OPERATING IN THE ‘DANGER ZONE’: CONTACTOR DROPOUT VS. FUSE CLEARING TIME

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Abstract – The most common and economical arrangement for medium voltage motor controllers is to self-supply from the primary motor circuit. In this arrangement a short-circuit collapses the line voltage, causing the contactor to ‘dropout’. For low-level faults which nevertheless exceed the interrupting rating of the contactor it is common for the dropout time to be faster than the clearing time for the fuse. Although this fault current is extremely unlikely to occur, no provisions exist in current standards to permit application of contactors in this manner. To prevent the contactor from attempting to clear a fault current above its rating, less than optimal fuses must be selected or complex and expensive supplemental power supply circuits are added to ensure the holding coil remains energized until the fuse clears the fault. The trade-offs of short-circuit clearing time versus rated current to achieve a take-over point below the interrupting rating of a contactor are illustrated. In response to a customer request, an alternative test procedure to demonstrate capability where contactor dropout precedes fuse clearing was performed; actual results of such tests are included.

Index Terms– Medium voltage motor control, vacuum contactors, medium voltage fuse, takeover current, coordination

I. THE DANGER ZONE

A. *Motor Controller Capabilities*

Medium voltage motors are often required to start and stop many times per day. This high switching capability is beyond the capability of a normal circuit breaker. Specialized electrical switching devices suitable for this extreme duty, called contactors, exist to fulfil this need. To deliver this high switching duty performance fault clearing capability is traded for enhanced mechanical and electrical endurance.

The maximum short-circuit current “I_{SC}” rating of a contactor is relatively low. By standard, all contactors must be able to break at least 8 times their rated continuous current (IEC) or 10 times their rated continuous current (ANSI). All currents up to I_{SC} will be interrupted by the ; the contactor only required to withstand a few milliseconds of arcing current. Above this level, an additional Short-Circuit Protective Device (SCPD) is required. The combination of a SCPD and a contactor in series, plus appropriate control elements, is a motor controller. In medium voltage, fuses are most often used as the SCPD.

With a fuse in series, the I_{SC} of the controller is about one order of magnitude higher than for the contactor alone. High short-circuit currents will be cleared quickly by the fuse within the contactor opening time, so that the interrupter is spared from the fault current energy.

B. *The Danger Zone, a.k.a. the Gray Zone*

The “Danger Zone” is a short-circuit current above the short-circuit interrupting capability of the contactor, but low enough that the fuse interrupting time is longer than the contactor opening time, such that if the contactor opens the interrupter is exposed to an arc with a current which it cannot interrupt. The contactor must wait for the fuse to clear while absorbing a considerable amount of energy. This zone is illustrated in Fig. 1(b).

More euphemistically, the ‘Danger Zone’ is often called the ‘Gray Zone’ in motor control application discussions when considering work arounds to avoid the specific situation which results in the excessive fault duty imposed on the contactor interrupters. Even where the term is not employed, industry standards and published papers make it clear that allowing the contactor to open at currents above its rated interrupting capability prior to the fuses clearing the fault is a dangerous situation [1], [2], [3]. Various solutions exist to avoid operation in this ‘Gray Zone’. Some of these solutions include:

- Extending the Motor Protection Relay (MPR) delay time to ensure contactor will not attempt to clear too soon or employing a current inhibit (50B) blocking relay [2].
  Note: Extended relay delays must be coupled with either using a latched contactor or providing a separate assured source of control power to hold the contactor shut. In some cases a constant voltage transformer (CVT)
- Non-optimal fuse selection which may limit starting capability, maximum motor load, or lack of selectivity.

The above solutions add complexity and cost to the system or expose the system to fault currents longer than necessary. In cases where the area of the ‘Gray Zone’ is small enough, it might be seen as representing a minimal chink in the armor of the overall motor protection scheme and the decision is taken to simply accept operating in the gray zone. Currently this is done without a clear understanding of the risks involved.

This paper examines the real risks associated with such a decision for the most common type of motor controller by examining actual tests performed in the gray zone.

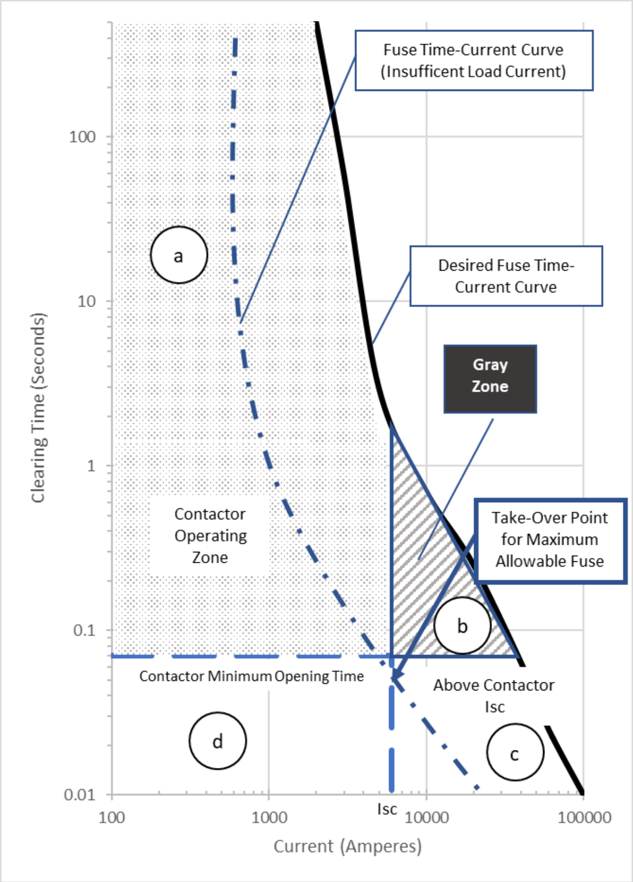

Fig. 1 The Danger / Gray Zone Illustrated

II. MOTOR CONTROLLER CHARACTERISTICS

A. *Contactor Ratings*

Voltage: Most common voltage ratings for contactors without fuse are 7.2 kV and 12 kV. With fuses, 5 kV, 7.2 kV, 12 kV and 15 kV are common.

Rated Current: Most common rated currents for contactors are 400 A and 800 A. Fuses are commonly available between 63 A and 900 A.

Short Circuit Current: The maximum short-circuit current ratings of contactors without fuses are between 4 kA and 12.5 kA. Combined with fuses, the maximum short-circuit current ratings are in the range of 50 kA to 65 kA.

B. *Motor Controller & Contactor Construction*

Certain design characteristics are common amongst nearly all manufacturers. The most common characteristics of medium voltage motor controllers and their constituent contactors are:

- Contactors have very limited fault current interrupting capability, typically in the range of 4 kA to 12.5 kA.
- Protection against short-circuit faults is provided by a separate short-circuit protective device (SCPD) typically a fuse.
- Solenoid closing, spring opening operating mechanisms are the most common, with mechanically latched solenoid or permanent magnet bi-stable actuators occasionally used. Spring stored energy mechanisms are virtually unknown in modern designs. Non-latching solenoid mechanisms require a continuous supply of control power to remain closed.
- In the most common, and generally most cost effective implementation, solenoid operating mechanisms are held closed with a small maintaining coil and the entire system is self-supplied from the high voltage bus. See Fig. 2.

C. *Contactor Interrupter Technologies*

Vacuum interrupters (VI) are the predominant technology employed by modern contactors. However, SF6 interrupting technology is occasionally used and air-magnetic contactors, although not being actively promoted, still exist in the field. The testing described in this document was exclusively conducted on vacuum interrupter technology contactors. Although the vacuum interrupters used are of high quality, they do not represent a significant change in the basic technology utilized in most vacuum interrupters. It is likely that these results may be applicable to other vacuum interrupter based contactors, but suitable testing should certainly be carried out prior to implementation. The authors offer no opinion as to the applicability of other technologies to perform similarly.

D. *Control Scheme*

The most common construction for the AC contactor utilizes a solenoid operated mechanism which uses spring power to open. In this manner, the contactor 'fails safe' (open) but requires a constant supply for it to remain closed; although the holding power is a fraction of that required to close the device. The simplest and most economical method to reliably supply control power to the motor controller is from the primary supply circuit that drives the motor itself. The most basic version of such a control scheme is illustrated in Fig. 2.

A 'Start' pushbutton energizes an interposing relay which both closes the contactor and seals itself in. The contactor closes and starts the motor which continues to run until: the 'Stop' pushbutton is pressed, the motor protection relay acts to stop the motor in response to some overload situation, or the protective fuses open in response to a short circuit.

The motor protection relay (MPR) upon sensing a fault current may cause the contactor to open before the fuses can act to clear the fault; or in the case of a self-supplied motor controller, the short-circuit collapses voltage on the primary bus causing the contactor supply voltage to fall and the contactor to open.

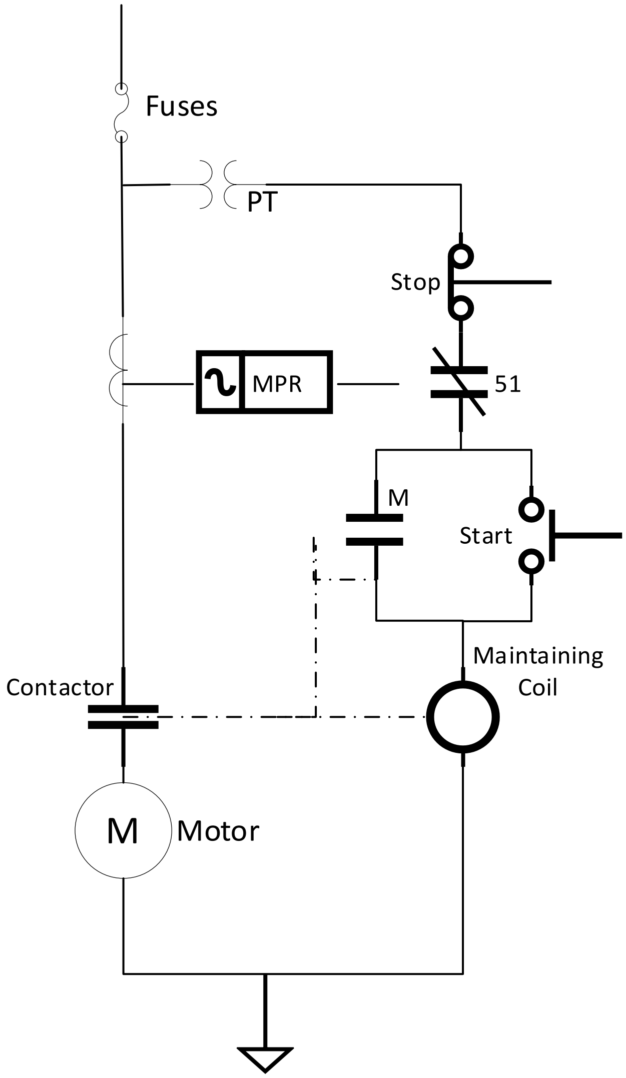

Fig. 2 Simplified Control Scheme

III. STANDARD REQUIREMENTS AND TESTING

A. Relevant Standards

UL 347 [4] is an approved American National Standard Institute (ANSI) and covers the ANSI market. It is also accepted by both Mexico as an ANCE standard (NMX-J-564/106-ANCE) and Canada as a CSA Standard (CSA 22.2 No. 253:20). The rest of the world either directly uses or has adopted a nationalized version of International Electrotechnical Commission IEC 62271-106 [5]. Edition 5 of UL 347 included an effort to harmonize with IEC standard 60470, the predecessor to IEC 62271-106. The harmonization was not complete, but the two standards are similar enough that they may be discussed together.

B. Current Switching Requirements of Standards

Both ANSI and IEC standards define four capabilities:

1. Contactor switching of normal load current.
2. Contactor switching of overload currents.
3. Contactor switching at the take-over point.
4. Breaking of rated short-circuit current (via fuses).

Capabilities 1 and 2 are shown in Fig. 1(a) and will not be further discussed. The items of interest are 3 and 4. The take-over point is that current where fuse clearing curve intercepts the maximum rated breaking current of the contactor, it should be at or below (faster) than the contactor opening time. The standards require that the manufacturer define the maximum rated fuse which may be used in the controller. The fuse rating defines the fuse continuous current, time-current clearing characteristics, and maximum fault current. The standards also require that every contactor be able to switch, without the use of an SCPD, at least 10 times the rated load current (ANSI) or 8 times the rated load current (IEC). At higher currents, there exists some time on the fuse characteristic where the fuse will clear the fault. The higher the current, the more quickly the fuse will clear. At lower currents the time for the fuse to clear may be considerable. Wherever this take-over point occurs, the capability of the contactor to break this current satisfactorily must be demonstrated. Ten such take-over point interruptions are required by ANSI, three by IEC.

The next tested current is the maximum fault current for which the controller is rated. This current is always cleared by the fuses and because of the magnitude of the fault current the total fuse clearing time is some tens of milliseconds. It is only required that the contactor's interrupters endure the let-through current of fuses without permanent damage. Because fuse clearing times generally follow a curve proportional to the energy given by $I^2 \cdot t$, and this same energy is what is generally accepted as damaging the interrupters, testing at intermediate currents is not required.

There are two implicit assumptions in this methodology:

1. The contactor always remains closed at any current above the take-over current regardless of the time it may take the fuses to clear.
2. The motor load characteristics and the system fault current capability permit selection of a fuse which coordinates not only with the contactor but with upstream protective devices for acceptable selectivity.

IV. BEHAVIOR NEAR TAKE-OVER POINT

A. Gray Zone: Definition

The gray zone is a range of fault current values slightly higher than the maximum contactor short-circuit current rating (take-over point) where the total clearing time of the selected fuses is higher than the selected contactor opening time. Illustrated by Fig. 1 (b).

The end of the gray zone depends on both the contactor and the fuses. More precisely, it is the value of current cleared by the fuses at the opening time of the contactor. If a fault happens in this zone, the contactor is faster than the fuses and it tries to interrupt the fault current without succeeding.

Although a fault in the gray zone is extremely unlikely to occur, there are three options to counteract:

1. Select a different fuse which clears faster at the maximum fault current of the contactor such that it is impossible for the contactor to open prior to fuse clearing. Unfortunately, this size fuse may be unacceptable for other reasons.
2. Introduce an intentional delay in the contactor opening time: the contactor becomes slower than the fuses and they clear the fault before the contactor opens or apply a blocking relay to inhibit contactor opening when the fault current exceeds the capability of the contactor.
3. Make sure that the contactor can withstand the fault current until the fuses break: the contactor contacts separate attempting to break the fault current without succeeding, but they withstand the energy flowing until fuse intervention without damage to the contactor.

This zone is just partially mentioned by international standards, where specific tests are well described.

B. *Gray Zone Mitigation Techniques*

1) *Option 1, Intentional Delay*: The intentional delay to be introduced in the contactor opening time depends on the contactor itself and on the fuses with which it must be coordinated. Consider a contactor rated 7.2 kV 800 A with an opening time of 70 ms and with a maximum short circuit current of 12.5 kA, coordinated with R type fuses rated 57X (fuses rated current: 900A).

To calculate the intentional delay which must be added to the contactor opening time to make it slower than the fuses, a fuse characteristic curve graph (Fig. 3) for candidate fuses is examined and the following steps are followed:

1. Pick the Current-Total Clearing Time fuse graphic and select the correct fuse curve. In this example the fuse curve is the one corresponding to 57X rating.
2. Select the contactor opening time. In this example it is 70 ms (point 1 in Fig. 3).
3. Select the maximum contactor short circuit current – in this example it's 12.5kA (point 2 in Fig. 3*)* – and plot a vertical line to intersect the fuse curve.
4. Plot a horizontal line starting from the intersection point to obtain the fuse total clearing time at that specific value of current. In this example the obtained value is 350ms (point 3 in Fig. 3).
5. The intentional minimum delay to be introduced is the interval '4' in Fig. 3 as calculated below:

Fuse Total Clearing Time	350 ms
— Contactor Opening Time	— 70 ms
Minimum Relay Delay Time	280 ms

When a minimum intentional delay of 280 ms is added to the contactor standard opening time, the contactor becomes slower than the fuses. Therefore, when a fault happens in the gray zone, the fuses break the fault without any damage to the contactor. A less desirable consequence of this strategy is that fault currents which are within the interrupting capability of the contactor (e.g., 10 kA) are also delayed by 280 ms and some method of ensuring the contactor will not drop out due to collapse of line voltage must also be engineered into the system.

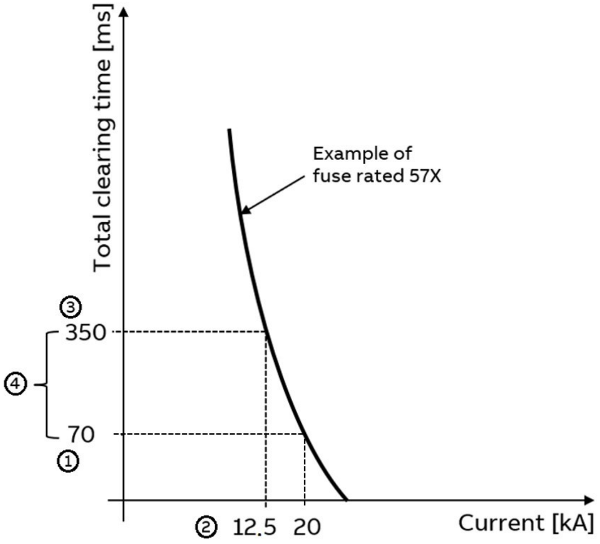

Fig. 3 Typical Fuse Clearing Curve

2) *Option 2, Contactor capability*: If an intentional delay is not added, the contactor must be able to withstand the fault current until the fuse intervention without damage.

Consider as an example a contactor rated 7.2 kV 800 A with an opening time of 70 ms and with a maximum short circuit current of 12.5 kA, coordinated with R type fuses rated 57X as before. Examine a fault happening in the gray zone at 15 kA. Fig. 3 may again be referenced, but for clarity no additional lines are sketched. The fault current under consideration is slightly to the right of the existing vertical line at 12.5 kA.

The contactor opening time with no intentional delay is 70 ms, while at this current type 57X fuses have a total clearing time of 180ms.

In this example, the gray zone starts at 12.5 kA (Maximum contactor short-circuit current) and ends at 20 kA, which is the value of current at which the fuse total clearing time is the same as the contactor opening time. Above 20 kA value, the fuses become faster than the contactor and they break the fault. Fig. 4 is a current only representation of this situation.

When the fault happens in the gray zone, the contactor contacts separate, attempting to break the fault current without succeeding. The fuses, which have an inverse-time-exponential curve, take longer time than the contactor to interrupt the fault.

3) *Option 3, Constant Voltage Transformer (CVT)*: If the required extension of the contactor hold-in time is short, a constant voltage transformer may be able to provide sufficient energy as the line voltage sags to allow the contactor to ride-through the sag until the fuses clear the fault.

Contactors are required to ride-through a voltage sag which does not fall below 75% of rated control voltage but must open when the supply voltage falls below 10% of rated voltage. The actual drop-out values certainly vary from one type of contactor to the next, and perhaps even from one production lot to the next of the same type. Ferraro, et. al. [6] consider the use of a CVT or ferro-resonant transformer to mitigate the effects of voltage sags on industrial equipment. A case study is presented in which CVT's were utilized to combat the effects of various power quality issues including voltage sags. The results were promising with protected equipment being able to survive voltage sags of up to one-half second and down to 30 percent voltage. Although this solution increases cost (the paper indicates an installed cost of $5000 per CVT), the solution was demonstrated to be field retrofittable solution. For consistent results a CVT which maintains power above 75% of rated control voltage would need to be selected.

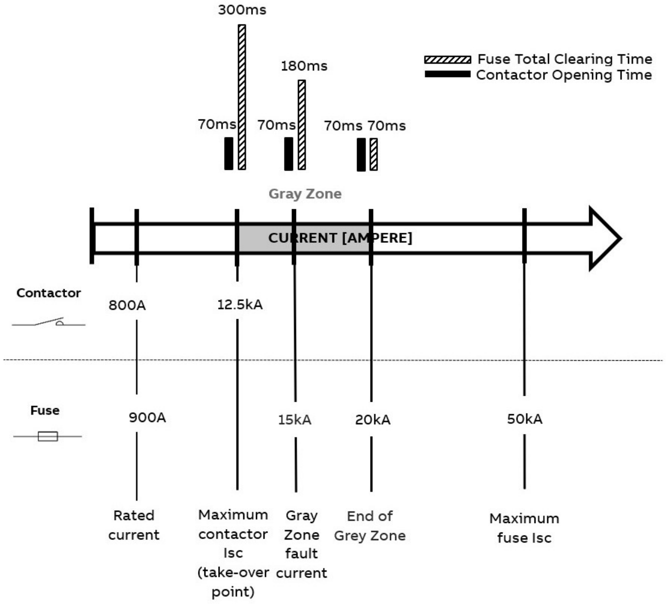

Fig. 4 Gray Zone Example Represented by Current Only

C. *The Dimensions of the Gray Zone*

In Table I the gray zone current values for the above example contactor and fuse combination are reported, with corresponding fuse total clearing time and energy that the contactor shall withstand until fuse intervention (I^2t arcing). Although actual energy must consider the resistance of the contacts, it is common engineering practice when evaluating interruption capability in vacuum interrupters to treat resistance as constant and utilize I^2t as a proxy for energy.

As highlighted in the table, the most dangerous current value is not the highest one, but it is dependent on the difference between fuse total clearing time and contactor opening time:

$$I^2t = I^2(Fuse\ Clearing\ Time - Contactor\ Opening\ Time)$$

Higher rated normal current fuses have longer total clearing times; therefore, the gray zone is larger as well.

In summary, when a fault happens in the gray zone, and a method is not provided to ensure the contactor remains closed, the interrupters must withstand the arcing energy flowing through its open contacts without any damage until the intervention of the fuses. As noted in section III.B above, current international standards assume that the maximum fuse permitted is such that no gray zone exists for the minimum contactor opening time, or a combination of intentional relay delay times and methods to ensure the contactor remains closed are employed. The former case may be too restrictive for the customer's needed application, and the latter case introduces additional complexity and cost into the equipment. Thus, there is a strong motivation on the part of the application engineer to accept the risks of accepting neither option; instead choosing to live with the gray zone

A test procedure was developed and executed to evaluate the capability of a vacuum contactor to withstand the arcing energy dissipated by a gray zone interruption.

TABLE I
ARCING ENERGY OF EXAMPLE CONTROLLER

Gray Zone Isc [kA]	**T_O Contactor [ms]**	**T_{CLEAR} Fuse [ms]**	**Arcing I^2t [kA^2 ms]**
13	70	220	25 350
14	70	210	27 440
15	70	180	24 750
16	70	110	10 240
17	70	90	5780
18	70	80	3240
19	70	75	1805

T_O: Contactor Opening Time (milliseconds)
T_{CLEAR}: Fuse Total Clearing Time (Type 57X Fuses)

V. TEST PROCEDURE AND RESULTS

The purpose of this test is to replicate a situation where the separation of the interrupter contacts precedes the fuse clearing at a current value inside the gray zone. In this case the contactor should not be able to break the current. The ability to withstand the energy flowing until the fuse clears is assessed.

A. *Test Parameters*

1. ***Test voltage*****:** equal to the rated voltage.
2. ***Transient recovery voltage:*** equal or higher than the requirements of the standard fault interruption test / short circuit making and breaking test.
3. ***Power frequency recovery voltage:*** shall be maintained active at least for the entire duration required by the fuse intervention.

Test current: As close as possible to that resulting in the maximum arcing energy inside the gray zone (example given in Table I).

B. *Test Procedure*

The following test sequence was conducted, each item of Table II references the corresponding point in

Fig. 5. It should be noted that in order maximize the severity of the test on the contactor and minimize the contribution of the fuses to clearing the current, a commonly utilized test procedure known as "pre-tripping" was used. Pre-tripping

sends the ‘trip’ signal to the contactor before starting fault current flow. The timing is such that the fault current begins approximately one-half cycle prior to the contactor opening. This creates a more severe case of a very fast contactor opening combined with a very slow fuse clearing, even for the larger than usual fuses utilized in the test arrangements (see Table III).

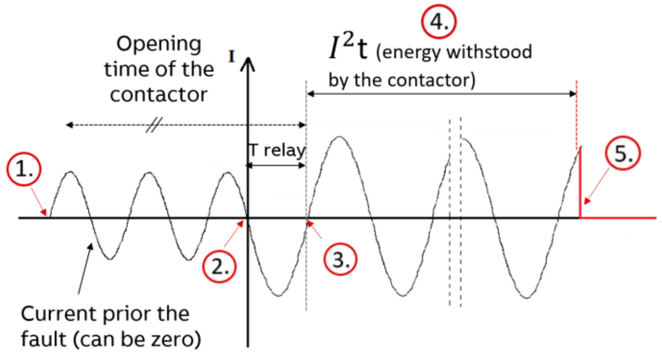

Fig. 5 Test Procedure Interruption Illustration

TABLE II
GRAY ZONE TESTING PROCEDURE SUMMARY

#	Description
1.	Contactor is closed. Current flowing can be zero or a normal value lower than rated current (not fault value).
2.	Fault is initiated through a making operation of test laboratory making switch. A symmetric fault current starts flowing in the main circuit. Test current prospective value shall be equal to the predefined value falling inside the gray zone. It is not recommended to inject asymmetrical current as the peak will cause a faster clearing of the fuses and the contactor may open under no load condition, resulting in an invalid test.
3.	Main contacts separation shall take place in the first half cycle of the fault current. If needed, pre-tripping of the contactor may be utilized to achieve the required timing.
4.	Contactor opens but current is not interrupted because it exceeds the short-circuit capability. Arcing occurs between main contacts until fuse intervention.
5.	Fuses clear the fault in a time equal to the fuse total clearing time. This may be simulated by opening the test laboratory breaker. Note that use of laboratory opening device deprives the interrupter contacts of any current limiting benefit available from type ‘R’ fuses.

C. Evaluation criteria:

Contactor must withstand an arc energy across the open gaps of the main contacts waiting for fuse clearing; this may cause some deterioration to the contactor or to the switchboard. Depending on the amount of damage, tests results can be classified as follows:

1. Contactor interrupts the fault current → no need of opening delay
2. Contactor doesn’t interrupt, no external visible damage to the vacuum interrupter (VI), resistance and dielectric check positive → no need of opening delay.
3. Contactor doesn’t interrupt, non-visible damage confined inside the VI, resistance and dielectric check negative → contactor needs to be replaced, no damage to the panel. Opening delay needed to avoid contactor replacement.
4. Contactor doesn’t interrupt, visible damage to the VI but confined inside the contactor (e.g., VI ceramic broken) → contactor needs to be replaced, no damage to the panel. Opening delay needed to avoid contactor replacement.
5. Contactor doesn’t interrupt, obvious damage to the controller beyond the contactor itself (e.g., housing, or main circuit path damaged) but no damage to the panel. → Controller needs to be replaced. Opening delay needed to avoid controller replacement.
6. Contactor doesn’t interrupt, damage to the panel → contactor and panel to be replaced. Opening delay needed to avoid panel replacement.

Resistance check is acceptable if the measurement after the test across the contactor terminal does not exceed 2 times the same measurement taken before the test. Dielectric check passes if the insulating medium (vacuum) across the main contacts withstands without discharge 80% of the rated power frequency withstand value.

Even if conditions 1 and 2 can be considered successful, main contacts have been subjected to an arcing time much longer than usual for terminal fault current which is about 8 – 10 milliseconds. Here, the contactor must wait until fuses clear. Additional making and breaking operations at rated voltage and current can be carried out to judge the contactor’s capable to operate. If case condition A or B occur during real service, special maintenance may be recommended by the manufacturer to mitigate risk of malfunctions that cannot be detected by resistance or dielectric check.

D. Tests on Actual Contactor / Fuse Combinations:

Three different vacuum contactors from the same manufacturer have been tested at different current values falling inside the gray zone. Contactors have been tested in series with three different rating of fuses from the same manufacturer.

TABLE III
RATINGS OF TESTED CONTACTORS & FUSES

Device	Normal Current I	Short Circuit Isc	Rated voltage E	Opening/ Clearing time
Contactor 1	400 A	6 kA	7.2 kV	90ms
Contactor 2	400 A	6 kA	7.2 kV	70ms
Contactor 3	800 A	12.5 kA	7.2 kV	70ms
Fuse 1	(18R) 390 A	50 kA	7.2 kV	
Fuse 2	(24R) 450 A	50 kA	7.2 kV	
Fuse 3	(57X) 900 A	50 kA	7.2 kV	

TABLE IV
TEST COMBINATIONS, GRAY ZONES, CURRENTS

Test #	Combination [series]	Gray Zone Range	Test Current	Excess Arc Energy (kA^{2}ms)
Test #1	Contactor 1 +Fuse 1	6 - 7 kA	7 kA	3023
Test #2	Contactor 2 +Fuse 2	6 - 10 kA	9 kA	5807
Test #3	Contactor 3 +Fuse 3	12.5 - 20 kA	15 kA	38 633

In the above table the excess arc energy is calculated as: (test current)^2 x (total clearing time of the fuse-8.3 ms):8.3 ms is one-half cycle at 60 Hz and it is subtracted from arc duration since it is considered as the minimum fault current that should flow through the main contacts before their separation. With the intention of testing the worst possible condition, the opening command during each test has been triggered prior the fault initiation. This should result in the maximum arc duration across the main contacts.

Test current has been selected as the best tradeoff between the value leading to the maximum arc energy and a value that provides at least 3 current cycles for 400 A and 10 cycles for 800 A between contact separation and fuse intervention. This is to avoid interference between the opening of the contactor and the fuses intervention, minimizing the use of testing time and objects, still providing a worst testing condition.

1) *Test #1:* During the first trial a combination between lowest rated contactor and fuse has been tested.

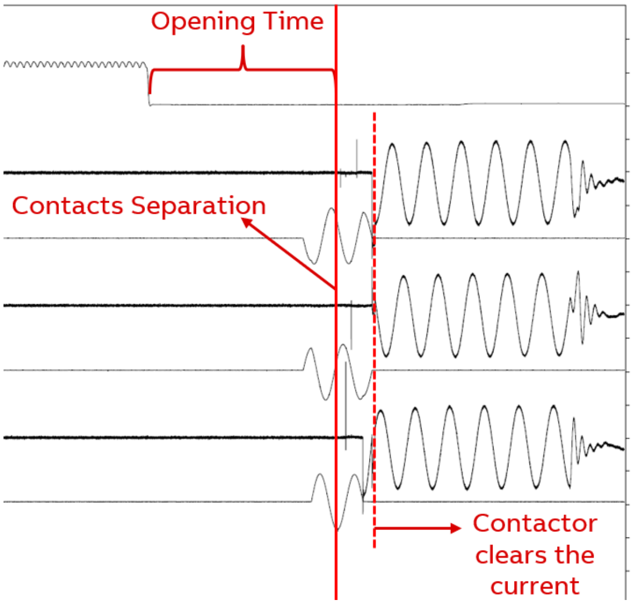

Fig. 6 Test #1 Oscillogram

Oscillogram Interpretation:

The first line shows the closing signal on the contactor. It is removed to signal the contactor to open. Below the control signal are three pairs of line voltage and current traces respectively, which provide information on each of the three phases of the controller. In each pair, phase voltage is presented above phase current.

As can be seen on the lower of each pair of traces, current flow is initiated prior to the contacts parting in the interrupters. Following contact separation, small upticks on the voltage traces (upper of each pair) can be observed as the vacuum contactors attempt to clear the current. Larger disturbances later in the voltage traces illustrate the arcing in the fuse and the beginning of current interruption. When interruption is complete the voltage traces return to a sinusoid and the current traces are flat.

Test Result #1: the contactor was capable of breaking the fault current without waiting for the fuses intervention. The higher than claimed performance can be explained by the absence of the asymmetrical component (peak) and by the manufacturer taking a conservative view in their claimed ratings. After the test the dielectric strength was intact and main contacts resistance did not increase above the limit given in. International standards as an increase of 200% compared to initial measurement. The result can be classified as result 1: *Contactor breaks the fault current → no need of opening delay.*

2) Test #2: The second combination puts in series a contactor with same ratings of that tested in test #1 but capable to be combined with higher ratings fuses.

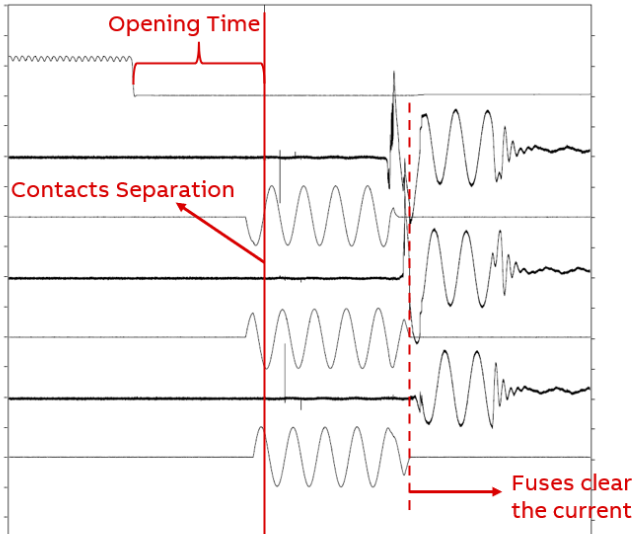

Fig. 7 Test #2 Oscillogram

Test Result #2: as intended, the contactor could not break the fault current, while the fuses clear within the expected time. Across the open gap of the vacuum interrupters three arcs are established. After the test the dielectric strength was intact and main contacts resistance did not increase above the limit. The result can be classified as result 2: *Contactor doesn't interrupt,* *no visible external damage to the VI, resistance and dielectric check positive → no need of opening delay.*

3)Test #3: The third combination puts in series a contactor and a fuse set with highest current ratings among the selected group of products.

Test Result #3: as intended, the contactor could not break the fault current, while the fuses clear within the expected time. Across the open gap of the vacuum interrupters three arcs are established. After the test the dielectric strength was intact. The result can be classified as result 2: *Contactor doesn't interrupt, no visible external damage to the VI, resistance and dielectric check positive → no need of opening delay.*

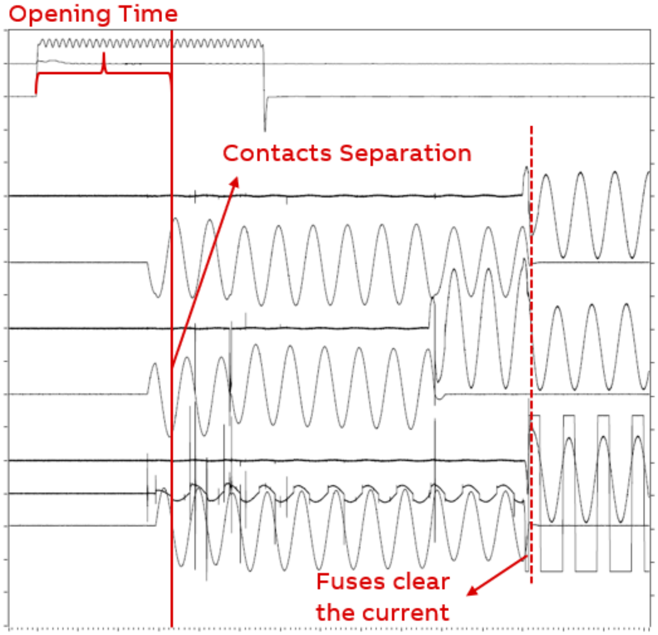

Fig. 8 Test #3 Oscillogram

Table V presents a summary of the key parameters and results of the testing conducted including the proxy for arc energy (I^2t) and the percent increase in contact resistance.

TABLE V
SUMMARY OF TEST RESULTS

Test #	Current Isc	Arcing Time	Current Duration	Arc Energy (kA^2•ms)	% Ohm Change
Test 1	7.74 kA	17.3 ms	33.5 ms	1036	30% - 60%
Test 2	9.07 kA	76.4 ms	87.8 ms	6285	≈ 20%
Test 3	15.17 kA	180 ms	190 ms	41 423	40% - 90%

VI. CONCLUSION

A. *Application Considerations*

The gray zone condition represents an unusual situation, occurring in only a small fraction of actual applications. For this analysis, the largest practical fuses were selected, which yields the largest range of fault currents falling into the gray zone. In practice, reduction, or elimination of the gray zone with different fuses is often possible.

The most serious gray zone situation exists when the actual system fault current falls within the gray zone. Otherwise, a gray zone fault requires some short-circuit impedance downstream of the contactor which is other than a complete dielectric breakdown at the point of failure. Proper system analysis requires that all fault-currents up to the maximum possible be considered, but some are more likely than others.

Where the most-likely fault current falls within the gray zone then strong consideration should be given to employing one of the mitigation strategies expressed above. But where gray zone fault currents are unlikely, consideration may be given to evaluating the ability of the contactor to withstand a gray zone interrupting event.

The reader is strongly cautioned that such consideration must be done in consultation with the manufacturer. It is possible that the manufacturer may have test data to confirm (or deny) the capability of their contactor to withstand a limited number of gray zone interruptions. Furthermore, it must also be declared that while the presented tests were done using vacuum interrupters of typical technology and construction, the results obtained are not necessarily extendable to other VI's. Also, no opinion whatsoever is offered regarding the possibility of obtaining similar results using SF6 or other interrupting technologies.

B. *Standards Considerations and Changes*

UL 347 only provides for motor controllers where the contactor interrupting capability is coordinated with the clearing of the fuses and the system has completed the necessary type testing at the take-over point (e.g., the system design and application prevents the existence of a gray zone). IEC 62271-106 contains a clause titled "Coordination and acceptable damage classification" (5.107.3.4) which considers three levels of possible damage resulting from a gray zone interruption (although not named as such). These damage levels correspond to test results 3, 4, and 5 in section V.(C). It further states: "Cases where the applications call for a practically negligible risk of contact welding are subject to agreement between manufacturer and user and are not covered by this document."

Where such agreement between manufacturer and user is undertaken the authors suggest that the test program presented in section V is a valid method of demonstrating capability within the gray zone. As experience is gained with this procedure among a larger group of stakeholders, it may be prudent to include some version of this test program in the relevant standards as an optional test routine specifically to demonstrate this capability. At the time of this writing no such proposal has been made to the responsible standards bodies.

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IX. VITAE

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