OVERCURRENT PROTECTION IN LOW VOLTAGE ELECTRICAL CIRCUITS - THE PERILS OF ADJUSTABILITY

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Introduction

Utility generated and distributed electricity is one of the cheapest, cleanest, most convenient and safest forms of energy. It is difficult however, for the average user of this energy to comprehend the power behind this energy in an uncontrolled form.

Misapplication, misuse, or accident can unleash the frightening powers of uncontrolled electrical energy. Such uncontrolled release of electrical energy will invariably result in damage to both life and property through electrical shock hazard and fire hazard.

This uncontrolled flow of electrical energy is generally the result of such misapplication, misuse or accident and manifests itself in the form of electrical fault currents either in intended or unintended electrical circuits or paths.

Electrical fault currents fall into three main categories, including:

- Overload currents
- Short circuit currents
- Earth fault currents

The newsworthy nature related to the often spectacular or tragic results of electrical accidents in the form of fire or electrocution have resulted in a proliferation of technical articles or papers pertaining to the protection against short circuit currents and earth fault or shock hazard currents.

On the contrary, while much has been written about the components and technologies for protection against *overload current,* the specification requirements for overload current protection remain clouded in confusion and contradiction.

Circuit protection and protection components

Protection of electrical circuits from damage or destruction, together with the attendant danger to life and property has received continuous attention from electrical engineers and designers all through the history of the distribution of electrical energy. Protection in the circuits is necessary primarily to guard against the danger caused by overloads or unusually heavy current surges due to short circuits.

The earliest protective devices were of the simplest form. Initially the sole objective was to open the circuit, if necessary at the expense of destroying the protective device itself. Thomas Edison invented the first protective device, the fuse, which was a controllable weak link in a wire.

Since those early days and despite vast improvements in the design and manufacture of fuses, a general recognition in regard to the limitations of fuses, has led to the wide acceptance of the moulded case circuit breaker as being the most reliable overcurrent protection device. This has been particularly evident in countries like South Africa whose wiring rules, as an example, do not even permit the use of fuses in final circuits of residential installations.

We often think of an electrical installation in terms of its large and impressive components such as generators, transformers, cables, overhead lines and large motors. While these are the most expensive parts of any electrical installation, the most important components affecting the performance and safety of personnel under abnormal conditions are found in the protection

system. Protection devices are designed to detect electrical faults and promptly disconnect the faulty component in order to reduce the effect of the fault on the rest of the installation.
One of the most extensively used and hence costly components in the low voltage network is the cable, which guides the electricity, from its point of generation to its point of application. It is for this reason that the cable is considered to be the component that requires and deserves the most attention when protection components are applied into an electrical distribution network.

Cable Protection

The main parameter that is used by protection components to detect the fault and then protect the cable is the electrical current. Provided the current is contained within the capabilities of a particular cable, no damage to the cable or its insulation will result. In the event however, of the load current exceeding the cable rating, a potentially damaging or hazardous situation could arise. Protection components will detect overcurrents and cause the switching device associated with the protection component to open and interrupt the flow of electrical current

Accepting that the preferred overcurrent protection device is the moulded case circuit breaker, the prime function of the circuit breaker is to provide overcurrent protection to the cable to which it is connected. Overcurrent protection is divided into two discrete zones viz.

- *Overload Protection*
- *Short Circuit protection*

Overload Protection

Every component making up an electrical installation is designed for use at a particular rated current. When the component is used within these limits it will have a specific service life expectancy, that is the length of time for which the insulation will remain operationally safe.

Under normal conditions, the heat generated by the flow of current through the resistance of the component must be transferred across the insulation to the cooling medium. Unfortunately, materials that are good electrical insulators are often good thermal insulators and if the current rating of the component is exceeded, there is a build up of heat within the insulation.

Overloading of electrical cables causes degradation of the insulation because of the thermal build-up at the interface between the conductor and the insulation.
If this is not controlled, it can lead to a reduction of the service life of the cable, resulting eventually in a short circuit (with often spectacular results), when the insulation fails.

The heat energy developed in a conductor depends on the square of the current (I^2), the resistance (R) of the conductor and the time (t) for which the current flows. The resistance (R) depends on the cross-sectional area of the conductor. Assuming that this has been correctly chosen for the maximum load, the overloading depends on the value of I^2t. It is thus possible to detect an overload condition by monitoring the current flowing into an item of equipment and the time for which it flows.

An obvious and practical requirement of the overload protection device is that it should be capable of holding at least 100% of its rated current continuously.
For test purposes it is generally assumed that the circuit breaker or fuse will not trip or open once it has held the conventional operating test current for a period of one to two hours (3 to 4 hours in the case of large fuses).
The degree to which the cable would be protected can be determined by the minimum level of current that is required to trip the circuit breaker or blow the fuse, taking into account the limiting operating current level that is permitted by the relevant standard.

It is curious that installation rules often accept, *on an equal basis,* for general protection as well as for cable protection, overload protection devices complying with various standards but having conventional operating currents that differ widely.

This is illustrated by some of the examples listed in Table 1.

Overload Protection Device	Rated Current (amps)	Application	**Standard**	Conventional Non-operating current	**Conventional Operating current**
Low Voltage Fuse	In <= 4	Industrial	**IEC 269-2-1**	1,5 In	**2,1 In**
Low Voltage Fuse	4 <In< 16	Industrial	**IEC 269-2-1**	1,5 In	**1,9 In**
Low Voltage Fuse	63<In<160	General	**IEC 269-1**	1,25 In	**1,6 In**
Circuit Breaker	<= 125A	Household	**IEC 60898**	1,13 In	**1,45 In**
Circuit Breaker	In <= 6000A	General	**UL 489**	1,0 In	**1,35 In**
Circuit Breaker	In <= 1000A	General	**SABS 156**	1,0 In	**1,35 In**
Circuit Breaker	Any	General	**IEC 60947-2**	1,05 In	**1,3 In**

Table 1.

After taking into account the difference in the reference temperatures that are used in the standards, the limiting conventional operating currents for IEC 60947-2, UL 489 and SABS 156 are approximately the same, (with IEC 60947-2 requiring a closer calibration tolerance).

Whilst acknowledging that this may not be ideal practice, it is possible that cables could be loaded to the limits permitted by the protection device.
Cables that are protected by HRC fuses or by IEC 60898 circuit breakers could reach temperatures that are significantly higher than those that are protected by IEC 60947-2, SABS 156 or UL 489 circuit breakers, before overload tripping occurs.

It is well known that temperature rise is proportional to the SQUARE of the current.

The impact of the higher conventional operating currents of HRC fuses or of IEC 60898 circuit breakers and the consequential increases in cable temperature rise relative to IEC 60947-2, SABS 156 or UL 489 limits can be seen in Table 2.

Overload Protection Device	Rated Current (amps)	**Standard**	**Conventional Operating current**	**Relative Temperature Rise**
Low Voltage Fuse	In <= 4	**IEC 269-2-1**	**2,1 In**	**260,9%**
Low Voltage Fuse	4 <In< 16	**IEC 269-2-1**	**1,9 In**	**213,6%**
Low Voltage Fuse	63<In<160	**IEC 269-1**	**1,6 In**	**151,5%**
Circuit Breaker	<= 125A	**IEC 60898**	**1,45 In**	**124,4%**
Circuit Breaker	All	**IEC 60947-2** **SABS 156** **UL 489**	**1,30 In**	**100%**

Table 2.

Table 2, whilst considering the limiting conditions, based on the conventional fusing currents or tripping currents in the case of circuit breakers, does not include an even more aggravating condition that is permitted in IEC 60364.

IEC 60364-4-43 defines the current ensuring effective operation of the protective device as being:

- The operating current in conventional time for circuit breakers.
- The fusing current in conventional time for fuses.

It then goes on to permit the current ensuring effective operation of the protective device (I_2) to be as high as *1,45 times the continuous current carrying capacity of the cable !*

In partial recognition of this strange and curious rule, IEC 60364-4-43, in a note to clause 433.2 includes the following cautionary:

“Protection in accordance with this clause does not ensure complete protection in certain cases, for example against sustained overcurrents less than I_2 nor will it necessarily result in an economic solution. Therefore it is assumed *that the circuit is so designed that small overloads of long duration will not occur”.*

The National Electric Code that is used in the USA is not as forgiving.
However, for devices rated at 800A or less it still permits the use of the next *higher* standard overcurrent device rating (above the ampere rating of the conductors), provided the feeder or branch circuit rating is not less than the non-continuous load *plus 125% of the continuous load*.

It is also well known that every 8 to 10 degrees Celsius increase in temperature rise (over rated values), reduces the prospective life of insulating materials by one half. Furthermore, a major cable manufacturer reports that the cable insulation resistance will drop by a factor of 10 for similar increases in temperature.

Unlike the National Electric Code that is used in the USA, neither the South African nor the International Wiring Codes include any specific requirements mandating the use of higher temperature cable insulation such as XLPE.

The maximum sustained conductor temperature for PVC insulated cables is 70 degrees Celsius.
In recognition of the wide and relatively uncontrolled use of low voltage PVC insulated power cables in South Africa and other regions, Table 3 indicates the impact on the life expectancy of PVC insulated cables, under conditions of temperature rise that exceed the design limits.

Since “life expectancy” of electrical equipment (and particularly that of electrical cable) is an extremely subjective and controversial matter, and obviously dependent on the particular installation and environmental conditions, for this comparison, the author has chosen a totally arbitrary value of 40 years for low voltage PVC insulated cable.

The theoretical “life expectancy” values (although extreme) as determined in Table 3 were based on the following assumptions:

- Conventional “life expectancy”	- L_o	40 years
- Over – temperature resulting in halving of L_o	- t_x	10 ^oC
- Life reduction due to 10^oC temperature increase	- L_x	0,5
- Maximum sustained conductor temperature	- t_c	70 ^oC

The calculations were then based on the relationship:

$$L_e = L_o * e^{(q*(t-t_c))}$$

Where L_e = Relative “life expectancy”
L_o = Conventional “life expectancy”
t = Final temperature ^oC
t_c = 70 ^oC
e = exponential

$$q = \ln(L_x) / t_x$$

Where L_x = Life reduction due to 10^oC temperature increase
t_x = Over – temperature resulting in halving of L_o
ln = Natural logarithm

Overload Protection Device	Standard	**Conventional Operating current**	**Limiting Temperature Rise (degrees C)**	**Relative "Life expectancy"**
Low Voltage Fuse	IEC 269-2-1	**2,1 In**	**183**	**6 days**
Low Voltage Fuse	IEC 269-2-1	**1,9 In**	**150**	**1,9 months**
Low Voltage Fuse	IEC 269-1	**1,6 In**	**106**	**3,3 years**
Circuit Breaker	IEC 60898	**1,45 In**	**87**	**12,3 years**
Circuit Breaker	IEC 60947-2 SABS 156 UL 489	**1,30 In**	**70**	**40 years**

Table 3

Overload Adjustability in Circuit Breakers

The potential misapplication hazards that are encouraged by the use of adjustable moulded case circuit breakers are often ignored as a result of the perceived short term advantages of adjustability.

In recognition of such misapplication hazards, several circuit breaker product standards impose strict limitations, not only on the range of adjustability, but on the concept of adjustability itself.

For obvious reasons, these limitations are fully justified in residential applications, and also specifically excluded by the scope of IEC 60898.

UL 489 does not permit adjustability in circuit breakers rated at less than 200A or 250V. UL 489 is supported by the National Electric Code in the strong restriction that requires the rating of an adjustable trip circuit breaker to be the maximum setting possible.

In addition to the concerns relating to residential installations, one of the main concerns in regard to the concept of adjustability in circuit breakers, can be found in the case of circuit breakers that are assumed to be under the control of "skilled persons".

Maintenance personnel are generally measured by the preservation of "normal" conditions that are transparent to the average user.

This author has on many occasions identified that, amongst other criteria, maintenance electricians are understandably measured and regarded as "excellent" by:

- The lack of interruption of lighting.
- The continued operation of motors.

Such measurement criteria can unfortunately lead the best of maintenance personnel into temptations that could lead to hazardous consequences.

With the preservation of "normal" conditions being paramount, in the event of an electrical circuit interruption due to circuit breaker operation, there is unfortunately, a high probability of the priorities of maintenance personnel changing due to the very availability of adjustable features in the overcurrent protection device.

Despite the above negative perceptions in regard to adjustable circuit breakers, the flexibility and application advantages of electronically controlled circuit breakers cannot be ignored. For economic reasons, circuit breakers that include electronic sensing means, except for rather special applications, are generally restricted to use with larger blocks of power. These circuit breakers are generally installed closer to the source of energy and for obvious reasons and come under the control of maintenance personnel who have a more appropriate appreciation of the hazards of misapplication of overcurrent protection devices.

The sometimes misguided practices relating to the usage of adjustable type circuit breakers originate in Europe. It is assumed that by virtue of the highly regulated and law abiding European society, widespread problems are not encountered through such usage in that region. It is patently obvious that similar cultures cannot always be guaranteed in other regions of the world.

The original reason for the inclusion of features of adjustability in European type circuit breakers found it's origins in the application of these devices in motor protection circuits. IEC type motor starters have always included continuously adjustable overload protection relays. On the contrary, overload relays that originate in the USA (NEMA rated) have had and still include discrete fixed ampere rated heaters for motor protection.

It appears that for reasons of standardization, and in consideration of their historic culture of discipline, the Europeans have chosen to ignore the possibilities of misapplication in extending the concepts of adjustability in circuit breakers from the original intended application in motor circuits to general circuit protection applications.

The earlier discussions in this paper related to some potentially hazardous application conditions due to the incorrect choice of protection components, that could lead to severe reductions in prospective cable life.

In a similar way, this analysis is directly applicable to situations involving improper or inappropriate settings of adjustable circuit breakers, be this for intended, mischievous or accidental reasons.

Short circuit protection

Moulded case circuit breakers that are intended for application in industrial and related circuits with ratings that exceed some hundreds of amperes, often include facilities for adjusting the instantaneous or "magnetic" pick-up current level.

In contrast to the identified hazards of adjustment of the *rating* of these protective devices, this type of "magnetic" adjustment is often essential to ensure not only nuisance free operation, but also to ensure that adequate protection is ensured under particular operating conditions.

Some examples of this include the following:

- <u>Motor protection</u> - The instantaneous pick-up current setting is required to be *high enough* to avoid unwanted tripping of the circuit breaker due to inrush currents during starting.
- <u>Cable protection</u> - The instantaneous pick-up current setting is required to be *low enough* to suit the energy withstand capabilities of the cable. This is particularly true for very small conductor cross sections.
- <u>Long cables</u> - The limited available fault currents that result from high conductor impedance necessitate the use of low instantaneous pick-up current settings.

- Load Inrush - Non-damaging, short duration inrush currents are often associated with loads such as transformers, capacitors, power supplies and incandescent lamps etc. The instantaneous pick-up current setting is required to be *high enough* to avoid unwanted tripping of the circuit breaker due to these inrush currents.

Conclusions

This paper has examined present practices relating to the overload protection of cables and other circuit components, together with the possibly hazardous consequences of inadequate or inappropriate overload protection. The cautionary that has been included in the IEC wiring rules for the Electrical Installation of Buildings is particularly disturbing in consideration of the "International" nature of that document which assumes a disciplined, technically skilled and law abiding first world culture.

In recognition of the less controlled society that exists in countries like South Africa, the practice of using moulded case circuit breakers that include rating adjustment facilities is brought into question. The imagined cost savings related to the perceived and limited short term advantages, including lower stocking levels and "easy" application, that are derived from the adjustment facility are put into question, once these are offset against the potential problems of basic product reliability together with the hazards of misapplication.

Fixed rating circuit breakers are shown to be more reliable, if only due to their reduced component count, and are certainly less prone to either intended, accidental or mischievous misapplication.

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