A circuit feeding a motor may include one, two, three or four switchgear or control gear devices fulfilling one or more functions. When a number of devices are used, they must be coordinated to ensure optimum operation of the motor.

Protection of a motor circuit involves a number of parameters that depend upon:
- the application, such as type of machine driven, operating safety and starting frequency
- the level of service constantly imposed by the load or the application
- the applicable standards to ensure protection of life and property

The necessary electrical functions are of very different natures, namely:
- protection (motor-dedicated for overloads)
- control (generally with high endurance levels)
- isolation

Disconnection functions include the isolation of a motor circuit prior to maintenance operations.

Short circuit protection is intended to protect the starter and the cables against major overcurrents (> 10 In).

Control should start and stop the motor and, if applicable, provide gradual acceleration and speed control.

Overload protection protects the starter and the cables against overcurrents (I < 10 In).

Additional specific protection includes limitative fault protection (while the motor is running), and preventative fault protection (monitoring of motor insulation with the motor off).

**Overloads (I < 10 In) and Impedant Faults**

An overload may be caused by an electrical problem, for instance, on the mains (loss of a phase, voltage outside tolerances, etc.), or a mechanical problem, such as excessive torque due to abnormally high demands by the process or motor damage (bearing vibrations, etc.).

A further consequence of these two origins is excessively long starting. Impedant faults are when 10 < I < 50 In. Deterioration of motor winding insulation is the primary cause.

Thermal relays provide protection against overloads and they may be either separate or integrated in the short circuit protective device.

**Short circuit (I > 50 In)**

This type of fault is relatively rare, a possible cause being a connection error during maintenance. Short circuit protection is provided by a circuit breaker. Protection against insulation faults may be provided either by a residual current device (RCD) or an insulation monitoring device (IMD).

**Applicable Standards**

A circuit supplying a motor must comply with the general rules set out in IEC 947-1, and in particular with those concerning contactors, motor starters and their protection, as stipulated in IEC 947-4-1, notably:
- Coordination of the components of the motor circuit
- Trip classes for thermal relays
- Contactor utilisation categories
- Coordination of insulation.

**Coordination of the Components of the Motor Circuit**

There are two types of coordination, and the standard defines tests at different current levels. The purpose of these tests is to place the switchgear and control gear in extreme conditions. Depending upon the state of the components following the tests, the standard defines the two types of coordination.

**Type 1**

Deterioration of the contactor and the relay is acceptable under two conditions:
- danger to operating personnel
- danger to any components other than the contactor and the relay

**Type 2**

Only minor welding of the contactor or starter contacts is permissible, and the contacts must be easily separated. Following Type 2 coordination tests, the switchgear and control gear functions must be fully operational.

Selection of a type of coordination depends upon the operating conditions encountered. The goal is to achieve the best balance between the user’s needs and the cost of the installation.

Type 2 coordination is chosen where continuity of service is imperative and only limited maintenance service in necessary.
Aspects concerning contactors subject to high fault currents

When a high fault current though a contactor occurs, the contacts are subject to forces of repulsion due to loop and striction effects, as shown in Figs. 2, 3 and 4.

Loop and striction effects create forces which are proportional to the square of the current, and which combine to repulse the moving contacts. When the forces of repulsion are greater than the force of compression, contact separation takes place. An arc forms, and there is considerable fusion of precious metal (Ag/CdO). Solidification follows after the contacts reclose, and there is thus the risk of welding.

Making of a current at $\cos \varphi < 1$

Depending upon the instant of switching, the making of an alternating current at $\cos \varphi < 1$ (for instance 0.35 or 0.45) can cause an initial asymmetrical current which then decreases exponentially to reach its normal continuous symmetrical current after a few milliseconds.

If the closing of poles takes place at the instant that the voltage passes through zero, the value of the asymmetrical current peak is a maximum. This condition occurs whenever the contactor is switched on or when a fault occurs, and adds to the forces of repulsion acting on the moving contacts.

The value of peak current that a contactor must withstand without repulsion at a power factor of 0.35 is $10 \times AC3$ current rating, as prescribed by the standard.

Breaking/making capacity

The manufacturer provides a small safety margin between the making capacity of a contactor and point at which repulsion begins.

The tests to determine the making capacity consist of closing a defined number of contactors onto a standardised load circuit simulating a squirrel cage motor and having the characteristics as defined by the standard. The current value is steadily increased until the zones of contact sticking (i.e. a poor weld) and of welding become apparent.

Following a statistical analysis, the making capacity is defined in terms of a symmetrical RMS current value, and this is given the manufacturers’ respective catalogues.

Operational zones

Referring to Fig. 6, the two straight lines A and B define three operational zones:

1. The bottom part where the risk of welding is low. This corresponds to type 2 coordination.
2. The central part in which the contactor is damaged and welded. The thermal overload relay is damaged but the manifestations thereof are confined to the motor starter concerned. This corresponds to type 1 coordination.
3. The top part, where there is a danger of short-circuit propagation to other starters, with a fire hazard involved. This is a danger zone.

Repulsion of contacts under fault conditions

Fig. 7 indicates how the contacts open and arcing occurs between

Fig. 5.

Contactor energy resistance

Fig. 6.

Coordination of the protection devices

Fig. 7.

Contactor behaviour on short-circuit

Fig. 8.
the contacts when the fault current increases and repulsion forces become greater than the compression forces.

\textbf{Ipk cut off}

When the current is limited and reaches a maximum value of Ipk cut off, then \( L \frac{di}{dt} \) becomes negative and the arc is quenched.

The value of Ipk cut off is the result of the technique referred to as current limitation (see \textit{ENERGIZE} September 2004, page 13).

\textbf{Melting spots}

If the current is limited and the arc is quenched (extinguished), the melting spots on the contacts have sufficient time to cool before contact reclosure, and the contacts do not weld but remain operational.

If, during the first half cycle, the short circuit current is not limited, or only partially limited, then as the current decreases, the electrodynamic effect decreases and the contacts reclose, but the arc is not extinguished until reclosure. The melting spot is thus maintained on the surface of the contacts, and when the contacts close, the melting spot cools and the contacts become welded.

It is important to note that, whether in laboratory tests for the making capacity of contactors, or when contactors weld in service due to abnormal conditions, it is always during closing or reclosing of the contactor that the weld occurs.

However, the user generally notices the weld condition when the contactor is called upon to open. There is, therefore, a tendency to put the blame on the interruption, which should not be the case.

\textbf{Consequences and outcomes}

- **Ic**, **Ir**, and **Iq**: the different test currents

To qualify for Type 2 coordination, the standard requires three fault-current tests to check that the switchgear and control gear operate correctly under overload and short-circuit conditions.

\begin{enumerate}
  \item \( I_c \) current (overload \( l < 10 \text{ In} \))
  \item \( I_q \) current (short-circuit \( I > 50 \text{ In} \))
\end{enumerate}

The thermal relay provides protection against this type of fault, up to the \( I_c \) value defined by the manufacturer. IEC 947-4-1 stipulates two tests that must be carried out to guarantee coordination between the thermal relay and the short circuit protective device:

1. At 0.75 \( I_c \) only the thermal relay must operate
2. At 1.25 \( I_c \) the short-circuit protective device must operate

Following the tests at 0.75 \( I_c \) and 1.25 \( I_c \), the trip characteristics of the thermal relay must be unchanged. Type 2 coordination thus ensures continuity of service. The contactor must be able to be closed automatically following clearing of the fault.

\( Ir \) current (impedant short-circuit 10 \( \text{In} < I < 50 \text{ In} \))

The primary cause of this type of fault is the deterioration of insulation. IEC 947-4-1 defines an intermediate short-circuit current \( I_r \). This test current is used to check that the protective device provides protection against impendent short-circuits.

There must be no modification in the original characteristics of the contactor and the thermal relay following the test. The circuit breaker must trip in \( \leq 10 \text{ ms} \) for a fault current \( \geq 15 \text{ In} \).

\( Iq \) current (short-circuit \( I > 50 \text{ In} \))

Short-circuit protection is provided by devices that open quickly. IEC 947-4-1 defines the \( Iq \) current as generally 50 kA. The \( Iq \) current is used to check the coordination of the switchgear and control gear installed on a motor supply circuit. Following this test under extreme conditions, all the coordinated switchgear and control gear must remain operational.
The finding of the technical report IEC 1459-1996 for coordination between contactors/motor starters and HRC fuses was that for test current $I_q$, high values of clearing time increase the risk of welding of the contacts of the contactor. In evaluating the “clearing time” for this purpose, the report considers that the current is “cleared” when it becomes a small percentage (ca. 5%) of its limiting peak value. This value may be difficult to obtain, and an acceptable alternative method is to assume that the limiting curve is a sinusoidal waveform and from the total $I^2t$ value (in A²s) and the peak let-through current value $I$ (in A), an “equivalent clearing time” $t_{eq}$ may be calculated, given by:

$$t_{eq} = \frac{2xI^2}{I^2}$$

A satisfactory value for this equivalent clearing time has been found to be: $t_{eq} \leq 5$ ms.

Note: The risk of contact welding increases when, after being thrown apart, contacts close again while relatively high arcing currents remain established between the contacts. Considering the inertia of moving contacts, the probability of reclosing with such currents increases if these currents persist 5 ms after the beginning of the short circuit.

For test current $Ir$ (repulsion test) the value of $t_{eq}$ that has been found to be acceptable at this level of current is $t_{eq} < 6$ ms.

**In summary**

Type 2 coordination and beyond (IEC 947-6-2) is achieved when the short circuit protection device clears the fault (arc is extinguished) in less than 5 to 6 ms, and the withstand ability of the associated components are rated to withstand the cut-off current and energy let-through.

Alternately, the associated components can be upsized to withstand the repulsion forces and energy where the clearing times are greater.

In circuit breakers, the technology of pressure/reflex tripping (implemented in the Merlin Gerin Compact NS range of circuit breakers up to 630 A, and which provides current limitation equal to a corresponding rated HRC fuse), and high speed accelerated unlatching (implemented in the Telemecanique TeSys model U and Integral range of motor starters) has enabled the required clearing times to be reached some ten years ago, and Type 2 coordination and beyond is now in use in standard products from Schneider Electric South Africa.

The intention of this document is also to give the reader an appreciation of the principal constraints affecting the making capacity of contactors and to indicate the solutions used by Telemecanique and Merlin Gerin.

As the subject is relatively complex, we have deliberately avoided the finer points which would have complicated this technical brief.

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<table>
<thead>
<tr>
<th>Operational current $I_e$ (AC3) of the motor in A</th>
<th>&quot;Ir&quot; current (in kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_e \leq 16$</td>
<td>1</td>
</tr>
<tr>
<td>$16 &lt; I_e \leq 63$</td>
<td>3</td>
</tr>
<tr>
<td>$63 &lt; I_e \leq 125$</td>
<td>5</td>
</tr>
<tr>
<td>$125 &lt; I_e \leq 315$</td>
<td>10</td>
</tr>
<tr>
<td>$315 &lt; I_e \leq 630$</td>
<td>18</td>
</tr>
</tbody>
</table>