OVERCURRENT PROTECTION IN LONG LINES

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Background

In recent months and years, the financial and economic crises in South East Asia and Brazil have left their unfortunate mark on most developing countries as well as in many developed countries across the globe. Southern Africa, despite being geographically and economically remote in world terms, did not escape unscathed. Furthermore, South Africa's internal problems only served to exacerbate it's own economic woes.

Optimism, together with an understanding that economic cycles do turn, are only a few of the necessary elements for survival through these difficult times. An old proverb told us to always look for the silver lining in every dark cloud. While this is an invaluable attribute and excellent advice for the optimists, it remains inadequate for short term solutions.

Individuals or groups are no different from countries in their need for a strong incentive to be the driving force in initiating positive corrective action, for whatever reason. As only one example, the disaster of Pearl Harbour in 1941, served as the impetus for the United States to become the economic powerhouse of the world, that it is today.

With the magic of the developing "tiger" economies of the 1990's now something of the past, some good can still be salvaged from the present critical global economic situation. This could and should be the impulse for not only corrective action, but for possible innovative solutions covering a multitude of activities where complacency has led to waste and imperfection.

In the engineering world, the importance of good economic engineering design, whilst being a given, is regrettably not always fully appreciated or implemented. This has been particularly apparent during thriving and prosperous economic periods.

As a general rule, simple solutions usually result in the best and most economic solution. Often, the solution may already exist. Complacency, can however mask even the obvious.

This paper describes a method of achieving significant cost savings in low voltage electrical reticulation and distribution networks, through the prudent application of appropriate overcurrent protection components in these systems.

Overcurrent protection

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.

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

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.

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.

In electrical networks, the most common protection components used are moulded case circuit breakers and fuses. 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, National and International Standards generally require that the circuit breaker or fuse will only trip or open once it has held the conventional operating (or tripping) 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.

A recently published paper by this author (1) clearly demonstrated that the prospective "life expectancy" of electrical cables is critically dependant on the type of overcurrent protection device used and on the Standard to which the protection component is manufactured.

<u>Overcurrent protection component technologies</u>

The experience gained over the past several decades of highly effective application and usage, has shown that the preferred overcurrent protection device is the moulded case circuit breaker.

It is of interest to examine the technologies for achieving overload current sensing that have been incorporated into circuit breakers.(2) The overload current sensing means is usually achieved through the use of one of three different technologies which include:

- Thermal - magnetic sensing
- Magnetic - magnetic sensing (also known as Hydraulic - magnetic)
- Solid state electronic sensing

Of these, due only to the global proliferation of manufacture of these devices, thermal - magnetic sensing is most common. This paper will however, identify both the known as well as the untapped benefits that can be realised through the use of magnetic - magnetic sensing breakers.

The expertise in the design and manufacture of magnetic - magnetic circuit breakers is restricted to only a few countries, with South Africa being the world leader in this field.

Recent research work in Botswana (3) has identified some previously untapped advantages of magnetic - magnetic circuit breakers, which are now being applied extensively in that country while achieving significant cost savings in both streetlighting reticulation and in the electrification of rural villages.

One of the main objectives of the Botswana research was to maximise cable circuit length in order to minimise the number of control cubicles and/or transformers which are expensive and subject to maintenance and vandalism etc.

Thermal - Magnetic circuit breakers

The performance and operating characteristics of thermal - magnetic type circuit breakers are suitable and adequate for general circuit protection. As with other circuit breaker technologies and depending on the Standard to which those circuit breakers are manufactured, together with the relevant selection and application criteria, limitations in regard to their efficacy in the protection of cables have been identified. (1)

These limitations are aggravated even further by the design restrictions that result from the inherent performance limitations of the bimetal component that constitutes the main overload sensing element of these devices.

Magnetic - magnetic circuit breakers

The pragmatic and economic advantages relating to the use of current sensing circuit breakers as opposed to thermal sensing circuit breakers in reticulation and distribution networks, has long been recognised by utilities and other sellers of electrical energy.

In addition to the temperature independent attributes of magnetic - magnetic circuit breakers, the design and construction of these devices is eminently suited to achieving application-specific operating characteristics.

A good understanding of the application requirements of magnetic - magnetic circuit breakers has resulted in the major South African manufacturer of these devices being able to produce standard, freely available circuit breakers, whose operating characteristics are ideally suited to cable protection in reticulation and distribution networks.

In particular, the Botswana research [3] has shown that the operating characteristics of magnetic - magnetic circuit breakers can be used to advantage in achieving indirect contact shock hazard protection in street lighting reticulation applications. Additionally, the unique close overload protection capabilities of these circuit breakers has shown them to be ideal in the design of distribution circuits for both street lighting applications as well as in rural electrification.

<u>Essential specification requirements</u>

The arduous application environment found in low voltage reticulation and distribution applications, demands at the outset, certain minimum safety specification parameters to be satisfied for the protection components. This is particularly true for components such as circuit breakers, whose suitability or lack of suitability, for particular applications can easily be misinterpreted and misunderstood, mainly due to the proliferation of available specifications covering these devices.

One glaring example of this, is that some utilities have, possibly for reasons of cost, been tempted to install circuit breakers rated to IEC 60898 [7] in low voltage reticulation and distribution applications.

Such misapplication is known to exist, despite the fact that by definition, IEC 60898 circuit breakers are restricted to *“household and similar”* applications.

A fundamental difference that exists between IEC 60898 circuit breakers and circuit breakers that are manufactured in accordance with standards such as IEC 60947-2 [8] or SABS 156 [9] is that IEC 60898 permits clearance and creepage distances that are *as small as 3mm* and are applicable to *all critical live parts*.

The current edition of IEC 60898 does not include any impulse test voltage withstand requirements. Furthermore, as one consequence of the extremely small clearance and creepage distances permitted in IEC 60898, the draft technical revision of IEC 60898 [10] included only a limited impulse withstand voltage requirement of 4kV for installations rated up to 440V.

Any possibility of the inclusion of impulse voltage withstand requirements into IEC 60898 has been delayed even further into the future, due to the recent rejection in the voting procedure of both IEC documents 23E/306/CDV and 23E/368/CD covering the technical revision.

Extensive research in recent times re-affirms the rated impulse withstand requirements that are included in IEC 60364-4-443. [11] This latter standard states that for equipment used at the origin of an installation, overvoltage category IV is required. For 230/400V systems, the required impulse withstand voltage for overvoltage category IV is 6kV.

Only standards like IEC 60947-2, together with it's well advanced amendments, and it's derivatives, including the draft revision of SABS 156, incorporate such mandatory impulse voltage test and marking requirements.

For all low voltage reticulation and distribution applications, in the interests of fundamental safety, and more particularly, in those regions of the world that are subject to high atmospheric lightning flash densities, only circuit breakers that have certified and marked ***" U_{imp} – 6kV "*** should be considered.

It is also essential that for these applications, documentation (preferably from an independent authority) is provided, confirming that the circuit breakers have been tested and certified at power frequency test and power frequency recovery voltages that are permitted according to the upper tolerance limits of the delivered voltage.

In increasing parts of the world, (including South Africa), and in accordance with IEC 60038, the upper tolerance limit of the delivered power frequency voltage is U_n +10%.

Electrical Protection of highway power supplies and street furniture.

Since safety requirements are generally covered by mandatory regulations, many electrical wiring codes do not always include specific provisions for the protection of highway power supplies and street furniture. One particular example that does include such specific provisions is the British IEE Wiring Regulations – Sixteenth Edition – BS 7671:1992. [4]

Although IEC 60364 [5] does not apply to public street lighting installations, the IEE Wiring Regulations are based on and derived from the fundamental safety rules of International Standard IEC 60364.

A draft proposal for a technical revision of the South African Wiring Code [6] will introduce similar requirements.

In addition to the normal requirements pertaining to the overcurrent protection of cables, the IEE Wiring Regulations includes a requirement for protection against indirect contact shock hazard.

Protection against indirect contact is achieved by co-ordinating the characteristics of the protective device with the relevant circuit impedance and earthing arrangements, so that during an earth fault, the voltages between simultaneously accessible exposed conductive parts are of such a magnitude as not to cause danger.

For a phase to earth fault in earthed electrical distribution systems, commonly known as TN systems, this requirement is met where the following condition is fulfilled.

$$Z_s <= U_o / I_a$$

Where Z_s = earth fault loop impedance.
I_a = current causing automatic operation of protective device in a time <= 5 seconds.
U_o = nominal voltage to earth (230V).

Case study – Street lighting design exercise

The approach that was used in the Botswana study [3], in arriving at a satisfactory solution, was to determine the maximum practical cable length on the basis of three different controlling parameters viz:

- Maximum cable length based on available earth fault current.
- Maximum cable length as a function of maximum allowable voltage drop.
- Maximum cable length as a function of circuit breaker current rating.

The study used the following parameters which were based on cable data taken from BS 7671:1992 together with the IEE guidelines in regard to typical values for source impedance.

Maximum source earth fault loop impedance:	Z_e = 0,5 ohms.
Phase conductor:	10sq.mm. copper.
Earth conductor:	25sq.mm. bare copper earth wire.
Cable working temperature (light load)	50^oC

Since it was anticipated that voltage drop would be a deciding criterion, the cable selection of 10sq. mm. was chosen on the basis of being considered to be about the largest size cable that could be reasonably terminated in a pole access housing. The bare copper earth wire selection of 25sq. mm. was chosen as being the smallest size allowable for direct burial.

a) Maximum cable length based on available earth fault current

It can easily be shown [4] that using the above phase and earth conductors, the average impedance at a working temperature of 50^oC, would be 2,82 milliohms per metre (Z_c).

The maximum value of the earth loop impedance at the point of fault can then be expressed as:

$$Z_s = Z_e + Z_c$$

(giving $Z_s = 0,5 + 2.82 * 10^{-3} * l_c$ for the above parameters.)

and since Z_s can also be expressed as $Z_s = U_o / I_f$

the cable length can be derived from the relationship $l_c = 10^3 / Z_c * (U_o/I_f - Z_e)$

where
- l_c = cable length (metres)
- Z_c = cable impedance per metre (ohms)
- U_o = Nominal supply voltage (230V)
- Z_e = source impedance (ohms)
- I_f = Fault current required for 5 second disconnection

The parameter I_f , which is the fault current required to result in circuit disconnection within 5 seconds, becomes the key factor in determining the maximum cable length l_c.

The value I_f can be further expanded into $I_f = x * I_{bkr}$

Where
- I_{bkr} = circuit breaker ampere rating
- x = multiple of breaker rating resulting in 5 second operation

From the above relationships, the maximum cable length as a function of the circuit breaker operating characteristic can be seen for circuit breakers rated at 10A, 15A and 20A in Figure 1.

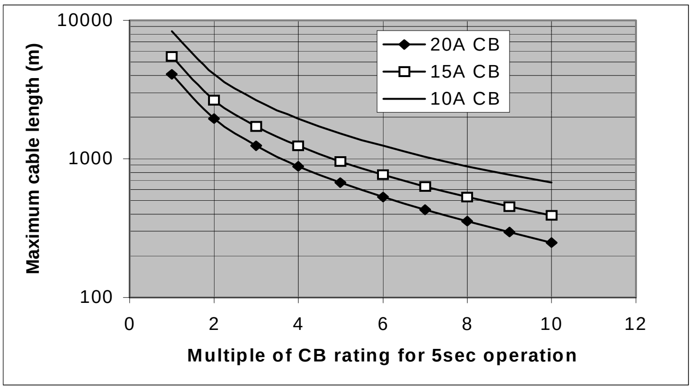


Figure 1

b) Maximum cable length as a function of maximum allowable voltage drop

In the same case study, voltage drop limits were then used as the controlling parameter in determining the maximum cable length.
Once again, the study was based on a 10 sq. mm. copper conductor, but basing the calculations on a 4-core cable, assuming an equal distribution of luminaires across the three phases. Using the same references as above, the phase to phase voltage drop can be shown to be 3.47mV per ampere of load, per metre, at 50^{o}C.

For *n* streetlights, spaced at *d* metres apart, total cable length $l_c = n * d$.
Under lamp starting conditions, the total starting current is: $I_{start} = (I_s * n) / 3$ amps per phase.

For the study, three different types of lamps were chosen as shown in Table 1, with the luminaire types and spacing determined by the specific lighting design requirements.

Lamp type	Streetlight spacing (m)	Lamp rating (watts)	Running current (amps)	Starting current (amps) (I_s)
HPS	50	150	0,88	1,3
HPS	50	70	0,45	0,72
MV	60	80	0,46	0,9

Table 1

If the voltage drop V_d under starting conditions is limited by design to be 6% of the phase to phase voltage, the starting voltage drop can be calculated from the relationship

$$V_{d\ start} = 6\%\ U_n = Z_c * I_{start} * l_c * ½$$

Where U_n = phase to phase voltage
Z_c = cable impedance per metre
l_c = cable length (m) = (n * d)
n = number of lamps *per circuit*
d = spacing between streetlights (m)
I_{start} = starting current for n lamps (I_s * n) / 3
I_s = starting curent per lamp

Since the luminaires are equally distributed across the three phases, the actual lamp spacing per phase conductor is *(3 * d)* with roughly one third of the total lamps per circuit being connected to each phase conductor.

For this example balanced load conditions are assumed. It is further assumed that with the voltage drop more or less equally distributed down the circuit, the equivalent voltage drop at the end of the circuit will be ½ of the voltage drop if the total load were concentrated at the midpoint.

Then $V_{d\ start} = 3{,}47 * 10^{-3} * (I_s * n) / 3 * d * n * ½ = 6\%\ U_n = 24V$

From the above, the limiting number of lamps per circuit (n) can be calculated from:
$n = \{(24 * 10^3 * / 3{,}47) * (3 / I_s) * (1 / d * 2)\}^{0,5}$ which can conveniently be reduced to:
$n = \{(41499 / (I_s * d)\}$

Using this simplified relationship, for the predetermined lamp spacing, Table 1 can be expanded to identify the limiting cable length and associated maximum number of lamps per circuit, within the limits of a 6% voltage drop under lamp starting conditions.

Lamp type	**Lamp rating (watts)**	**Spacing between streetlights (m)**	**Running current (amps)**	**Starting current (amps) (I_s)**	**Number of lamps per circuit**	**Max. cable length l_c (m)**	**Voltage Drop (start)**	**Voltage Drop (run)**
HPS	150	50	0,88	1,3	25	1250	6%	3,97%
HPS	70	50	0,45	0,72	34	1700	6%	3,76%
MV	80	60	0,46	0,9	28	1680	6%	3,13%

Table 2

c) Maximum cable length as a function the circuit breaker rating

In order to ensure that lamp starting inrush currents do not result in unplanned tripping of the protective circuit breakers, the limiting number of lamps per circuit can be determined by dividing the circuit breaker rating by the lamp starting current, and applying an appropriate derating factor. In consideration of typical ratios between starting and running currents, a derating factor of 0,7 has been shown to be suitable.

The maximum number of lamps per circuit (i.e. across the three phases) can then be determined using the relationship $n = \{(I_{bkr} * 0{,}7) / I_{start}\} * 3$.

Table 3, using rounded numbers, summarizes the maximum number of lamps per circuit together with the associated limiting cable lengths of each circuit, depending upon the ampere rating of the circuit breaker.

Lamp type	**Lamp rating (watts)**	**Spacing between streetlights (m)**	**10A Breaker**		**15A Breaker**		**20A Breaker**	
			Number lamps	**Cable length**	**Number lamps**	**Cable length**	**Number lamps**	**Cable length**
HPS	150	50	16	800	24	1200	32	1600
HPS	70	50	29	1450	44	2200	58	2900
MV	80	60	23	1380	35	2100	47	2820

Table 3

Summary and interpretation of results

With the 10sq. mm. cable being more than adequately rated, in the final design, the limiting cable circuit length will be determined from voltage drop considerations as shown in Table 2.

The circuit length so obtained identifies the minimum amp rating of the circuit breaker (Table 3) for a particular type of lamp.

These two values can then be inserted into figure 1, from which a value for the required multiple of the circuit breaker rating (for 5 second operation) can be obtained.

This procedure is applied in turn to the three types of lamp being considered, with the results being summarized in Table 4.

Note that it is important to confirm that the number of lamps per circuit so obtained from Table 3 does not exceed the equivalent number from Table 2.

	Table	**150 - HPS**	**70 - HPS**	**80 - MV**
Maximum circuit length (m)	2	1250	1700	1680
Minimum Circuit Breaker rating (A)	3	20	15	15
Reqd. CB multiple for 5 second operation	Fig. 1	3,0	3,0	3,0

Table 4

Examination of Figure 1 clearly shows that for any given circuit breaker rating, the limiting circuit length is critically dependent on the level of overload current together with the operating time of the circuit breaker. Since shock hazard protection in the event of indirect contact requires the circuit breaker to trip within a time period of 5 seconds, the limiting cable length will be reduced as the 5 second operating level of the circuit breaker increases.

The application of an approximately 10% safety factor to the maximum circuit lengths as shown in Table 4 will yield the following final design result (Table 5).

	150 - HPS	**70 - HPS**	**80 - MV**
Streetlight spacing (m)	50	50	60
Maximum circuit length (m)	1100	1500	1500
Number of luminaires per circuit	22	30	25
Minimum Circuit Breaker rating (A)	20	15	15
Reqd. CB multiple for 5 second operation	3,0	3,0	3,0

Table 5

The operating characteristics of standard magnetic - magnetic circuit breakers manufactured in South Africa are such that repeatable values of low level instantaneous tripping currents can easily be achieved. This can be used to advantage in achieving the 5 second operating requirement at 3 times rated current as shown in Table 5. The availability of circuit breakers having instantaneous tripping levels even lower than (3 * In) will result in further performance enhancement, especially in cases where fault resistance is encountered.

Case study - Distribution Circuit design exercise

In recognition of the superior protection characteristics of the magnetic-magnetic circuit breakers in the street-lighting application, together with the cost savings that resulted from the increased circuit lengths that were shown to be possible, some of these concepts were then extended in the Botswana study to the protection of general distribution circuits.

It was additionally realised that the unique close overload protection capabilities of these circuit breakers would be ideal in the design of distribution circuits for rural electrification applications.

This case study was based on a low density rural village electrification programme that included 50 kVA 11 / 0,4 kV transformers and 50 sq. mm. 4 core ABC overhead lines (continuous rating 165A), protected by a 150A three phase feeder circuit breaker.

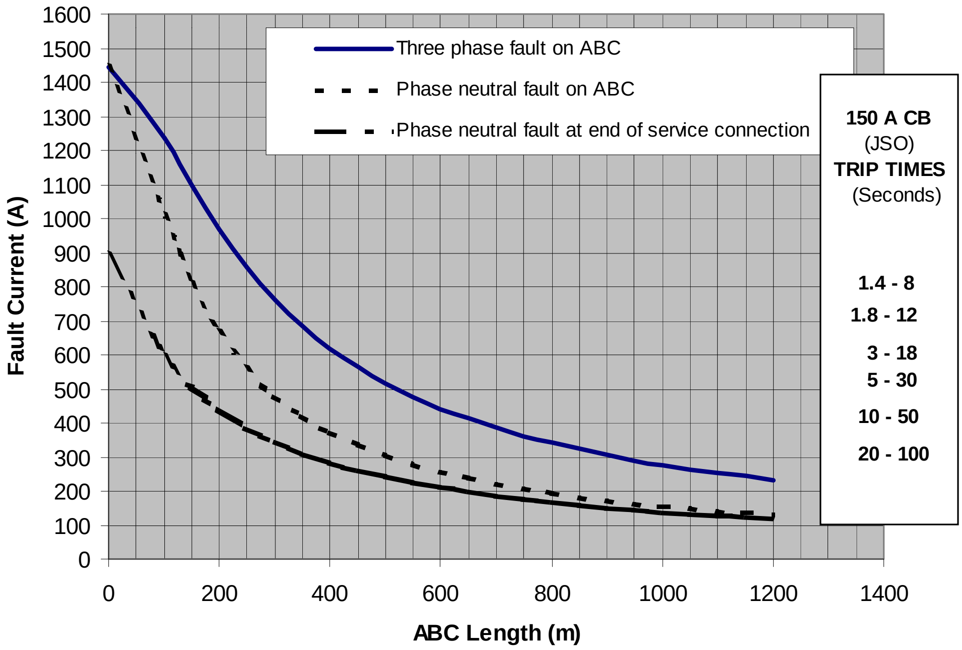
It was originally anticipated that on a typical village feeder with sparsely situated consumers each having a low ADMD (generally less than 1 kW per house), feeder lengths of up to 1200m could perform within allowable voltage drop limits.

However, in order to establish the actual maximum permissible feeder length, consideration had to be given as to the allowable maximum fault clearance time for the worst case condition which is represented by the lowest phase to neutral fault current.

Figure 2 is a plot of the available fault currents for varying lengths of 50 sq. mm. ABC cable connected to a 50 kVA 11 / 0,4 kV transformer in an earthed neutral distribution system. The relationship to the operating times for a 150A rated magnetic-magnetic circuit breaker are also included in the figure.

FIGURE 2

50 kVA 11/0.4 kV PMT, 50 sq mm ABC and 50 m 10 sq mm Airdac Service Connection Conductor 50 deg C



The 150A magnetic-magnetic circuit breaker that was chosen for this application requires a minimum of 125% of rated current (187,5A) to ensure tripping. Based on a phase to neutral bolted fault, and referring to figure 2, this equates to a feeder cable length of about 850m.
For positive tripping of the circuit breaker, this is therefore the upper limit of feeder length without any safety factor or allowance for fault resistance.

The introduction of an arbitrary safety factor of 1,5 would increase the minimum fault current required to (1,5 * 187,5) = 281A. From figure 2, this shows that for practical conditions, not even the use of a close overload protection magnetic-magnetic circuit breaker, would permit feeder lengths exceeding about 550m, if acceptable phase to neutral fault clearance times were to be ensured.

It is obvious that the use of circuit breakers having time-current operating characteristics that are less sensitive than those of the chosen magnetic-magnetic circuit breaker, would reduce the permissible feeder lengths to even lower values.

Since much longer feeders had been shown to be an identified need, the reduction of feeder lengths down to 550m would have required the installation of additional transformers together with the associated capital and ongoing maintenance costs.

As indicated above in consideration of the protection of the circuit, worst case conditions are encountered when the prospective fault current is lowest and as a result, the resulting operating times of the circuit breaker are slower. The most likely fault in an ABC feeder is a phase to earth (or neutral) fault. As can be seen from figure 2, this relatively low level of fault current also decreases inversely according to the length of the feeder cable.

Similar analogies to those that were used in the case study for street-lighting protection were then applied. It became immediately obvious that for a given feeder cable size, a reduction in the ampere rating of the overcurrent protection circuit breaker would permit longer feeder cable lengths while still providing the required fault clearance times.

As one example, it can be seen from figure 2 that a reduction in the circuit breaker ampere rating from 150A to 80A, and applying the same safety factor of 1,5 would permit the limiting feeder cable length to be increased in length from 550m to 1050m. Figure 2 shows that the required fault current of (80 *1,25 * 1.5) = 150A is derived with a corresponding cable length of 1050m and similar fault clearance times.

A similar exercise will show that a circuit breaker rating of 100A would still provide for an adequately protected feeder cable of up to 750m in length.

Protection against indirect contact

It should be noted that solutions which provide protection against indirect contact, require that at least minimum levels of fault current as indicated need to be developed. Even though indirect contact protection is provided, such solutions cannot be considered as a replacement for 30mA sensitive earth leakage circuit breakers, which will provide both additional protection, as well as shock hazard protection in the event of direct contact.

As a standard, the individual consumer supply circuit breaker is typically rated at 60A. It was shown in the case study for street-lighting circuit protection, that through the use of suitable circuit breakers, protection against indirect contact can be ensured in accordance with both IEC 60364 and BS 7671 requirements. This requires a circuit breaker which has a time-current tripping characteristic that will ensure tripping within 5 seconds at three times rated current (i.e. 180A for a 60A circuit breaker).

Again from figure 2 and assuming a 50m service connection in addition to the ABC distribution cable, this corresponds to a maximum ABC circuit length of 750m.

When considered together with the earlier analysis, this indicates that 750m should be the maximum allowable feeder length.

Feeder lengths longer than 550m.

Extension of the ABC distribution cable beyond 550m, up to a maximum of 750m is typically required to service a few isolated consumers located on the fringes of the village.

In such cases, an 80A (or 100A) rated in line circuit breaker, (bearing in mind the discrimination requirements against the pole top circuit breaker), can be installed at the 550m location. An option such as this has negligible cost implications and avoids costly system reinforcement with additional transformers or larger ABC conductor size.

Standard Circuit Breaker Ratings

For villages having sparsely situated consumers such as those in this case study, with each having a low ADMD, it may be appropriate to reduce the standard rating of the consumer service circuit breaker from 60A to 20A.

In the interests of improving discrimination between the various circuit breakers included in the distribution network, such a change could also permit a reduction in the ampere rating of the pole top circuit breaker.

Transformer Protection

The prime consideration in this case study was the protection and economics of the ABC distribution cable, which, in consideration of it's 165A continuous rating [12] will be fully protected by the 150A rated circuit breaker. It is however recognized that the overload protection provided by a circuit breaker rated at 150A for the 50 kVA pole mounted transformer, may not be adequate. It is further recognized that for economic reasons, utilities will generally acknowledge that some degree of transformer overloading could occur.

A further possible advantage that could accrue from a reduction in the circuit breaker ampere rating as proposed above, would be an improvement in the protection offered to the transformer.

Whilst transformer protection has not been considered in this paper, in recognition of the need to make provision for the overloading of transformers, consideration could be given to the inclusion of over-temperature sensing devices in the transformer. Such devices could be adapted to operate in conjunction with the distribution circuit protection circuit breaker.

Conclusions

The challenges that are initiated by economic constraints have once again demonstrated that it is possible to maximize the latent benefits of existing technologies without having to resort to costly and largely untried solutions. The Botswana research shows that magnetic-magnetic circuit breakers, which are widely used and freely available in Southern Africa, are eminently suited to low voltage reticulation protection applications. In addition to meeting the arduous environmental requirements of such applications, cost savings have been achieved together with improved protection through significant increases in achievable line lengths.

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