INDUCTION MOTORS - PROTECTION and STARTING

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ABSTRACT

It is well understood that induction motors draw higher currents during their starting operations than is the case under full load running conditions. Since the early days of induction motor availability, starting methods other than Direct-on-Line have been used, and in some cases mandated by Utilities, to reduce the effect of these high starting currents on the electrical distribution network. What is generally not recognised, is the existence of short duration inrush currents, that greatly exceed these starting currents. Furthermore, the introduction of complex starting methods to reduce starting currents is often compromised by other unanticipated inrush currents introduced by the starting system itself, unless special precautions are taken. This paper examines the sources and consequences of these inrush currents on the distribution system, as well as on the motor protection components.

Recommendations are given in regard to the selection of both overcurrent and earth leakage protection of induction motors that consider not only the motor protection requirements, but also the limitations on the protection devices that may result from the abnormal circuit disturbances that could be introduced through the starter.

INTRODUCTION

One of the prime motivating factors behind the original 1927 USA development of the Moulded Case Circuit Breaker (MCCB) was the identified need for a reliable and economic device to protect induction motors. The almost seven decade history of the MCCB has seen this valuable low voltage protection component evolve mainly as a circuit protection device, in recognition of the importance of the cable which forms the nucleus of any electrical distribution system. Whilst both MCB's and MCCB's are intended mainly for cable protection, in recognition of their superior protection capabilities these devices are being increasingly applied for induction motor protection.

Up to relatively recent times, the high inrush currents normally associated with motor starting, presented conflicting requirements of making provision for these inrush currents and the obvious need for close overload protection. In the absence of a good understanding of the inrush currents involved in motor starting, almost arbitrary derating values were applied to the MCCB's to prevent spurious tripping of the breaker during starting. As a result, MCCB's were historically used for mainly short circuit protection in induction motor circuits. Developments and improvements in MCCB technology, together with a better understanding of the nature, the cause of, the duration and the amplitude of starting inrush currents, have made it possible to develop MCCB's whose tripping characteristics are more suited to induction motor starting and protection.

METHODS OF MOTOR STARTING

In general, there are five basic methods of starting induction motors. These include

i) Direct - on - Line (DOL) starting
ii) Star - Delta or WYE - Delta starting
iii) Autotransformer starting
iv) Reactor or Resistor starting
v) Soft starting

Except for DOL starting, the prime objective of these alternative starting methods is to reduce the supply voltage to the motor, with the express purpose of reducing the inrush currents that occur during the starting operation. Reducing the supply voltage is an extremely effective way of reducing inrush currents, since the starting currents are directly proportional to the supply voltage.

Unfortunately, as a consequence, the starting torque is reduced by the SQUARE of the supply voltage, so that this limitation needs serious consideration when choosing a method of starting induction motors.

INRUSH CURRENTS

It has been a popular belief that for Direct-on-Line starting, the starting inrush currents that occurred were in the order of 6 times to 8 times the motor full load nameplate current rating. The star-delta principal of starting assumed that these starting currents would be reduced roughly to 3 times or 4 times the motor full load current due to the effective reduced voltage applied to the stator during starting, and that full voltage would only be applied once the motor had stopped accelerating.

This assumption ignores the transient inrush current that is now known to result from the temporary disconnection of the motor from the supply line during the star-delta switching process. Mainly for cost considerations, this so-called OPEN CIRCUIT TRANSITION switching procedure, is by far the more common method of star-delta starting. Resulting from this momentary power interruption, the stator current drops to zero whilst the rotor current continues to flow. This in turn results in a voltage being generated in the stator. This voltage is at a frequency less than the line voltage so that its phase relationship with the line is constantly changing. The resulting current surge depends on the phase relationship between these two voltages at the instant of switching, being a theoretical maximum when the two voltages are out of phase. Current surges can typically attain peak values of up to 20 times the motor full load current rating but generally last for only 10 to about 40 milliseconds. The amplitude of these open circuit transition surge currents are often higher than the inrush surges experienced during DOL starting. One consequence of such high current surges, is that the starting torque could be reduced even further, which is highly undesirable. Besides light flicker and possible information data loss, circuit breaker tripping is likely to occur during the switching transition. The negative effects of open circuit transition switching are similar for all forms of open circuit transition starting.

CLOSED CIRCUIT TRANSITION

The identified problems of current inrush surges during open circuit transition switching can be avoided by the use of additional circuitry and components which temporarily connects resistive or reactive components across the windings to ensure that the motor remains connected to the power source while transferring from the start to the run condition. Whilst closed circuit transition switching is very effective, heat loss in the transition resistors is obviously objectionable.
The additional space requirements and the high cost of such systems have also tended to restrict their usage.

DIRECT - ON - LINE STARTING

Direct-on-line or DOL starting has been used with success for many years, particularly with smaller squirrel-cage induction motors. It is unfortunate that many utilities still have restrictions in place that limit the size of motors that can be started direct on line. It is acknowledged that actual run-up starting currents are higher with DOL starting at 6 to 8 times motor full load current. This could present a problem on restricted or high impedance supplies, but becomes less of a problem as the power supply becomes stiffer. Less well understood is a higher inrush current, usually lasting for less than one cycle that occurs at the instant of DOL switching. The amplitude of these half cycle inrush currents is dependent mainly on the sub-transient reactance of the motor. With smaller motors, the increased cable impedance will have the effect of reducing the amplitude of the inrush current.
When compared to the current surges that are experienced during open circuit transition switching, DOL inrush currents are at least 25% to 30% lower.
Motors are not damaged by these inrush currents, but any impact of mechanical shock to the motor load or gearbox needs to be considered.
Since closed circuit transition starting is not the norm, it is becoming more and more obvious to users that the perceived advantages of open transition starting methods such as star-delta starting may not reach original expectations. It follows also that the additional cost and space requirements of such starting methods may not always be justified. An obvious consequence of this realisation is that the DOL method of motor starting is becoming more widely used. Utilities that maintain unreasonable restrictions on DOL starting of induction motors may need to revisit and review their present restrictions. A typical Time - Current starting characteristic is shown in figure 1.

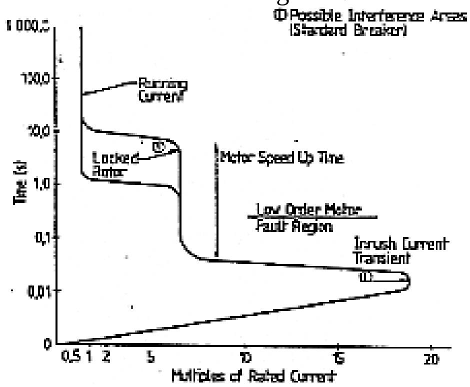

Figure 1

MCCB's and DIRECT - ON - LINE STARTING

It has been said that the prime function of MCCB's in a low voltage electrical distribution network is to protect the cable. It has however, not been uncommon for MCCB's to be used for motor protection. Until relatively recent years, depending on the size of the motor, it has been common practice to uprate the MCCB by anything from 20% up to 100% in order to ensure that no nuisance tripping of the breaker was experienced during starting. In such circumstances, it is obvious that no overload protection was provided for the motor and even locked rotor protection was questionable. When used in conjunction with a contactor and overload relay, overload and locked rotor protection would be achieved, with the MCCB providing the short circuit protection. Modern MCCB's that have been designed with motor protection as well as cable protection in mind can provide overload protection up to at least
IEC 947-4-1 Class 30 levels, together with good locked rotor and short circuit protection without the danger of nuisance tripping under DOL starting conditions. It is important that when selecting MCCB's for motor starting duty and motor protection, the protection curve of the MCCB is matched to the starting characteristics of the motor. Responsible manufacturers will provide application tables for this purpose.
It is common practice in Europe to use MCCB's that have adjustable overload tripping releases for motor protection duty. There is some merit in this approach, particularly in mature and responsible first world environments to allow for fine tuning the MCCB to the motor full load rating.
In a developing and mixed economy such as in South Africa, priorities can often be different with short term operation requirements winning over ideal protection. Fixed rating circuit breakers can in such circumstances, provide superior motor protection by avoiding the chances of mal-adjustment and eliminating the mischief element, provided they are correctly selected at the design stage. Fixed rating thermal-magnetic breakers are often limited in availability to ampere ratings not

lower than about 15 amperes. The reason for this limitation is that the very light bimetals that are necessary for the lower ampere ratings are often incapable of withstanding the stresses of the high let through or short circuit currents for which MCCB's are normally designed. One way of solving this problem is through the use of hydraulic-magnetic MCCB's. It is a relatively simple matter to match the ampere ratings of hydraulic-magnetic MCCB's to the actual motor requirements and produce so-called non-standard fixed ampere ratings. The high impedance current sensing coils that are used in such devices often have the added advantage of limiting fault currents.

APPLICATION CRITERIA

In applying MCCB's to motor protection and starting duty, it is most important to be aware of and consider all applicable application criteria.
Some of these criteria can include:

- *Protection requirements*
- *Discrimination and co-ordination requirements*
- *Inrush Currents*
- *The effect of long cables*

PROTECTION

There are three separate levels of protection that need to be considered when applying MCCB's particularly for the protection of squirrel cage induction motors.
These include

- *Overload protection*
- *Locked rotor protection*
- *Short circuit protection*

OVERLOAD Protection and LOCKED ROTOR Protection

Whilst this is dependent on design, modern induction motors in general do not enjoy the generous overload capabilities that existed in earlier times. The protection of induction motors against overheating due to overload, as a result, possibly needs more consideration than that which may have been given previously. The International standard covering electro-mechanical contactors and motor starters is IEC 947-4-1.
IEC 947-4-1 makes provision for four defined protection trip classes which are directed at overload relays in motor starters. These are described in the table below:

TRIP CLASS	**Tripping Time at multiple of Ie**		
	120 %	**150 %**	**720 %**
10A	> 2 hours	2 min.	2-10 sec.
10	> 2 hours	4 min.	4-10 sec.
20	> 2 hours	6 min.	6-20 sec.
30	> 2 hours	12 min.	9-30 sec.

Whilst not all MCCB's have motor protection capabilities, those manufacturers whose products do have such capabilities, specify both overload and locked rotor protection according to the above trip classes.

SHORT CIRCUIT PROTECTION

An important factor that needs to be considered in estimating short circuit current levels is to take into account the effect of connected induction motors on the actual short circuit current levels seen by MCCB's.
Under short circuit conditions, the kinetic energy in connected induction motors results in the motors behaving as generators which will pump energy into the short circuit, as if these generators were connected in parallel with the main power supply network. Assuming that typical induction motors have an internal impedance of about 25%, it is generally accepted that the additional contribution to the short circuit current level is four times the aggregate full load current rating of all connected induction motors. In order to reduce the complexity of calculations, the limiting cable impedance between the motors and the point of short circuit is usually ignored.

Comparison between CONTACTORS and MCCB's

The two main differences between MCCB's and contactors or motor starters are :

- *MCCB's are designed for THOUSANDS of operations while contactors and starters are designed for MILLIONS of operations*
- MCCB's *have short circuit ratings of THOUSANDS of amperes while contactors can only interrupt HUNDREDS of amperes*

IEC 947-4-1 in its scope, in fact states that starters and contactors are not designed to interrupt short circuit currents. Furthermore, that same document requires suitable short circuit protection to form part of the installation. In recognition of their superior protection capabilities, the use of MCCB's as the back-up short circuit protection device is rapidly becoming the norm.
The emerging overload and locked rotor protection capabilities of MCCB's in some cases can obviate the need for overload relays in the motor starting arrangement. IEC 947-4-1 makes provision for two categories of performance at the rated conditional short circuit current with the contactor or starter backed up by a short circuit protective device.
Type 1 co-ordination allows damage to the contactor or starter, provided there is no danger to persons or the installation.
Type 2 co-ordination requires the contactor or starter to be suitable for further use after short circuit, recognising that light contact welding is permitted.

DISCRIMINATION

Selective co-ordination or discrimination must not be confused with short circuit back-up co-ordination. In order to selectively co-ordinate the MCCB with the motor starting characteristics, ideally the MCCB tripping characteristic should be superimposed on the motor starting characteristic. Whilst the former is freely available, it is unlikely that motor starting characteristics can be obtained.

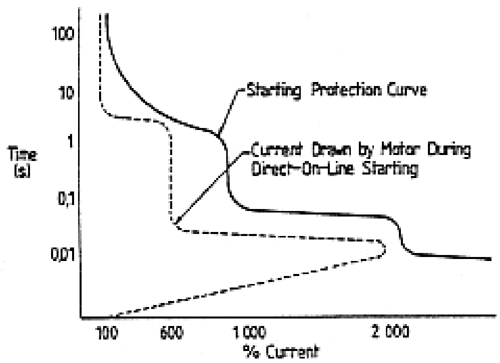

Figure 2

Fortunately, there are only three sets of criteria to consider in order to ensure that unplanned tripping of the MCCB does not occur during starting. These are :

i) MCCB tripping curve related to motor load inertia (run-up time)

ii) MCCB instantaneous pick-up level related to starting or locked rotor current

ii) MCCB instantaneous pick-up level related to DOL inrush current

A prime concern is that the MCCB instantaneous pick-up level is higher than the locked rotor current of the motor. For low inertia loads, where the run-up time is less than about 2 to 5 seconds interference with the MCCB overload tripping curve is not generally likely.

High inertia loads require the MCCB overload tripping curve to be slow enough to ensure that tripping does not occur before the motor has achieved synchronous speed. With DOL starting, inrush currents are often limited by the cable impedance, particularly with small motors and light cables. As a general rule however, motor protection breakers need to be selected with instantaneous pick-up levels that are higher than would be necessary for normal circuit protection.

Typical motor protection MCCB's will have instantaneous pick-up levels of twelve to fifteen times the breaker ampere rating.

Such high instantaneous pick-up current levels represent a compromise between good locked rotor protection and the freedom from unplanned tripping of the MCCB during starting. Depending upon their utilisation category, contactors are only required to have a making and breaking capacity of 8 to 10 times their operational current. Even under pure MAKE conditions, these figures do not exceed 10 to 12 times the contactor operational current rating. It is obvious that there is a possible unprotected or poorly protected region that could start as low as 8 times the contactor ampere rating and certainly exists between 12 and 15 times its rating. There is no strong evidence of these shortcomings being addressed in the short term by either the Standards organisations or by the manufacturers of contactors and motor starters. These shortcomings can however be overcome to a large degree by the use of specialised motor protection MCCB's that incorporate solid state electronic trip-units. The intelligence incorporated into such devices allows for short time delays that make the MCCB "blind" to the DOL inrush currents, whilst permitting low level instantaneous pick- up currents that are only marginally above the motor starting or locked rotor current. Such electronically controlled MCCB's do have a cost premium. This premium however needs to be considered in relation to the specific application and the consequences of motor or starter failure that could be related to compromised protection.

INRUSH CURRENTS

In addition to ensuring that inrush currents occuring during the starting procedure do not cause unplanned tripping of the MCCB, it is also important to understand that high inrush currents can have deleterious effects on the MCCB itself. High speed current limiting MCCB's as a general rule, are more prone to be damaged by high inrush currents, whether these result from DOL starting current inrushes or from the current surges that can occur during star-delta or autotransformer open circuit transition switching. Most current limiting breakers achieve high speed interruption of fault currents through electromagnetic repulsion of their contacts. It is normal practice to ensure that the instantaneous tripping levels of motor protection MCCB's is kept below the point of electro-dynamic contact separation due to magnetic forces. In extreme cases, and depending upon the nature of the inrush currents, it is not impossible that contact separation with its attendant damage to the contacts could take place at lower than anticipated inrush current levels due to high rates of rise of these inrush currents.

As a result motor protection MCCB's can only very rarely be applied up to the limits of the ampere ratings of a particular MCCB frame size. The limits on motor kilowatt ratings that can be used with a particular MCCB frame is usually specified by the MCCB manufacturer. Whilst it has been historically believed that the limits on motor kilowatt ratings per MCCB frame size could be extended if star-delta starting was used, this has now been shown to be incorrect. Due to the very high current surges that have been detected during open-circuit switching transitions, the limits on motor kilowatt per MCCB frame size need to be restricted even more than is the case with DOL starting.

LONG CABLES

It is not unusual, particularly with motor circuits, to encounter loads at the end of cables that could be many hundreds of metres long. Whist the inherent limiting impedance of cables is generally an advantage in restricting short circuit current levels, there are reasonably well defined limits at which such long cables, particularly if these are of small cross sectional area can introduce problems to both the circuit designer and user. The most obvious problem is one of voltage drop. Voltage drop is usually limited by specification requirements to about 5% of nominal voltage, and in the case of long cable circuits requires the use of oversized cables to limit the voltage drop.

DOL starting results in run-up currents of between 6 and 8 times the motor full load ampere rating. In such circuits, the voltage drop that occurs during starting should, if possible, not be allowed to exceed 15% of the nominal motor voltage rating. The implication of such a requirement is that permissible voltage drops in motor circuits should not exceed about half of that permitted in circuits that do not have motors.

The low starting torque that results from star-delta or autotransformer starting is even further aggravated by the extremely high switching transition surge currents, suggesting an even more serious problem where long lengths of cable are involved.

A further problem that is not often considered, is that short circuit fault currents that are severely restricted by long cable lengths can quite conceivably be of such a magnitude that these fault currents fall below the instantaneous pick-up level of the MCCB. This condition can result in the cable carrying a high level of OVERLOAD current for a significant period. The consequential heating of the conductors will lead to a marked increase in the cable resistance which in turn will result in even further reduction of the fault current.

This could result in a situation where the reducing fault current is never high enough to trip the MCCB, but is still well in excess of the cable thermal rating.

The consequence of such a situation could be one of incendiary ignition together with all the consequential fire hazards.

EFFECTS OF SYSTEM VOLTAGE

One parameter that is sometimes given inadequate attention in the selection of MCCB's is that of VOLTAGE RATING. It is important to understand that the short circuit interrupting capacity rating of an MCCB does not have a linear relationship with the system voltage. MCCB short circuit interrupting ratings are in fact extremely voltage dependent, and particularly so with modern "current limiting" circuit breakers.

Particular points of concern in South African mining applications are :

- *the commonly used 525 volt system, which has been known to rise to 600 volts during lightly loaded periods.*
- *the rapidly emerging 1000 volt system in both coal and gold mining environments.*

It should be ensured that all MCCB's that are applied at system voltages above 415 volts are specifically tested and certified for such voltages.

Approvals at 500 volts, which is not uncommon in Europe and the Orient are inadequate for South African mining applications.

MCCB's that are rated for 1000 volt applications should be certified by accredited independent test laboratories and specifically marked as suitable for 1000 volt application.

HARMONICS

The increasing use of power semi-conductor equipment, including variable speed drives has introduced a new dimension into power supply networks and the application problems of equipment connected to those systems. The most visible of these problems is the introduction of harmonics into the supply network.

Harmonics can result in overheating of both motors and MCCB's. In some cases, overvoltage problems can be aggravated by the presence of harmonics leading to premature failure of protection components, should these be applied beyond their design limits.

It is important to take cognisance of harmonics and their presence and to take appropriate action in this regard.

EARTH LEAKAGE PROTECTION

The very original motivation for South Africa's pioneering work in sensitive earth leakage protection arose out of the identified need for improved electrical protection in deep level underground mining. Way back in the latter half of the 1950's, it had already been recognised that such protection could provide significant advantages in the early detection of faults in induction motors, since most motor faults generally involve earth prior to their escalation into catastrophic phase to phase faults. With 250mA sensitive earth leakage relays becoming almost an industry standard, four decades of experience and application of these devices in underground mining applications, have resulted in cost savings to the industry that are today virtually taken for granted.

These cost savings in part, are a result of restricted motor winding damage, due to early fault detection, allied with reduced repair costs and lower down time.

CONCLUSIONS

Having examined the application and impact of MCCB's on the protection and starting of squirrel cage induction motors, it is clear that the MCCB has become not only the ideal component for short circuit protection duty, but provided the MCCB is properly selected, it can provide good locked rotor protection, and in many cases, also good overload protection to the motor.

Unless sophisticated starting methods are used, the perceived advantages of reduced voltage starting are often diluted by the unexpected high current surges that are introduced by the interruption of the stator supply voltage during star-delta or autotransformer winding connection transitions.

The very presence of these high current surges has, in many cases, led to a re-evaluation of the concept of DOL starting of induction motors and may require utilities to re-examine existing restrictions on the size of induction motors that can be started by the DOL method.

Whilst the MCCB is not intended to replace the contactor for DOL starting, in cases of light or infrequent starting duty, or where the MCCB life expectancy reduction can be economically justified, MCCB's can in addition be applied for DOL starting functions.

Four decades of appropriate application of sensitive earth leakage protection to large induction motors, particularly in underground mining applications, have proven that the additional investment in such protection is more than justified by the savings in repair costs and down-time in repairing motors.

As a general rule, the MCCB should be used for protection in motor circuits (with correctly rated and selected MCCB's sometimes replacing the overload relay), and the contactor used for all starting and control functions.

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