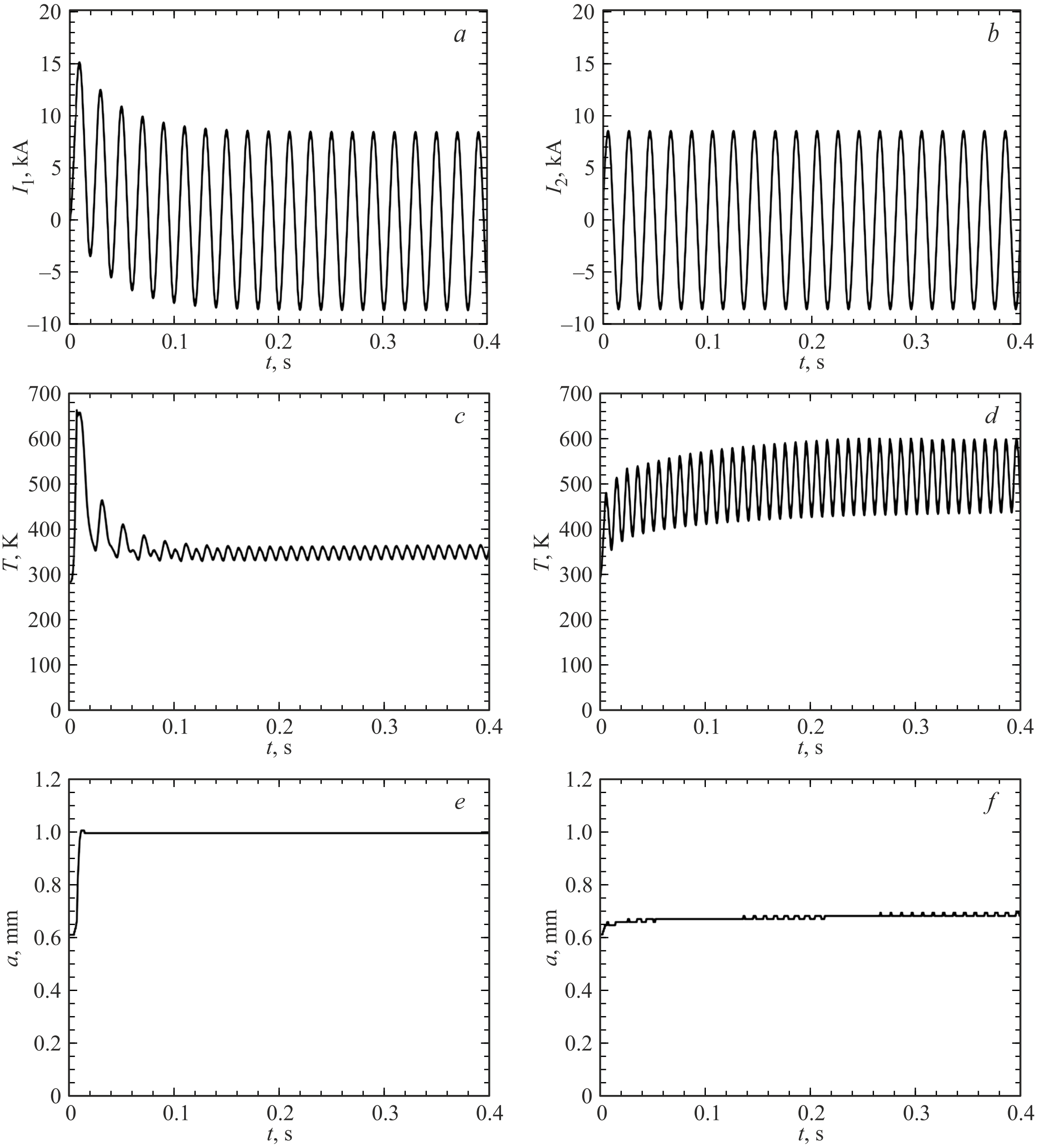

Figure 2. Time dependence of currents I_1 (a) and I_2 (b) and of CS temperature — (c), (d) and CS radius (e), (f). Case $I_{Short\,circuit} = 8.5\,\text{kA}$.

Behavior of dependence of CS temperature on time varies for different current waveforms. In the first case, there is a temperature jump in the first half-period, then achievement of the steady-state value T_{med_1} is observed during several periods. For $I_2(t)$, there is monotonic increase in temperature with achievement of T_{med_2} also during several first periods. These temperatures are close to each other — about 350 K. Overtemperature in the first period T_{med_1} for $I_1(t)$ is associated with 1.8-fold overtemperature compared with the steady-state current $I_{Short\,circuit}$.

The next pair of currents with $I_{Short\,circuit} = 8.5\,\text{kA}$ is an edge case of heating. Current with aperiodic component heat the contact region in the first half-period to a temperature above T_s, and heating by current $I_2(t)$ at these time is much lower than this temperature. This results in considerable difference in contact heating due to a difference in sizes of CS, through which this currents flow (Figure 2, d, e).

Mean temperature in the first case is about 350 K, in the second case is above 500 K. Their final overheating with respect to the initial temperature of 293 K differ by

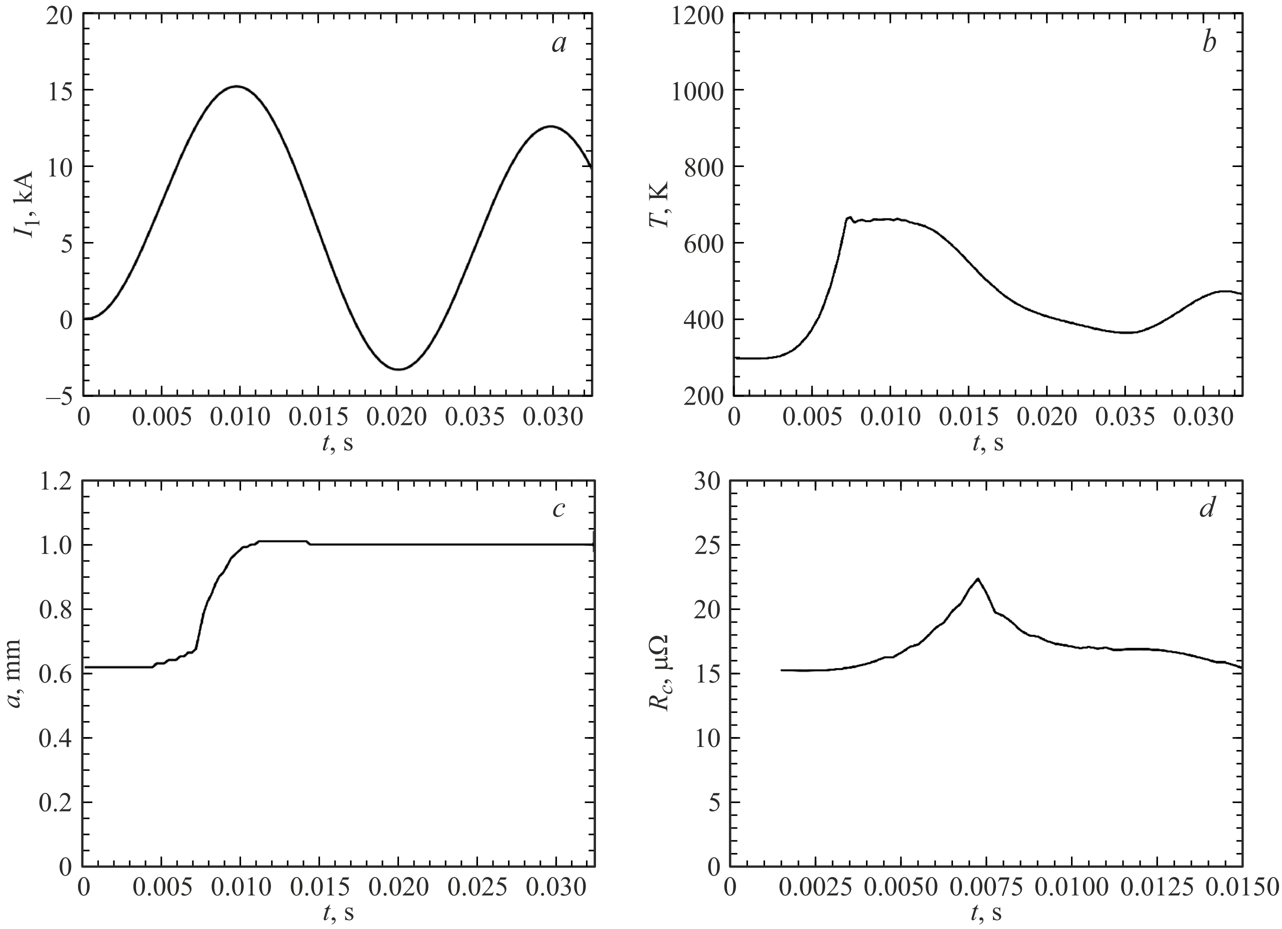

Figure 3. Fragments of time dependences of current I_1 (a), temperature (b), CS radius (c) and contact resistance (d). $I_{Short\,circuit} = 8.5\,\text{kA}$ case.

a factor of 3.5. The currents of interest cannot be treated as thermally equivalent any longer despite the fact that Joule integrals for them are equal.

Causes of such difference are clarified below. They are related to contact material softening in the first half-period of passage of $I_1(t)$. Figure 3 shows the fragments of time dependence of current, temperature and CS radius, and dependences of contact resistance on time. T_s is reached at time $t_s = 7$ ms. Further temperature growth stops regardless of the fact that current continues increasing (Figure 3, a, b). This is associated with the start of intense CS blooming and corresponding change in $R_c(t)$ (Figure 3, c, d). CS blooming occurs during a short period dT_s of about 2.5 ms. Then the CS area doesn't decrease despite the decrease in temperature below T_s because heat-induced deformations of the contact area are plastic and irreversible. Detailed analysis of heat-induced spot deformation is described in [12]. Further with $t > T_s + dT_s$ current $I_1(t)$ flows with much lower contact resistance compared with $I_2(t)$ because CS radius remained almost unchanged in this case. This causes so significant difference in final temperatures.

Finally, consider the case of current impacts where currents $I_1(t)$ and $I_2(t)$in the first half-period heat the contact area to a temperature above T_s (Figure 4). Due to spot softening in the first half-period under the action of $I_2(t)$, the temperature growth is not so intense as in the previous case (Figure 2, c), but the difference in the final heating is still considerable, overheating differs more than twofold (Figure 4, c, d).

From the calculations, one can conclude as follows. Aperiodic component doesn't affect final heating of CS only when the recrystallization temperature hasn't been reached yet. In this case, growth of contact resistance is provided by heating only the CS neighborhood.

If this temperature is exceeded and CS blooming occurs, then the final CS temperature for heating by the sinusoidal short-circuit current will be higher than the temperature achievable when current contains aperiodic component. Simplified models are discussed hereinafter considering contact heating by current without aperiodic component.

2. Building simplified numerical models

Computation scheme designed to calculate heating of closed contacts by short-circuit currents, which is used for

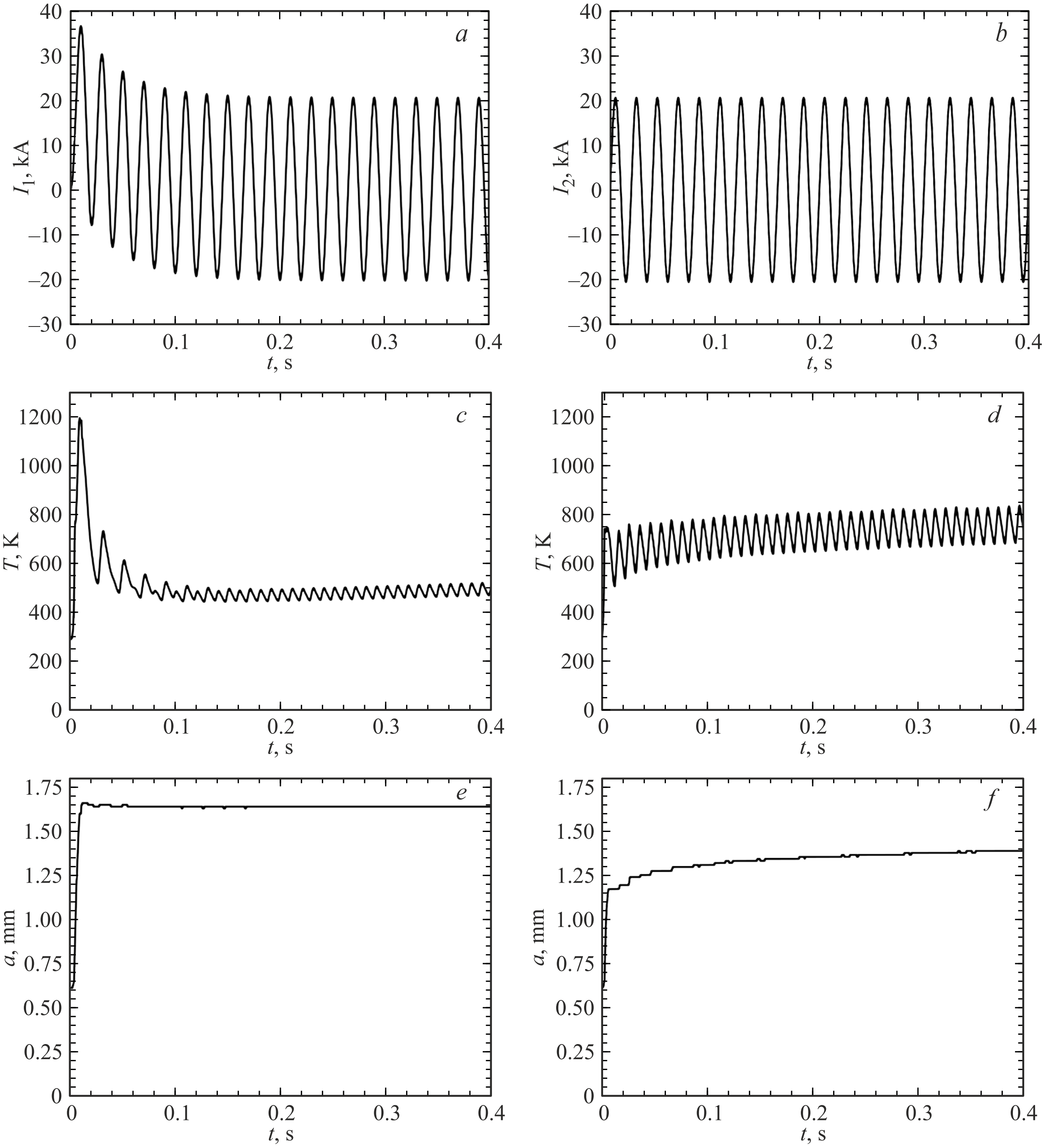

Figure 4. Time dependence of currents I_1 (a) and I_2 (b) and of CS temperature — (c), (d) and CS radius (e), (f). Case $I_{Short\ circuit} = 20.5\,\mathrm{kA}$.

solving the initial problem in this work and in [12], is extremely resource-demanding and requires longer computational time even for problems in axisymmetric setting. From three subproblems: mechanical contact problem, electric current density calculation and calculation of contact heating by known current, the first one takes the longest time, more than 80 %. Moreover, alternating form of current requires dividing the whole solution time into many intervals. Therefore, it is important to develop simplified numerical models, offering considerable reduction of the computational time without noticeable loss of accuracy. This is especially true for solution of three-dimensional problems, and all real contacts are three-dimensional objects not described by two-dimensional simplifications. Two methods considerably reducing the computational time compared with the initial problem are discussed below. One of them is based on reducing the number of mechanical contact problems by means of approximating the dependence of

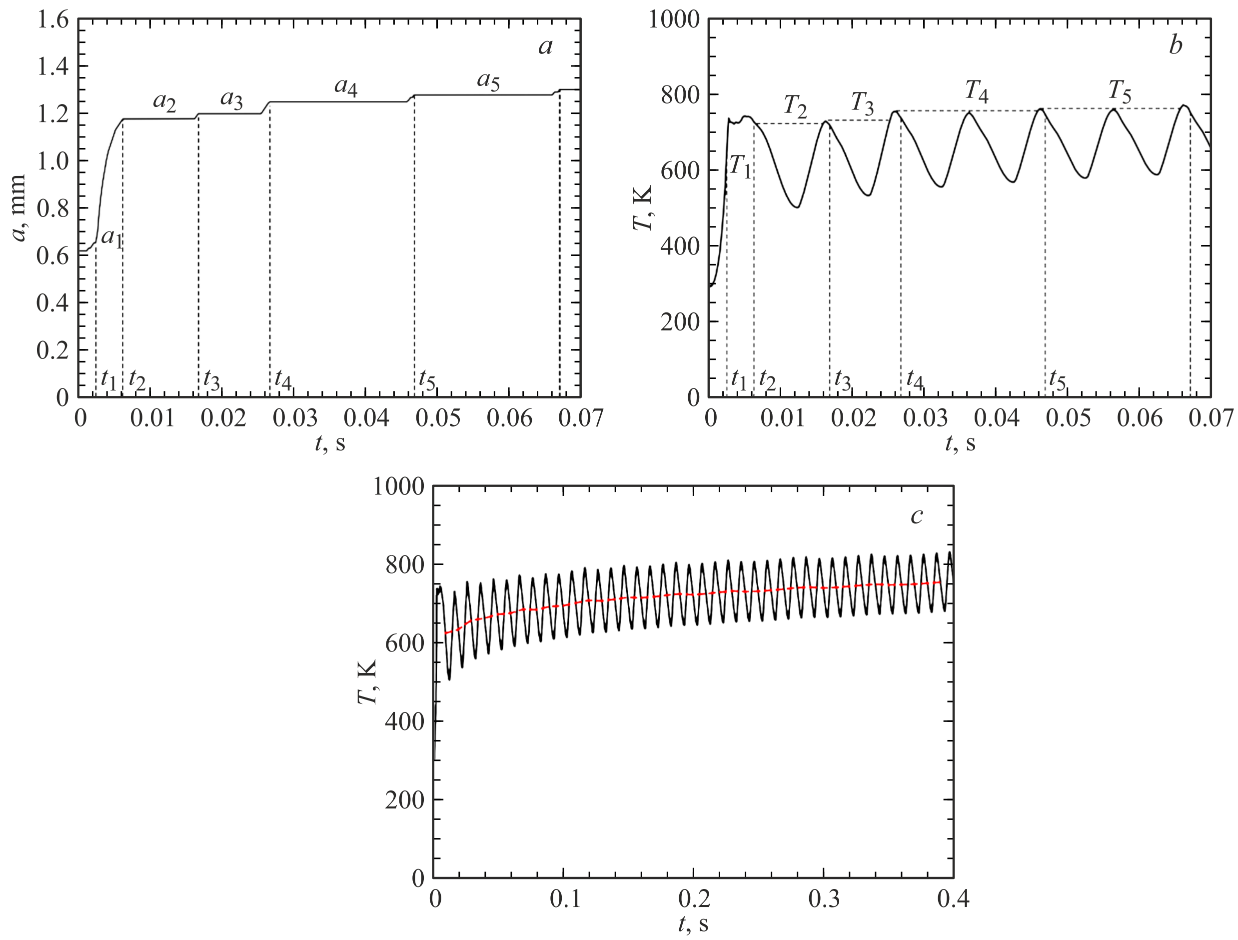

Figure 5. Fragments of dependences of CS radius (a) and temperature (b) shown in Figure 4, d, f. Time dependence of CS temperature for the initial problem (black curve) and time dependence of mean CS temperature for period for the simplified problem (red curve) (c).

the CS radius on time. The second method is based on replacement of the alternating current impact with a simpler one, which has a simpler waveform and requires much fewer divisions of the full computational time into smaller intervals.

The first method is explained below. The CS radius increasing process is hereinafter discussed in greater detail. Within the time range from $t = 0$ to t_1, the radius increases monotonically from the initial value to a_1 due to heating the contact area from the initial temperature to the recrystallization temperature $T_1 = T_s$ (600 K in our case). This is followed by intense spot blooming induced by material softening. CS radius increases by 80 % at t_2.

Then stepwise radius growth is observed. At each k-th time interval, radius equal to a_k is preserved until the current temperature exceeds T_k. Thus, there is not need at this time interval for solving the most resource-demanding mechanical contact problem. New radius value a_{k+1} shall be determined only when $T > T_k$ is satisfied.

In the calculations, one current period was divided into 100 intervals, each of which included, in particular, solution of the resource-demanding mechanical contact problem. Alternatively, it may be solved only at times t_3, t_4, t_5, etc., avoiding the intervals between them. This reduces the number of mechanics problems by approximately 200 times. Initial problem without simplifications is solved at the initial interval from $t = 0$ to t_2.

Compare the calculated results of the problem in the initial setting and in the above-mentioned approximate case (Figure 5, c). Mean temperature difference for period by the end of heating is max. 5 %. This shows high efficiency of this approximate method.

Proceed to the second simplified model. The first case approximated the CS radius variation with time after completion of CS softening process, keeping the alternating current as in the initial unsimplified problem. In this setting, the contact problem of finding the CS radius is solved at each time interval dT, and the current waveform is simplified — the sinewave current is replaced with rms current for most of the time. Such replacement takes place after achievement of the recrystallization temperature in the CS region and CS softening. Replacement of the sinewave current with rms current is used to considerably increase the calculation time step without noticeable loss of accuracy the obtained results.

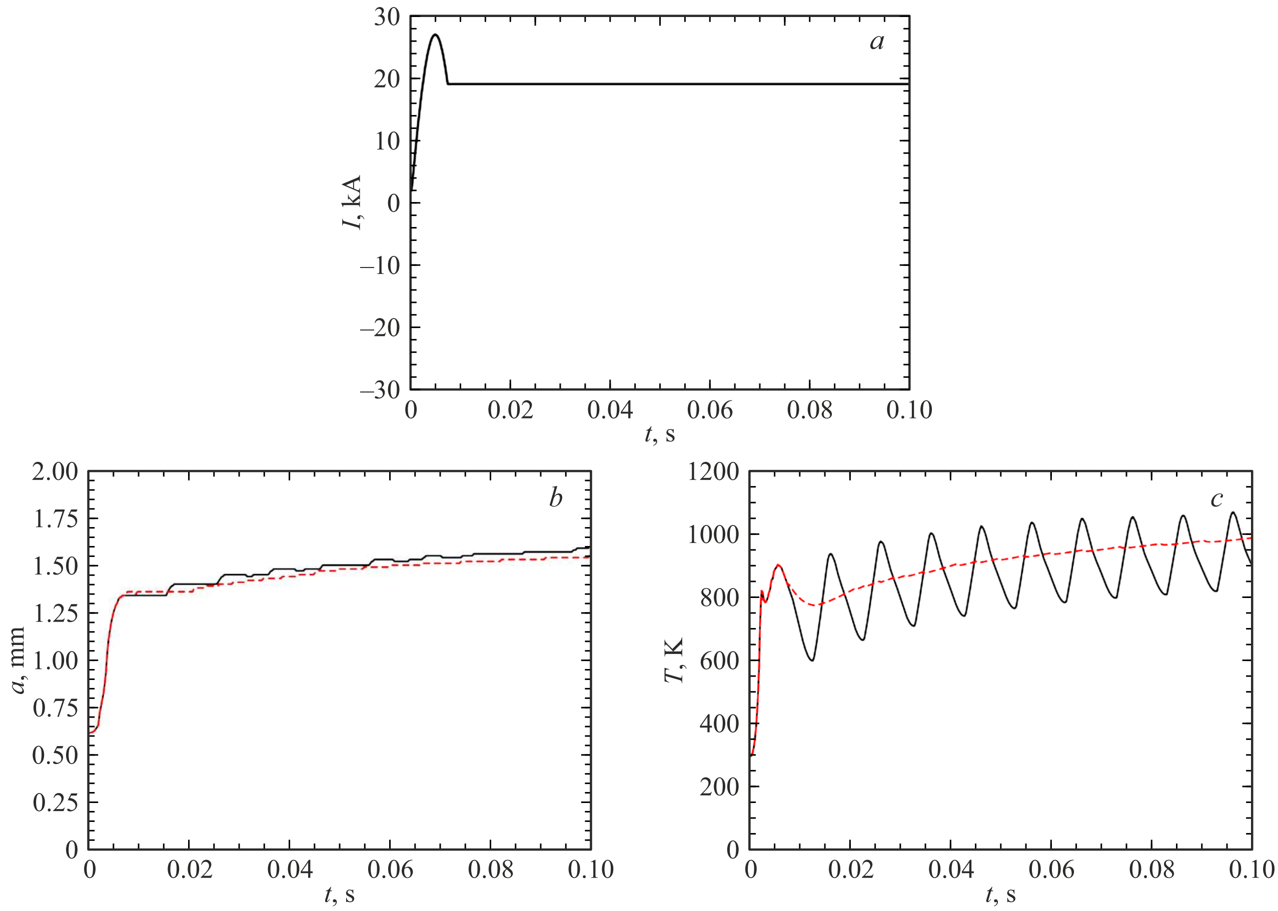

Figure 6. Current with simplified waveform (*a*), radius variation with time (*b*) and comparison of heating (*c*) for the initial problem (black curves) and simplified problem (red curves).

Consider the calculated results using this approximation for the case of T_s reached in the first half-period. Current waveform is shown below: alternating current is replaced with rms current after the first maximum (Figure 6, *a*). Replacement is performed in such a way as to avoid current jump.

Initial problem is solved until current replacement occurs. Therefore, the resulting dependences of temperature and CS radius on time are no different from the initial one. Then contacts are heated in direct current conditions. Temperature increases monotonically, but a little faster than the mean temperature in the initial problem. This is due to the fact that for alternating current, the temperature at maxima is higher by 100 K than the temperature at CS during heating by rms current, therefore CS blooming is somewhat more intense. Alternating current flows through contacts at lower Rc, therefore the mean contact temperature will be a little lower than for the rms current.

In the given example, after 40 current periods, difference between the temperature obtained from the second approximate calculation scheme and the mean temperature for period in the initial problem is 50 K in contrast to heating to 1000 K, which is quite acceptable for practical heating estimates. Note that such simplification is effective only when CS softening occurs during one of the first periods.

Conclusion

Proposed approximation methods for calculation of contact heating by short-circuit currents show adequate agreement between the calculated data and data obtained via solution of the initial thermo-electro-mechanical contact problem. The computational time decreases considerably both by means of reducing the number of mechanical contact problems, from which the current CS radius is determined, and by means of simplifying current impact waveforms. Such solution procedures can be recommended for achievement of reliable estimates of contact heating.

Conflict of interest

The authors declare no conflict of interest.

References

[1] A.M. Ershov. *Releinaya zashchita v sistemakh elektrosnabzheniya napryazheniem 0.38–110 kV* (Infra-inzheneriya, Vologda, 2024) (in Russian)
[2] V.I. Biryulin, D.V. Kudelina. *Releinaya zashchita i avtomatizatsiya elektroenergeticheskikh sistem* (Infra-inzheneriya, Vologda, 2022) (in Russian)
[3] N.K. Myshkin, V.V. Konchits, M. Braunovich. *Elektricheskie kontakty* (Intellekt, Moskovskaya obl., 2008) (in Russian)
[4] E.G. Porsev, B.V.Malozemov. *Elektricheskie i elektronnye apparaty* (NGTU, Novosibirsk, 2021) (in Russian)
[5] V.D. Tchervenchuk, A.L. Ivanov. *Elektricheskie apparaty. Teplovye protsesy v elektricheskikh apparatakh* (SibADI, Omsk, 2016) (in Russian)
[6] GOST R 52736–2007. Metody raschyota elektrodinamicheskogo i termicheskogo deistviya toka korotkogo zamykaniya Vved. 2008–07–01. (Standartinform, M., 2007) (in Russian)
[7] GOST R 52736–2007 *Korotkie zamykaniya v electroustanovkakh. Metody raschyota v elektroustanovkakh peremennogo toka napryazheniem svyshe 1 kV*. Vved. 2008–07–01. (Standartinform, M., 2008) (in Russian)
[8] T. Israel, S. Schlegel, S. Grossmann, T. Kufner, G. Freudiger. IEEE Holm Conf. Electr. Contacts, **254** (2018). DOI: 10.1109/HOLM.2018.8611641
[9] T. Israel, M. Gatzsche, S. Schlegel, S. Grossmann, T. Kufner, G. Freudiger. IEEE Holm Conf. Electr. Contacts, **40** (2017). DOI: 10.1109/HOLM.2017.8088061
[10] M. Gatzsche, N. Luecke, S. Grossmann, T. Kufner, G. Freudiger. Transactions on CPMT, **7** (3), 317 (2017).
[11] M.A. Pavleino, O.M. Pavleino, M.S. Safonov. Tech. Phys., **66** (1), 103 (2021). DOI: 10.1134/S1063784221010163
[12] A.V. Khrestin, M.A. Pavleino, M.S. Safonov. Tech. Phys., **68** (1), 137 (2023). DOI: 10.21883/TP.2023.01.55448.233-22
[13] R. Holm. *Electricheskie kontakty* (IIL, M., 1961), s. 464 (in Russian).

Translated by E.Ilyinskaya