

Joule's heat generated during a short-circuit current flow in function of phase angle

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Joule's heat (let-through energy) is an important factor in proper protection of electrical installations and devices. Studies were performed during which the relationship between amount of energy and phase angle of short-circuit current was examined. Typically used miniature circuit breaker was utilized as a protective device. Scilab software for numerical computation was used to calculate the let-through energy based on recorded oscillograms of short-circuit current. Results of this calculations are presented.

KEYWORDS: Joule's heat, circuit breaker, let-through energy

1. Miniature circuit breakers construction

Figure 1 shows schematically the main parts of a low voltage circuit breaker and its four essential functions [1]:

- a) circuit-breaking components, comprising the fixed and moving contacts and the arc-dividing chamber,
- b) latching mechanism which becomes unlatched by the tripping device on detection of abnormal current conditions, this mechanism is also linked to the operation handle of the breaker,
- c) trip-mechanism actuating device:
 - either: a thermal-magnetic device, in which a thermally-operated bi-metal strip detects an overload condition, while an electromagnetic striker pin operates at current levels reached in short-circuit conditions, or
 - an electronic relay operated from current transformers, one of which is installed on each phase,
- d) space allocated to the several types of terminal currently used for the main power circuit conductors.

Use of miniature circuit breakers (MCB) as protection devices for electrical installations is required by Polish law [2].

Miniature circuit breakers are used as protection devices against overload and short-circuit currents. Basic principles on how to protect electrical circuits and devices against these hazards are known and described in many publications [3,

4]. However there are not many information on the influence of phase angle on short-circuit current and the let-through energy (Joule heat).

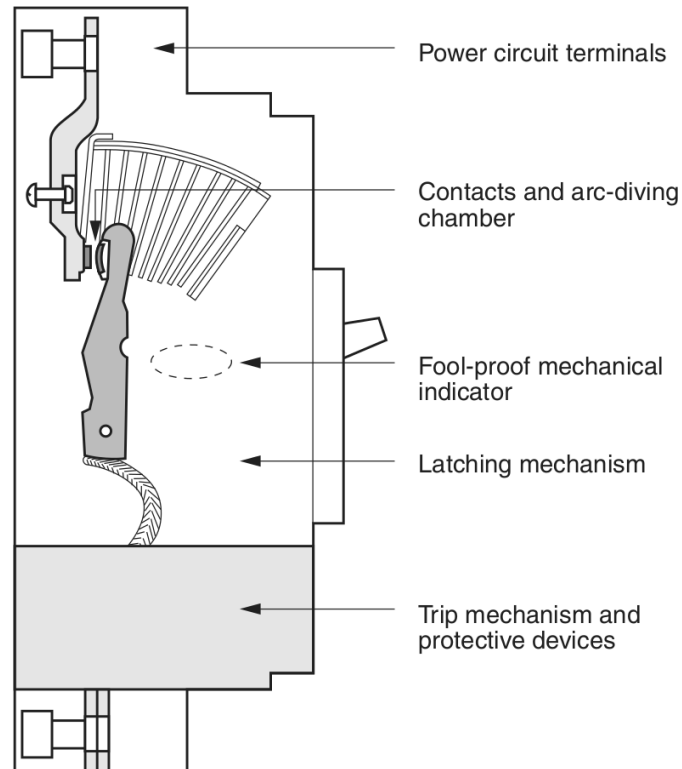


Fig. 1. Main parts of a circuit breaker

The amount of let-through energy can be an important factor in determining electrical contact temperature, during short-circuit current flow, as shown in [5]. Electrical contact resistance, which is an important factor determining contact temperature rise, can vary during the lifetime of electrical devices, especially for electromagnetic relays [8, 9, 11]. Analytical estimation of contact temperature is possible, but difficult [10, 12, 13].

2. Breaking an electrical arc in low voltage MCB

In AC installations electrical arc current reaches a zero value every half of period and changes its direction. So every half of period the electrical arc is turned off when the current value falls below the minimal value that can sustain it. During the zero-current phase (Fig. 2) the dielectric contact gap strength rises and the contact voltage rises to till it reaches the value of source voltage. If the rise of dielectric contact gap strength is too slow (Fig. 2a) then after time t_p a re-

arcing occurs, current rises and voltage drops. If however the dielectric contact gap strength is quickly rebuild (Fig. 2b) then there is no electrical spark and in result there is no re-arcing. Contact voltage reaches source voltage value [3].

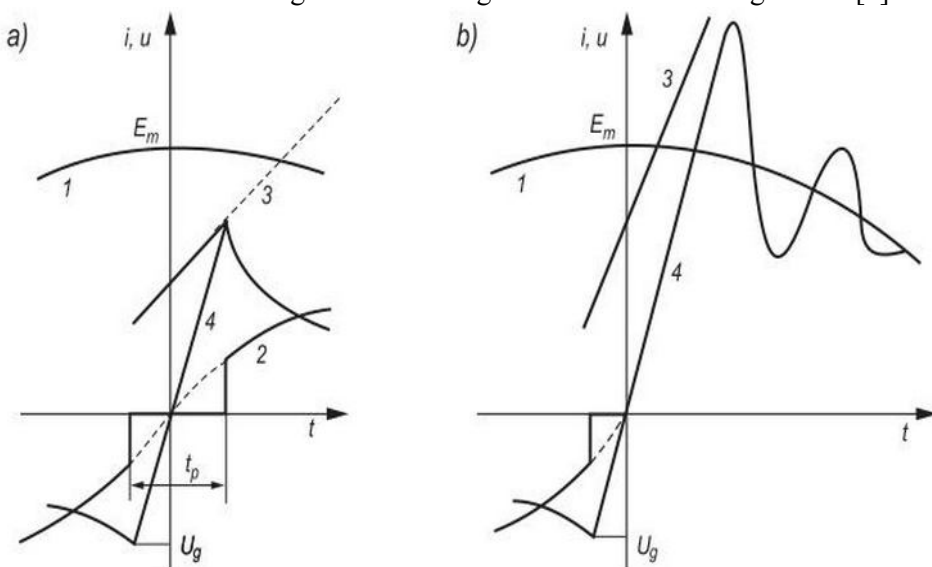


Fig. 2. Current and voltage during breaking of alternating current arc: a) with re-arcing, b) without re-arcing; 1 – source voltage, 2 – current, 3 - growth curve of dielectric strength of arc break, 4 - reverse voltage [3]

In purely ohmic circuit the moment current reaches zero source voltage also reaches zero. Favourable conditions occur for the electrical arc to dissipate. In an inductive circuit the moment current reaches zero source voltage reaches its maximum value. The conditions for arc extinguishing are far worse in inductive circuits than in ohmic ones. Zero current gap is longer in ohmic circuits than in circuits that include inductance or capacity [3].

3. Estimation of let-through energy

Joule's heat is the energy in joules liberated in one ohm of resistance in a circuit protected by a fuse is equal to the value of the operating I^2t expressed in $A^2 \cdot s$ [6]. It is also referred to as let-through energy as a parameter used for proper selection of protecting device for electrical installations (1).

$$\int i^2 dt [A^2 s] \quad (1)$$

Alternating current can be described with equation 2:

$$i(t) = I \sin(\omega t) [A] \quad (2)$$

and taking equation 2 and 1 Joule's heat can be described as (eq. 3):

$$\int (I \sin(\omega t))^2 dt [A^2 s] \quad (3)$$

After solving eq. 3 we obtain (eq. 4):

$$\int i^2(t) dt = \frac{\left(\frac{-\sin(2(\omega t + \varphi))}{2} + \omega t + \varphi \right) \cdot I^2}{\omega} + C [A^2 s] \quad (4)$$

where C is the integration constant. Integrating eq. 3. with limits from zero to t_z , where t_z is short-circuit time we get (eq. 5):

$$\int_0^{t_z} i^2(t) dt = \frac{(-\sin(2\varphi) - \sin(2\omega t_z + 2\varphi)) I^2 + 2\omega t_z I^2}{2\omega} [A^2 s] \quad (5)$$

It can be assumed that for low voltage circuits, when a fault occurs, the circuit can be treated as purely resistance, and frequency remains nominal. Presumed values are:

$$\omega = 2\pi f = 2\pi 50 = 314, \varphi = 0$$

The resulting let-through energy for those conditions is described by eq. 6.

$$\int_0^{t_z} i^2 dt = \frac{-(\sin(628t_z) - 628t_z) I^2}{628} [A^2 s] \quad (6)$$

Symbolic mathematical calculations were done using wxMaxima software [14].

4. Test circuit and results

In order to evaluate the relation between phase angle and the let-through energy a test circuit was created (Fig. 3). Its main parts were a miniature circuit breaker, with nominal current of 16 amperes and B-type characteristic, an electromagnetic relay, used to close the circuit, and a synchronization device, which enabled to close the circuit at a specific phase angle. Parameters of test circuit are presented in Table 1. Test circuit was measured using a Metrel MI 2086 EUROTTEST 76155 multifunctional digital measuring instrument for low voltage electrical installation safety. Prospective current was set close to a value of $10 I_N$ of used MCB. The circuit has a high power factor of 0,998, so we can treat that supply voltage and current are phase aligned.

For each of nine arbitrary selected phase angles five test were conducted. Using a GDS-3154 digital oscilloscope and HAMEG HZO51 current probe the short-circuit current was measured. Acquired data was then processed in Scilab as described in [7]. For each set phase the let-through energy (Joule's heat), maximum current and short-circuit times were calculated. Average values obtained are presented in Table 2. Table 3 presents more detail statistic overview of raw data (expanded uncertainty is $u = k_\alpha \sigma$, where $k_\alpha = 1,96$). Selected current-time oscillograms for different set phase angles are presented on Fig. 4.

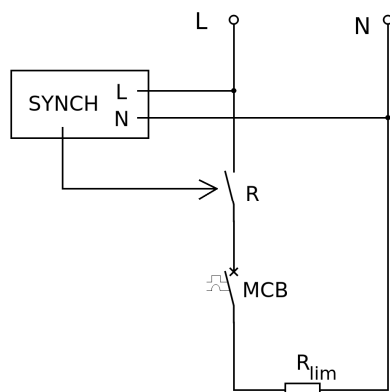


Fig. 3. Test circuit schematic: R – electromagnetic relay, MCB- miniature circuit breaker, R_{lim} – limiting resistor, SYNCH – phase synchronization device

Table 1. Test circuit parameters

Impedance Z	Reactance X	Resistance R	Prospective current I_K	Power factor $\cos \varphi$
[Ω]	[Ω]	[Ω]	[A]	[-]
1,49	0,08	1,49	162	0,998

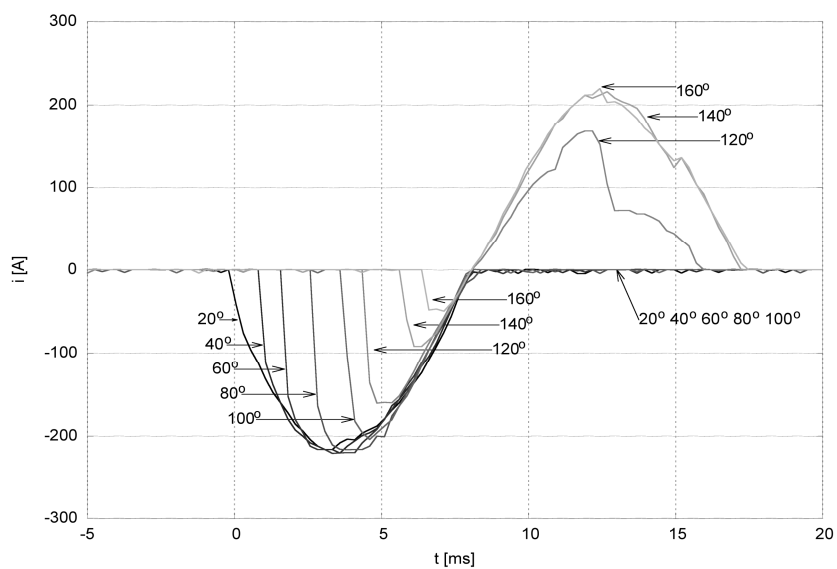


Fig. 4. Short-circuit current graph for different set starting phase

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Table 2. Average values of let-through energy, current and short-circuit time for different set starting phase

Phase angle	Let-through energy $\int i^2 dt$	Current i	Short-circuit time t_z
[°]	[A ² s]	[A]	[ms]
0	201,03 ± 6,36	217,08 ± 1,36	9,85 ± 1,42
20	197,55 ± 3,05	218,03 ± 3,17	9,11 ± 2,05
40	190,81 ± 3,18	219,60 ± 1,64	10,98 ± 8,11
60	176,61 ± 16,10	220,16 ± 0,23	8,11 ± 1,52
80	138,93 ± 6,82	217,64 ± 1,31	7,48 ± 1,83
100	87,70 ± 5,65	205,97 ± 4,13	4,54 ± 0,32
120	116,43 ± 123,20	183,69 ± 37,07	8,85 ± 7,53
140	204,62 ± 7,20	218,12 ± 2,39	11,57 ± 0,24
160	195,04 ± 1,78	217,14 ± 1,19	11,00 ± 1,15

Table 3. Detail statistic overview of raw data: \bar{x} - average value, σ - standard deviation, u - expanded uncertainty

Phase angle	Let-through energy $\int i^2 dt$			Current i			Short-circuit time t_z		
	\bar{x}	σ	u	\bar{x}	σ	u	\bar{x}	σ	u
0	201,03	3,24	6,36	217,08	0,69	1,36	9,85	0,72	1,42
20	197,55	1,56	3,05	218,03	1,62	3,17	9,11	1,04	2,05
40	190,81	1,62	3,18	219,60	0,84	1,64	10,98	4,14	8,11
60	176,61	8,22	16,10	220,16	0,12	0,23	8,11	0,77	1,52
80	138,93	3,48	6,82	217,64	0,67	1,31	7,48	0,94	1,83
100	87,70	2,88	5,65	205,97	2,11	4,13	4,54	0,16	0,32
120	116,43	62,86	123,20	183,69	18,91	37,07	8,85	3,84	7,53
140	204,62	3,67	7,20	218,12	1,22	2,39	11,57	0,12	0,24
160	195,04	0,91	1,78	217,14	0,61	1,19	11,00	0,59	1,15

For five phase angles: 20°, 40°, 60°, 80° and 100° short-circuit time was in range between 10 and 4,5 ms, with shorter times observed for higher phase angles. This can be correlated with current reaching zero value every 10 ms and thus the MCB can break the short-circuit current naturally, as described in paragraph 2. For 120°, 140° and 160° short-circuit time often exceeded 10 ms. It can be assumed that there is a relationship between this fact and the miniature circuit breaker opening time. Since the main contacts of MCB haven't started to open there is no contact gap. There is also a requirement that the current reaches at least value of 80 amperes in order to trigger the circuit breaker mechanism. For high phase angles that isn't always true. Summing the above statements the break process for high phase angles may start after the current reaches zero. This also explains higher short-circuit current times.

With this higher times the let-through energy rises, according to eq. 1. Figure 5 presents the relationship between let-through energy and phase angle of short-circuit current for both the experimental and the analytical results. The latter are based on eq. 6 and presumption that short-circuit time t_z was in the following ranges (eq. 7):

$$t_z = \begin{cases} 10 - \varphi \cdot \frac{10}{180} & \text{for } 0 \leq \varphi \leq 100^\circ \\ \varphi \cdot \frac{20}{180} & \text{for } 160^\circ \geq \varphi \geq 120^\circ \end{cases} \quad (7)$$

These short-circuit times where deuced from experimental results and the 100° boundary can vary for other types of MCB.

It can be seen that, similar as with short-circuit time, Joule's heat reaches lower values for higher phase angles up to 100°. With higher short-circuit times let-through energy rises. For phase angles up to 40° the difference between energy level is minimal.

Different conclusions can be drawn for the maximum short-circuit current values, as there is no apparent relation between its value and the phase angle. Because there is little or none inductance in the circuit short-circuit current can reach high values almost instantly, phased with source voltage value. This can be observed on Fig. 4 for short-circuit current oscillograms for 40° to 160°. At the beginning for short-circuit the current values rises fast in a very short time.

As shown on Fig. 5 there experimental and analytical results are similar for whole interval of phase angles between 0° and 160°. One significant difference can be seen for angle of 120°. Experimental results shown correspond to the average value of let-through energy. For this particular measurement both low and high short-circuit times were observed. Because of this the uncertainty at this point is high. Results obtained are correct only for one model of circuit breaker, however there can be useful as a point of reference for other types of MCB, as they share the same operating principal.

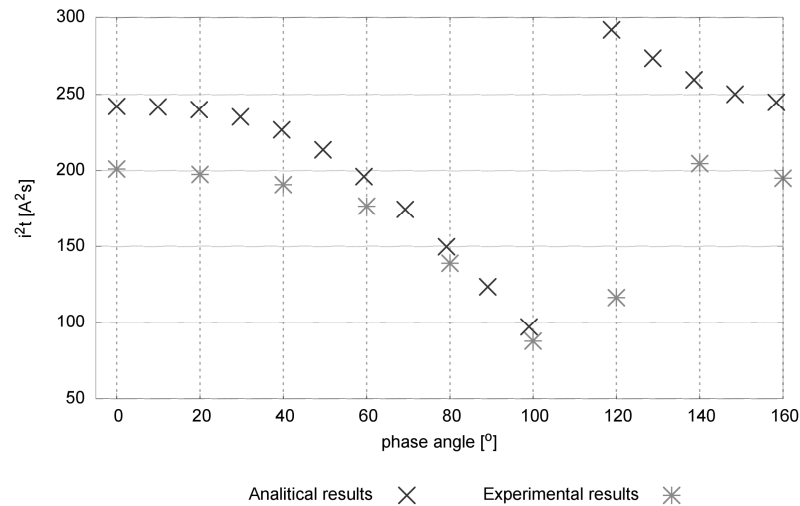


Fig. 5. Let-through energy for different set starting phase

5. Conclusion

Use of miniature circuit breakers is obligatory so it seems important to know every aspect of how they work. There is a clear relation between phase angle and the let-through energy (also true for short-circuit time). High values of Joule's heat can be observed for low, between 0° and 60°, and high, above 140°, phase angles. That means the thermal effects for the electrical circuit and devices protected by MCB differ with different phase angle and this relation isn't linear. However there is no obvious change of maximum short-circuit current value with change of phase angle. An analytical formula for the let-through energy in function of short-circuit time was created based on obtained results. This formula allows prediction of let-through energy for different short-circuit prospective currents and it is correct in almost the entire phase angle range.

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