# CRITICAL CURRENTS in CIRCUIT BREAKERS

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*ABSTRACT*

**The question of overcurrents in low voltage circuit breakers is examined in detail with the test requirements of product standards being studied for applicability in relation to practical applications. The relative importance of lower level overcurrents is considered and related to rated short circuit current interrupting ratings of moulded case circuit breakers. Critical current levels that may compromise safety, but are not always covered in existing specifications are questioned.**

## *INTRODUCTION*

In some circles of the low voltage electrical industry in South Africa, there has in the past, existed a perception that requirements for installations and equipment suffered from a degree of over-specification and excessive regulation. While there was some element of truth in this perception, the wide diversity of applications in environments that differed vastly from those found in the northern hemisphere, often justified more onerous specification requirements. In typical South African fashion, response to criticism usually results in over reaction that invariably results in further criticism. One example of this can be found in the Electricity Installation Regulations which have been deregulated as far as the installation work is concerned. The regulations now also only require a Certificate of Compliance to be issued by an accredited person rather than by the electrical utility.

Furthermore, the often misguided anxiety to *strictly* comply with the terms of GATT can also occasionally have negative effects. Such action can encourage those who may not have all facts at their disposal, to blindly accept International Standards such as those produced by the IEC as replacements without change for existing SABS product standards.

Several decades of South African application experience in diverse and harsh environments have resulted in the evolution of certain clauses of SABS product standards into meaningful and appropriate requirements. It would be short sighted to lose that experience through the uncontrolled adoption of sometimes questionable and inferior requirements. Such requirements frequently represent the result of compromise created simply to satisfy dissimilar needs for international consumption.

### ***Compromise***

With circumstances never being ideal, international product standards are usually a *compromise* between the various interests and highly diverse requirements of the approximately 50 countries represented at the International Electrotechnical Commission (IEC).

The need for such compromise cannot be argued.

In accepting *compromise* however, it may be appropriate to re-examine the meaning behind that word. Both the Concise Oxford Dictionary of Current English and the Heritage Illustrated Dictionary of the English Language, amongst others, include the following interpretations:

*i) A settlement of differences in which each side makes concessions.*

*ii) Something midway between different things or combining certain of their qualities.*

*iii) Bring under suspicion or into danger by indiscreet action.*

*iv) To give up (one's interests, principles, or integrity.)*

*v) A laying open to danger.*

Such varied meaning given to a word could be interpreted as a warning that may already have been anticipated during the development of the English language.

*It makes you think - doesn't it ?*

## *MOULDED CASE CIRCUIT BREAKERS*

Both miniature circuit breakers (MCB) and moulded case circuit breakers (MCCB) have, over the past four decades, found wide acceptance in South Africa. The circuit protection capabilities of these devices are accepted as a normal and expected part of any low voltage electrical installation. The main function of MCB's and MCCB's is to protect the cable that is used in the electrical installation.

### ***Protection Characteristics***

The overcurrent protection characteristic of typical MCB's and MCCB's is divided into two protection zones viz. - *Overload protection*
- *Short Circuit protection*

The transition point between these two zones is not always identified, and even when identified, is subject to a reasonably wide performance and manufacturing tolerance. Examination of the actual protection characteristic, in some cases, reveals a range of "critical currents" which can lead to increased stress on both the circuit breaker itself and on the protected circuits.

***Circuit Breaker Tripping Characteristic***

The tripping characteristic which identifies the time-current response for circuit breakers, has been developed in the main, to follow the overload withstand capabilities of electric cables. Protection of electric cables against damage due to overload currents and distress or destruction due to short circuit currents, is the most important function of a circuit breaker.

The inverse-time nature of the overload characteristic is important for two main reasons :

- *Utilisation of cable short time withstand capability.*
- *To provide for non-damaging short duration inrush currents without tripping the circuit breaker.*

In order to adequately and clearly display all the functions of a circuit breaker over widely varying parameter ranges, the tripping characteristic is normally presented with a double logarithmic scale covering both time and current parameters as shown in figure 1.

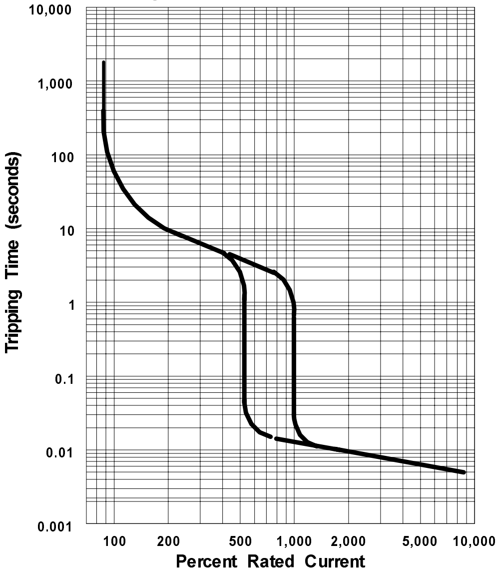


***Figure 1***
***Typical time-current characteristic***

***Energy Characteristic***

The circuit breaker time-current characteristic can also be used to derive a curve that represents it's joule energy let through characteristic in relation to the overload current.

This $I^2t$ versus current characteristic of a circuit breaker is obviously dependent on the actual shape of it's time-current characteristic curve, but understandably will tend to approach a constant for *thermal sensing* overcurrent devices.

It is interesting to note that circuit breakers that have a relatively flat time-current curve at higher levels of overload current, can result in $I^2t$ curves that actually show a tendency to *increase* with increasing overload current. (see figure 2)

For *current sensing* overcurrent devices, this is not necessarily the case. In such circuit breakers, the inverse-time delay is obtained through the use of hydraulic or electronic sensing elements. With the shape of the time-current tripping curve being more easily adjustable, the $I^2t$ values in the overload region can be reduced to levels that are significantly below the theoretically constant $I^2t$.

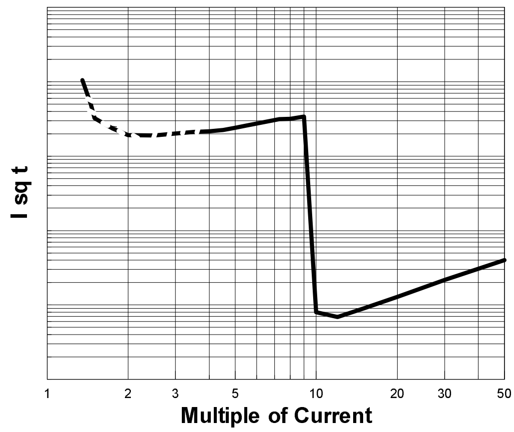


***Figure 2***

***Current and Heat***

The heating of a conductor due to the passage of electrical current is proportional to:

- *The square of the current*
- *The time that the current flows*
- *The specific resistance of the conductor*

For time periods that are shorter than approximately 5 seconds, it is generally assumed that all heat is retained inside the current carrying component.

This is known as *adiabatic* heating.

For time periods that exceed about 5 seconds, heat loss to the surroundings will take place mainly due to conduction and radiation.

This is known as *non-adiabatic* heating and is indicated by the dashed portion of the curve shown in figure 2.

In the adiabatic region the overcurrent withstand capability of cables follows an approximately constant $I^2t$ law. This is equally true for the current carrying parts of switching devices such as circuit breakers *prior to the switching or opening operation.*

It follows therefore, that for cases where the $I^2t$ characteristic shows an *increasing* trend with increasing current, unacceptable thermal stress may be indicated. This would be applicable both to the circuit breaker itself and to the cable that is being protected. Examination of figure 2 shows this trend at just below ten times rated current in the region just prior to the transition between the overload and short circuit protection curves.

***Low level Overload Currents***

Overload current levels that exceed the normal full load current rating of both circuit breaker and the cable which it is protecting, result in relatively long breaker tripping times. Depending on the level of overcurrent, these times could be as long as two hours at conventional breaker tripping currents, down to tens of seconds at somewhat higher overload currents.

The resultant heating of both circuit breaker and cable are influenced by the non-adiabatic heat transfer to the environment in which they are located. As a consequence, it is a relatively simple procedure to determine the performance limits of both by monitoring the temperature rise.

***Short Circuit Protection***

The dynamic nature of short circuit interruption in circuit breakers is verified through long established test sequences related to the application of the circuit breaker.

The short circuit protection elements of circuit breakers are designed to result in practically instantaneous operation, so that high level fault currents are interrupted in the shortest possible time. This is seen in the relatively flat protection curve of figure 1 for the region above about ten times rated current.

In this region (see figure 2), the $I^2t$ curve also increases as the fault current increases but at much lower amplitude levels of $I^2t$ than is the case for fault currents that are below about ten times rated current. This is due to the very short opening times involved. It must be remembered however, that figure 2 does not represent the *total* let through energy of the circuit breaker.

The *total* let through energy is the sum of the calculated $I^2t$ energy as shown in figure 2 plus the *arc energy* generated in the opening contacts.

***Arc Energy***

The arc energy is a physical quantity that can be expressed by the general equation

$$E_a = \int_0^t u_a(t)\, i(t)\, dt$$

where:

$E_a$ = *arc energy*

$u_a(t)$ = *arc voltage changing with time*

$i(t)$ = *arc current changing with time*

The arc energy as a function of arc current is additionally dependent on the circuit breaker contact material, size and shape.

For circuit breakers other than those for which the ($I^2t$ - current) characteristic lies well below the constant $I^2t$ level, this additional arc energy will even further aggravate the distress on both the circuit breaker itself as well as the “protected” cable.

***Critical Currents***

Arising out of the above preliminary investigation, there are indications that, depending on the particular shape of the circuit breaker time-current characteristic, a region of so-called “critical currents” may exist.

Such “critical currents” - if they exist - will fall in the region of overload currents just below the transition between the “Overload” and “Short Circuit” protection curves of circuit breakers.

Overload currents of these levels can become “critical” since the stored heat energy due to those currents, in both the circuit breaker and protected equipment such as the cable, becomes a maximum in this region of overcurrent. The stored heat energy under such conditions could well exceed the survival limits of all circuit elements.

***Tests for Critical Currents***

Many decades of installation and application experience with circuit breakers across the world, has shown that the likelihood of lower order overload current faults occurring, exceeds that of short circuit fault currents, by several orders of magnitude.

Fault currents having a magnitude of several hundreds of amperes are far more likely than those of thousands or tens of thousands of amperes since :

- *Most faults are not bolted short circuit faults*
- *Circuit impedance tends to limit fault currents*
- *Fault currents are limited by arc impedance*

Whilst the subject of critical currents in circuit breakers has been mooted for several decades, up to the present, no specific tests to identify this potential shortcoming have been introduced into the relevant product standards.

Most product standards for circuit breakers do however recognise the need for varying degrees of overload current tests in addition to the higher level short circuit current tests.

***Inrush Currents***

Inrush currents in low voltage circuits are most commonly associated with induction motor starting, operation and control. The average motor inrush currents for this purpose, has been assumed to be 600% of motor full load current.

Often forgotten, however, is that non-damaging, short duration inrush currents are additionally associated with loads such as transformers, capacitors, power supplies and incandescent lamps.

Tungsten filament incandescent lamps are of particular interest as loads that typically result in high inrush currents. Such inrush currents can have amplitudes of about fourteen times the rated operating load current. Certain product standards for circuit breakers such as UL 489 in the USA and JIS C 8370 of Japan include inrush current tests with incandescent lamp loads for circuit breakers rated up to 50A. This is in recognition of the high probability of large percentages of such loads being present.

An *interesting coincidence* can be observed if an analysis is made of the number of 230V, 100 watt incandescent lamps that will yield the equivalent of 600% overload on circuit breakers.

| # 100A lamps | Amps @ 230 V | 14 x load | 10A Inrush ratio | 15A Inrush ratio | 20A Inrush ratio | 30A Inrush ratio |
|---|---|---|---|---|---|---|
| 10 | 4.35 | 60.87 | 6.09 | 4.06 | 3.04 | 2.03 |
| 15 | 6.52 | 91.30 | 9.13 | 6.09 | 4.57 | 3.04 |
| 20 | 8.70 | 121.74 | 12.17 | 8.12 | 6.09 | 4.06 |
| 30 | 13.04 | 182.61 | 18.26 | 12.17 | 9.13 | 6.09 |
| 40 | 17.39 | 243.48 | 24.35 | 16.23 | 12.17 | 8.12 |
| 50 | 21.74 | 304.35 | 30.43 | 20.29 | 15.22 | 10.14 |

***Table 1 - Tungsten Lamps - Inrush Currents***

Table 1 above table indicates that coincidentally, the *number of 100 watt lamps* is *equal to the circuit ampere rating* for inrush currents that approximate 600% of rated current viz.

- 10 100W lamps on a 10A 230V circuit
- 15 100W lamps on a 15A 230V circuit
- 20 100W lamps on a 20A 230V circuit etc.

It would not be unusual for levels of tungsten filament lamp loads such as these to exist on typical installations.

Albeit for the wrong reasons, the 600% overload test, (that appears in most circuit breaker and other switching device standards), seems to be appropriate for incandescent lamp loads as well as for the originally intended motor loads.

***<u>The Overload Test</u>***

Whenever there is even a remote possibility of a requirement to switch motor loads, most product standards include a so-called *Overload Test.*

The Overload Test in most cases has been set at an overcurrent level of six times the rated current of the switching device (600%). It can however, be specified at other overcurrent levels (usually between 3 times and 10 times rated current), depending upon the utilization category of the particular switching or protective device.

In recognition of the higher inrush currents that are associated with modern high efficiency motors, the 1996 edition of the National Electric Code of the USA, has introduced amendments to cater for motor starting currents of 7x rated current compared to the historical 6x value. Similar changes to product test requirements are presently under consideration for UL 489 covering circuit breakers and circuit breaker switches.

The remaining variables, dependent on utilization category, in determining the Overload Test requirements, are:

- *The test power factor (0,5 to 0,65 for all motor applications)*
- *The ON/OFF test frequency.*

Table 2 compares the number of operations for the "Overload Test" requirements that are currently specified in various National and International product standards.

| Standard | Product | Rating / duty | Number of Operations |
|---|---|---|---|
| **UL 489** | Circuit Breakers | <= 1600A<br>2000/2500A | **50**<br>**25** |
| **JIS C 8370** | Circuit Breakers | <= 100A<br>100 / 1600A | **50**<br>**25** |
| **SABS 156** | Circuit Breakers | All ratings | **50** |
| **IEC 934** | CBE | Switching cap | **40** |
| **UL 1077** | Suppl. Protectors | All ratings | **50** |
| **CSA C22.2 235-M89** | Suppl. Protectors | All ratings | **50** |
| **IEC 947-2** | Circuit Breakers | <= 630A | **12** |
| **IEC 947-3** | Switches Annex A | Making/ Breaking cap | **50** |
| **IEC 947-4-1** | Contactors Starters | Making/ Breaking cap. | **50** |
| **IEC 947-5-1** | Control circuit devices | Making/ Breaking cap. | **10** |
| **IEC 947-6-1** | Automatic Transfer equip | Frequent operation | **50** |
| **IEC 947-6-1** | Automatic Transfer equip | *Infrequent operation* | **12** |
| **IEC 947-6-2** | Multi function CPS | *Distribution ccts - AC40* | **24** |
| **IEC 947-6-2** | Multi function CPS | AC 41 to AC 45 | **50** |

***Table 2 - Overload Test***

It is surprising to note from Table 2 that the very low number of operations required for the "Overload Test" in IEC 947-2 is *conspicuous in it's difference to most other standards.* Furthermore, the Overload Test requirements for circuit breakers complying with IEC 947-2 is only marginally different from that for small control circuit devices or auxiliary switches that are built in accordance with IEC 947-5-1 !

With the exception of certain higher ampere rated devices, only Automatic Transfer Equipment that are designed *specifically for infrequent operation,* and multi-function CPS devices intended strictly for distribution circuit application are required to withstand less than 50 operations in the "Overload Test".

The unusually low number of Overload Test operations in IEC 947-2 is further aggravated by a very low switching frequency when compared to certain other product standards.

***Electrodynamic Contact Separation***

Modern "current limiting" circuit breakers achieve their current and energy limiting performance mainly by ensuring sub-cycle interrupting times through very high speed contact opening. This high speed operation is generally initiated by opposing electromagnetic forces on the circuit breaker contact carriers.

In order to achieve optimum performance, a delicate balance is required between the high spring forces on contacts to meet temperature rise limits, and low spring forces to permit rapid contact opening.

Unless spring forces on contacts of circuit breakers are reasonably high, varying degrees of electrodynamic contact separation can be initiated by the current induced magnetic forces. Excepting in the case where instantaneous tripping elements of the circuit breaker are set to operate at current levels which fall below the point of electrodynamic contact separation, serious contact arcing can lead to contact welding, with often more spectacular or hazardous consequences. Circuit breaker product standards, for some unknown reason, do not appear to have adequately addressed all the implications of such operating conditions.

***Test Priorities***

Circuit Breaker product standards, as we have seen from the above, include various test requirements, usually performed according to prescribed test sequences. These requirements are necessary in order to verify that the circuit breaker is not only suitable for it's intended application, but that it's operation will not result in any consequences, that under abnormal operating conditions may be hazardous to human life or to equipment.

It is natural to assume that the short circuit current test, through it's most spectacular nature, is the most important test to check for such hazardous consequences. Short circuit faults certainly do occur and need to be catered for in both installation and equipment design.

Once it is realised however, that the greater percentile of all overcurrent faults have a magnitude that is far lower than the prospective short circuit level, the importance of lower level overcurrent tests becomes more evident. It is fortunate that circuit breaker standards do include such a lower level overcurrent test in the form of the "Overload Test".

***CONCLUSIONS***

This paper has demonstrated that in most applications, circuit breakers are subjected to varying levels of short duration overcurrents that are generally non-damaging to the circuits and equipment which are being protected by the circuit breaker.

Safety factors which provided for such inrush currents in circuit breakers have tended to reduce or disappear, as a consequence of the need for high speed circuit interruption and current limiting under fault conditions. It was not generally appreciated that these developments would have an effect on safety factors in circuit breaker design. As a result, the advent of "current limiting" circuit breakers did not result in any additional test requirements for circuit breakers.

In the absence of any specific tests on circuit breakers to check for the effects of inrush currents, possibly for the wrong reasons, the "Overload Test" seems to be eminently suitable for the purpose. In fact, a more detailed study into the starting currents of induction motors, reveals that *in addition* to the roughly 6x starting current, there is a higher level short duration current not all that different from the inrush currents to tungsten filament incandescent lamps. The origin of the required number of test standard operations for the "Overload Test" of circuit breakers is not all that clear. However, the fact that most standards, including many IEC documents, have for many decades without any obvious problem, set this number at 50, is a strong indication of it's acceptability.

It is unfortunate that IEC 947-2 has deviated from this requirement in a test that goes a long way towards addressing an important safety issue which needs to be verified should "critical currents" exist. With SABS 156 currently under review on the basis of IEC 947-2, it is essential that a similar shortcoming be avoided.

***References***

*i) SABS 156 : 1977 - Moulded Case Circuit Breakers*
*ii) IEC 947-2 : 1995 - Circuit Breakers*
*iii) IEC 947-3 : 1990 - Switches, disconnectors etc.*
*iv) IEC 947-4-1 : 1990 - Contactors and motor starters*
*v) IEC 947-5-1 : 1990 - Control circuit devices*
*vi) IEC 947-6-1 : 1989 - Automatic Transfer switching equipt.*
*vii) IEC 947-6-2 : 1992 - Control/protective switching devices*
*viii) UL 489 : 1991 - Molded Case Circuit Breakers*
*ix) JIS C 8370 : 1991 Molded Case Circuit Breakers*
*x) National Electric Code 1996*
*xi) "The inequality of circuit breaker standards" - V Cohen published in "Elektron" March/April 1996*
*xii) "Miniature and moulded case circuit breakers - V Cohen published in "Elektron" September/October 1994*
*xiii) "Arc erosion of high current contacts" E Walczuk University of Lodz, Poland*
*xiv) IEC 949:1988 - Calculation of short circuit currents*
*xv) IEC 934 : 1993 - Circuit Breakers for Equipment*
*xvi) UL 1077 : 1994 - Supplementary Protectors*
*xvii) CSA-C22.2 No. 235-M89 - Supplementary Protectors*