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The Application of the Cutler-Hammer Vacuum Interrupter to Switch, Control and Protect the World's Distribution Circuits

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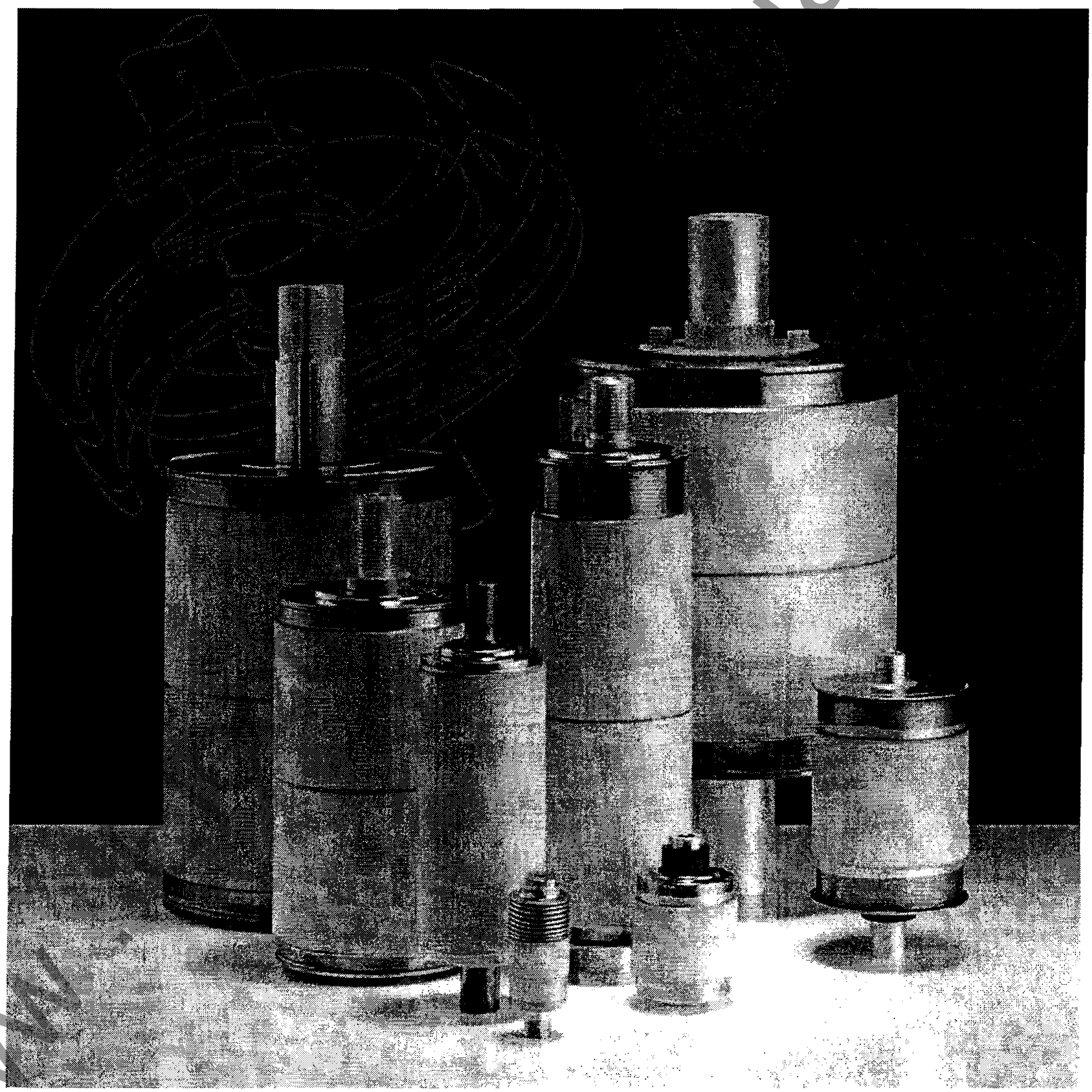

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Table of Contents

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THE APPLICATION OF THE CUTLER-HAMMER VACUUM INTERRUPTER TO SWITCH, CONTROL AND PROTECT THE WORLD'S DISTRIBUTION CIRCUITS

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ABSTRACT

This white paper provides application guidelines for, and will show the advantages of, applying vacuum interrupters (VI's) to switch and to protect a wide variety of power distribution circuits. The high voltage design and testing of the VI is discussed with special reference to both the internal and external requirements including the external creep distance. The performance of VI's for load switching and for short-circuit Interruption is discussed with reference to long-term switching life and low maintenance costs. During this discussion, the special advantages of the VI are presented as well as operating parameters to consider while short circuit testing. Transformer secondary protection, short line fault switching, non-sustained, destructive discharges and quality testing are also presented. The effects of current chop, virtual current chop and voltage escalation on the components in a distribution circuit are examined and straightforward methods to minimize them are presented. The advantages of using VI's for long life, maintenance-free performance for capacitor switching, and for motor switching are discussed. The white paper shows how the special characteristics of VI's can be used to produce a circuit breaker that will reliably protect all types of distribution circuit.

1. INTRODUCTION

Cutler-Hammer (C-H) (formerly Westinghouse Distribution and Control Business) has had close to 40 years experience in research, development, design and application of the Vacuum Interrupter (VI) [1]. There are over two million C-H VI's in the field controlling a wide variety of circuits in over 40 countries around the world. Research and development of the C-H VI began in 1960 at the then Westinghouse Research Laboratories in Pittsburgh, PA., U.S.A. By the mid-sixties, the technology had been transferred to the Horseheads Operation in New York State where the first commercial VI's were produced. From the mid-sixties to 1994 the Westinghouse Horseheads Operation and the Westinghouse Central R&D Center worked together to extend the range of current and voltage interrupted and to extend the application of the VI. In 1994 when Eaton/Cutler-Hammer took over the Distribution and Control Business from Westinghouse, the R&D department with its High Power Laboratory was moved to the Horseheads Operation. All VI activities were thus aligned in one facility. This has not only accelerated the development of the VI product, but has also allowed C-H to maintain the tradition of continuous development, product improvement, and application extension. The C-H VI has now found wide application not only in C-H circuit breakers and contactors, but also with many OEM customers: e.g. in circuit breakers, reclosers, load break switches, contactors, capacitor switches, sectionalizers, and ring main units.

The R & D we have undertaken has led to a continually improved VI product; for example the size of our modern VI is markedly smaller than ones built in the 1960's and the capability is greatly increased.

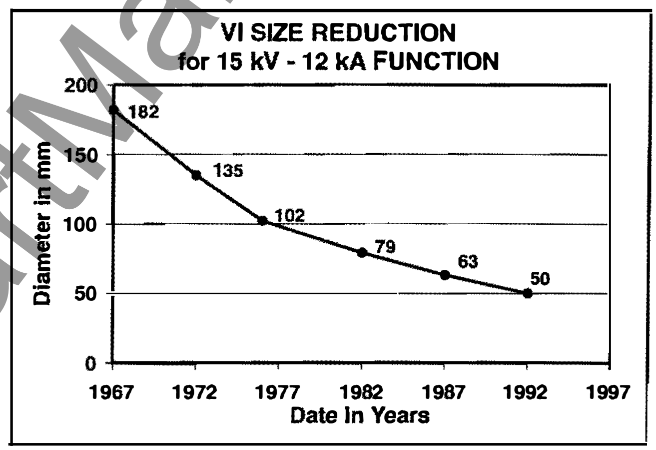

Fig. 1: Vacuum Interrupter Size Reduction for the 15kV, 12kA Function: Cutler-Hammer's Experience

Figure 1 shows an example for the 15kV, 12kA function. Here it can be seen that the diameter of the VI has been reduced from 180 mm In 1967 to 50 mm in 1997. This size reduction has resulted from our increased knowledge of vacuum technology, vacuum processing, vacuum contact materials [2], vacuum arc control [3,4] and VI design [5, 6].

The application of the VI to protect power distribution circuits has also grown in this time period as shown in Fig. 2. In fact, the acceptance of the vacuum circuit breaker (VCB) has been such that it is now recognized as having the highest level of reliable performance and the lowest level of required maintenance of all technologies available to control and protect distribution circuits. The design philosophy at C-H has always been and continues to be the application of the VI to the widest possible range of international application. This means that we have developed a thorough knowledge of all certification testing standards. When C-H works with an OEM in a given country, we make sure that the VI we supply will perform satisfactorily during that country's certification test series. C-H has VI's that can be applied in equipment designed to meet Chinese (DL & GB), IEC, ANSI, BS, VDE, and other standards. This does, of course complicate our development process, but we are proud to say that there is a C-H VI design that will meet any of the international certification tests in the voltage range from <1kV to 40.5V.

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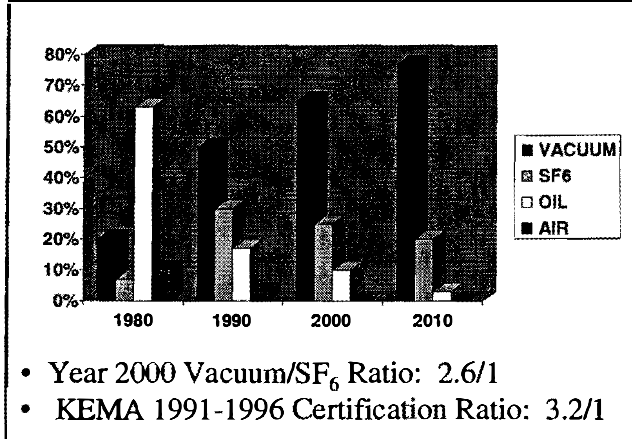

Fig. 2: World Wide Trend for Interrupters Used In Medium Voltage Circuit Breakers And Reclosers

The present worldwide consensus is that the VCB and the vacuum recloser will be the dominant technology in the first two decades of the twenty-first century, even though the SF_6 gas technology, primarily developed for transmission circuits (≥72kV), has been downsized to compete for the distribution protection market. There are three major areas where it is becoming increasingly difficult for SF_6 to compete with vacuum.

(1) Long life – it is now possible to produce cost-effective VI designs having electrical lives that exceed the required mechanical life of the circuit breakers, and will even be able to satisfy a recent IEC requirement of extended short-circuit operating life;

(2) Environmentally benign – VI's are constructed from environmentally benign materials. They do not provide a potential source of greenhouse gas (SF_6) that can enhance global warming [7]. The VI does not pose the potential health risk that exposure to arced SF_6 gas does [8], nor does it need the special hazardous waste handling that SF_6 interrupters require when routine maintenance is performed or when the SF_6 interrupter is disposed of at the end of its life; and

(3) Overall superior performance – this is a direct result of the extensive research and development that has been and continues to be performed by the universities and by the manufacturers of VI's [9].

This paper provides a background to the reader for the application of the VI to the protection and the control of power distribution circuits. It will also provide the potential user of this technology with a broad guide to the literature on these applications [5, 10-12]. The purpose is twofold: firstly, to provide the user with knowledge of the ability of the VI to satisfy all distribution circuit switching requirements, and secondly, to address some misconceptions of VI performance.

2. HIGH VOLTAGE VACUUM INTERRUPTER DESIGN

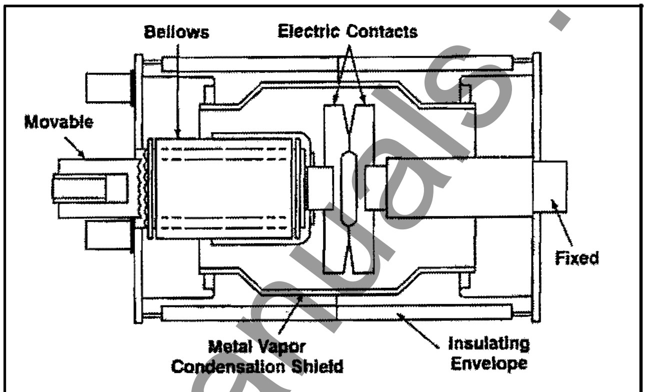

Fig. 3: Cross Section of a Vacuum Interrupter

A cross section of a vacuum interrupter is shown in Fig. 3. The contact material development and the design of the contacts have been well documented [2, 13]. Modern VI's using state-of-the-art vacuum-sealing techniques, such as vacuum furnace brazing [14], are built to retain their state of high vacuum for their entire lives: typically at least 30 years. One characteristic of vacuum brazing is that seal leaks are usually evident very early in the life of the VI. Cutler-Hammer therefore performs extensive quality assurance testing to identify those few VI's that have defective seals. Examples of this testing are high-pressure gas storage, vacuum measurement, and voltage withstand. This testing ensures that VI's reaching the field have an extremely high probability of maintaining their high vacuum condition. Table I shows another manufacturer's experience of VI reliability from 1970 to 1975 [15]. In our experience, once a VI has been in the field from three to four years, it will continue to be vacuum tight for life. Also, in these first few years, there is less than one chance in 100,000 of a vacuum leak occurring.

TABLE I: Statistics of Vacuum Life

YEAR OF MANUFACTURE	NUMBER	VACUUM LIFE, YEARS		
		<80	80 - 160	>160
1970 - 1971	9000	0%	19.3%	80.7%
1972	500	0%	1.6%	98.4%
1973 - 1975	3000	0%	1.5%	98.5%

There are two major aspects to VI design: (a) the high voltage design, and (b) the current interruption design. In this section we will consider the high voltage design and in the following sections we will consider current interruption under different circuit conditions. C-H VI's are designed to operate at the normal system voltages listed as preferred in the applicable standards. In addition, they are designed to satisfy the overvoltage withstand requirements for these system voltages, i.e.

(a) Rated AC power frequency withstand voltage.

(b) Rated lightning impulse withstand voltage.

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These ratings establish a conservative safety factor in the design to provide for an ability to withstand occasional overvoltages that can occur in a power system from normal switching operations, or from more abnormal natural causes such as lightning. These overvoltage withstand ratings can be expressed as multiples of the rated system voltage. At distribution levels of 3 to 72 kV these multiples are as follows:

Rated Overvoltage	Multiple Of The Rated System Voltage Or Normal Operating Voltage
Rated AC Power Frequency Withstand Voltage	2 to 4 times
The Rated Lightning Impulse Withstand Voltage	4 to 12 times

The test to demonstrate the ability to withstand the rated AC power frequency withstand voltage (sometimes called a Hipot test) is a deterministic test, that is, the test voltage must be withstood for 1 minute with no breakdowns. This is a simple pass or fail definition and at the stress level of 2 to 4 times the normal operating voltage, the AC hipot test is readily passed by properly designed and conditioned VI's. In contrast, the test to demonstrate the ability to withstand rated lightning impulse withstand voltage is a statistical test, that is, 1 or 2 breakdowns are permitted in a group of a certain number of tests. The impulse test is also readily passed by properly designed and conditioned VI's, but this test's criteria are tolerant of the occasional breakdown at the rated impulse voltage. In fact, according to the testing standards, a component satisfies the lightning impulse requirement when it withstands the rated impulse voltage about 90% of the time. The values of these two test overvoltages do not ensure that all possible overvoltages will be withstood, but the requirements do provide that the power circuit will be protected from the most typical overvoltages that can occur in service.

2.1 High-Voltage Vacuum Interrupter Design – Internal Design

The development of C-H VI's that satisfy the voltage withstand requirements has been greatly assisted by the advent of powerful, comparatively low cost, personal computers, and user-friendly finite element analysis (FEA) software. This has enabled Cutler-Hammer design engineers to routinely perform FEA on both electrical and magnetic fields, with the result that changes in design can be rapidly analyzed and compared to design rules established over the years by empirical methods. Figure 4 shows a typical two-dimensional potential plot for an experimental vacuum interrupter. As the computers have become more powerful, it is now possible to perform three-dimensional analysis. This type of analysis has been instrumental in optimizing the spacing between the vacuum interrupter components so that the development of vacuum interrupters capable of operating in sub-transmission circuits at 72kV [16] and at transmission voltages [17] has become possible. Using VI's in series we have, in fact, already demonstrated effective circuit breaker performance at 145kV [18]. We show in Table II C-H VI designs that have been successfully tested for operation at the distribution voltage range, 35kV – 40.5kV.

TABLE II: Cutler-Hammer Vacuum Interrupters for Circuit Breaker Application at 35kV – 40.5kV

VI DIA	CONTINUOUS CURRENT RANGE	SHORT CIRCUIT CURRENT RANGE	AC WITH-STAND VOLTAGE	IMPULSE WITH-STAND VOLTAGE
Mm	Amps	kA	kV, rms	KV
63	630 - 800	8 - 12.5	80	170
75	630 - 1250	12.5 - 16	80	170
102	630 - 1600	16 - 25	95	170 - 200
135	1250 - 3150	25 - 40	95	170 - 250

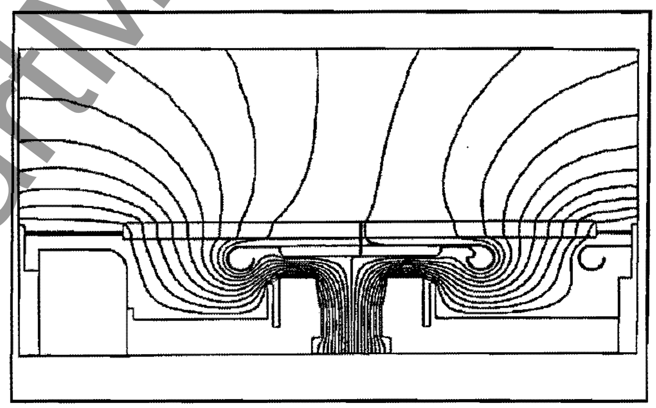

Fig. 4: Finite Element Analysis of a Floating Shield Vacuum Interrupter Showing the Equipotential Lines

For circuit breakers, the most important reasons to withstand voltage are to prevent:

- Phase-to-ground breakdowns,
- Phase-to-phase breakdowns, and
- Line-to-load breakdowns.

Phase-to-ground, phase-to-phase and line-to-load breakdowns external to the interrupter represent outright failures to support voltage and the design objective should be to avoid these within the required rating of the circuit breaker. As noted before, the power frequency withstand voltage provides a deterministic requirement to withstand higher than normal AC voltages up to 2 to 4 times the normal rated operating voltage of the circuit breaker. At the much higher stress of the lightning impulse voltage level, the statistically defined withstand abilities of all the equipment in a power system provide a reasonable level of confidence that undesired breakdowns will not occur. Moreover, protective elements, such as spark gaps and surge arresters are located at many points in the power system to keep the actual lightning caused overvoltages down to levels where the probability of a breakdown is extremely low.

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In service, circuit breakers are usually closed to serve their loads and are not left open for long periods of time. So overvoltages such as lightning are mostly seen by the line to ground or line to line insulation. When circuit breakers are to be open for a long period of time most are isolated from the system by disconnect switches or are racked out of their primary disconnect contacts especially in situations where maintenance is to be performed. In this case they will not be exposed to overvoltages nor are they used to provide the primary isolation.

In the cases where circuit breakers are open in service to separate two parts of a system, the vacuum breaker is unique in being able to provide a final measure of security that is not seen in most other types of circuit breaker. If the statistically rare event occurs that a high lightning impulse voltage above the breaker rating is applied across an open vacuum circuit breaker and is followed by an internal breakdown between the open VI contacts, then only a ½ cycle of current will flow that will be quickly interrupted by the open vacuum interrupter at the first current zero. So the circuit breaker can then be considered to have essentially preserved the open status of the power circuit. VI's are unique in being able to interrupt such a current, even when the contacts are in the full open position, because they do not require motion to accomplish the interruption. Thus, even if a breakdown does occur occasionally and results in a power frequency current, the VI will clear the circuit at the next current zero. This behavior is not seen in other techniques such as minimum oil, air magnetic or SF6 puffer interrupters. The VI, therefore, has a major advantage over other interruption technologies. Not only does it have excellent high voltage withstand capabilities, but it can also interrupt current flow in the open position.

Conditioning at high voltage is a normal part of the C-H manufacturing process for every VI. The contacts of the interrupter are opened to form a gap and the interrupter is then subjected to a high voltage from a high impedance source for many minutes. A great many discharges involving small currents from the high impedance source occur with decreasing frequency during the conditioning time as microscopic sharp spots are smoothed over or small particles on the contact surfaces are destroyed by the discharge currents. As a confirmation of the conditioning results, an impulse voltage test is then performed on the interrupter while the contacts are still in the open position. The test voltage is chosen to be typically around 10% greater than the rating. During the life of the VI when operating under load current, the VI is continually being conditioned; i.e. the arcing that accompanies a load- current switching operation reconditions the contacts and helps the VI maintain its high voltage performance throughout its life. Similar conditioning also occurs during the opening operation under short circuit currents as well.

A temporary deconditioning of the impulse voltage withstand ability in VI's can, however, also occur. Deconditioning can take place when the VI is opened and closed with no passage of current. This can happen when a new VI is installed in a circuit breaker and it is operated mechanically [19]. When the VI contacts open and close without current, rough spots may be introduced on the contact's surfaces. These rough spots may sometimes result in one or more breakdowns at impulse voltages less than the design rating of the VI. Therefore, before certification testing is done to demonstrate the impulse voltage withstand ability of the circuit breaker, it is typical to apply some high voltage pulses to the open vacuum interrupters in order to recondition the contacts, thus restoring their full ability to withstand impulse voltages.

2.2 Impulse Voltage Testing on the Vacuum Interrupters in a Circuit Breaker

Each interrupter in a vacuum breaker should be tested in the following manner. Preliminary tests should be performed starting at a fraction of the rated impulse withstand voltage. These preliminary tests provide some reconditioning of the vacuum interrupter to smooth sharp spots produced by mechanical touching of the contacts. In addition, the preliminary tests are especially important whenever changing from one polarity to the opposite to remove and reverse the charge that builds up on the floating vapor shield during the testing at the first polarity. Any disruptive discharges that occur in the preliminary trials at less than rated voltage are not counted in the statistics for pass/fail determination at the rated impulse voltage.

The sequence of the tests in Table III is recommended. This sequence is based on the ANSI/IEEE and IEC impulse voltage test methods described in the relevant switchgear standards. ANSI/IEEE has used a method called the 3x3 method (pronounced "3 by 3") for many years, while IEC has used the 2x15 method. A compromise method called the 3x9 method is now the standard method In the newest revisions of ANSI/IEEE standards, and is an acceptable alternative method in IEC standards. These test methods are explained below.

<u>3 x 3 Impulse Voltage Test Method [20]:</u>

STEP 1: Apply 3 Impulses Of A Desired Crest Voltage.

- If all 3 impulses are withstood, then the device has passed the test.
- If two disruptive discharges are observed in the 3 impulse trials, then the device has failed the test.
- If one disruptive discharge is observed in the 3 impulse tri als, then perform 3 more tests in Step 2 at the same crest voltage.

STEP 2: Apply 3 Additional Impulses Of The Same Crest Voltage (Only If 1 Disruptive Discharge Is Observed In Step 1)

- If all 3 additional impulses are withstood for a total of 1 dis ruptive discharge in 6 tests, then the device has passed the test.
- If a second disruptive discharge is observed, then the device as failed the test.

<u>3 x 9 Impulse Voltage Test Method [20, 21]:</u>

The 3 x 9 method is the same as the 3 x 3 method except for 2 changes:

- The number of additional impulse trials to perform is 9 if there is one disruptive discharge in the first 3 impulse trials, and
- If all 9 additional impulses trials are withstood for a total of 1 disruptive discharge in 12 tests, then the device has passed.

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2 x 15 Impulse Voltage Test Method [21]:

Apply 15 impulse trials of a desired crest voltage:

- If no more than 2 disruptive discharges are observed for a total of 2 disruptive discharges in 15 impulse trials, then the device has passed the test.

Figure 5 shows the breakdown rate for many C-H VI's designed to operate at impulse voltages up to 170V compared to the permitted breakdown rate allowed in the ANSI and IEC standards. It can be seen that while conditioning breakdown events did occur, the overall rate was lower than permitted by the standards.

The fact that a vacuum interrupter occasionally can break down on the application of an impulse voltage that is lower than the rated value during developmental testing presents no problem for vacuum circuit breakers in service on power distributions systems. There are a number of reasons for this:

(a) The VI contacts are conditioned each time the breaker operates under load.

(b) Surge protection in the distribution circuit usually keeps the observed impulse voltage low.

(c) Breakdown in two phases at the same time in an ungrounded system is statistically rare.

(d) The circuit breaker or recloser is normally closed (it is in the circuit to protect from faults caused by lightning strikes elsewhere in the circuit).

(e) If current does flow, the open VI's will interrupt the power follow current within one half cycle. Once the current is interrupted the open status of the circuit will be maintained.

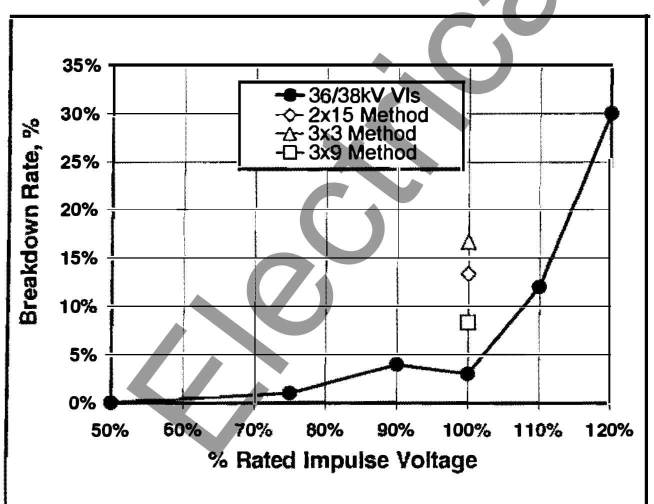

Fig. 5: Breakdown Rate in % vs % of Rated Impulse Voltage for 36/38kV VI's With 170kV BIL

TABLE III: Recommended Voltage Steps for Impulse Testing

Recommended Testing	Voltage	Test Voltage Applied	No. of Trials
INITIAL	POLARITY	% OF RATED	
Preliminary	Positive	50%	3 Note 1
	Positive	75%	3 Note 1
	Positive	90%	3 Note 1
Cerification	Positve	100%	N Note 2
REVERSE	POLARITY		
Preliminary	Negative	50%	3 Note 1
	Negative	75%	3 Note 1
	Negative	90%	3 Note 1
Certification	Negative	100%	N Note 2

Notes to TABLE III

Note 1: If a disruptive discharge occurs in one of these Trials, then use the 3x3 method at this voltage or, for more conditioning, perform additional trials at the same voltage until 3 to 5 impulses are withstood in a row.

Note 2: The number of trials performed at the rated impulse withstand voltage depends on the standard used.

For IEC tests to IEC standard 62271-100 and 60694 and 60060-1:N = 15 and Pass $\leq$ 2 breakdowns in 15 trials., i.e. <13.3%.

For ANSI tests to C37.09 and IEEE Standard 4:N = 3 or 6 and Pass $\leq$ 1 breakdown in 6 trials, i.e. <16.6%.

For both ANSI and IEC Standards, recent revisions: N = 3 or 12 and Pass $\leq$ 1 breakdown in 12 trials, i.e. <8.3%.

2.3 High-Voltage Vacuum Interrupter – External Design

FEA has evolved into an extremely useful design tool for optimizing the internal design of high-voltage vacuum interrupters. It has also been useful in developing VI's with a more uniform stress across the outside of the VI as is shown in Figure 4. It is essential to consider the external stress on the VI, because it is imperative that once the VI has opened that any circuit voltage impressed on the VI does not cause a breakdown across the outside of the VI's body. Looking at Figure 4, there are three things to consider in the external design.

(1) The length of the ceramic between the two end plates.

(2) The creep distance along the ceramic.

(3) The dielectric medium in which the VI will be housed.

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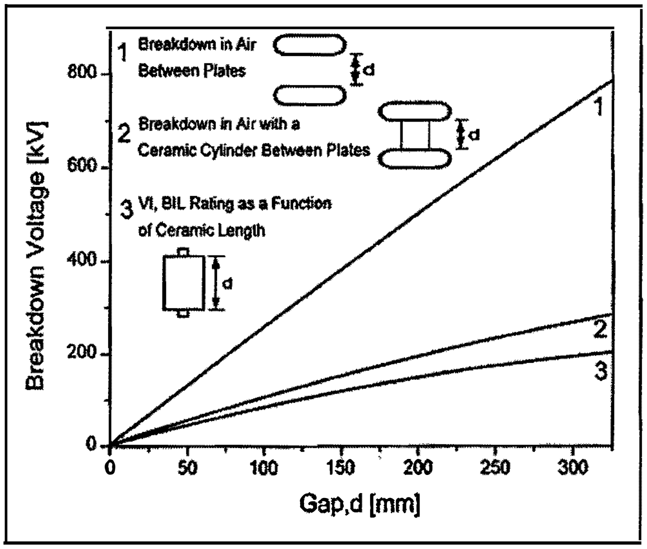

Fig. 6: Comparison of the Voltage Breakdown As a Function of Gap of Parallel Plates In Air, Parallel Plates With a Right Ceramic Cylinder Between Them, and the Length of VI Ceramic Used to Withstand a Given BIL Rating in Air.

The ceramic length

Figure 6 shows the breakdown strength of an air gap between two shaped plates. At 10 mm the breakdown is 31kV (or 3.1kV/mm), and at 300 mm the breakdown is 735kV (or 2.54kV/mm). If a right cylinder of ceramic if placed between the shaped plates, then the breakdown voltage is decreased dramatically. Now a 10mm gap will only have a breakdown voltage of 16kV (1.6 kV/mm), and at 300mm the breakdown voltage will be only 270kV (or 0.9 kV/mm). The lowering of the breakdown voltage results from a number of effects: collection of charge on the ceramic surface, higher field stresses at the ceramic to metal interface, condensation on the ceramic surfaces, etc. From these data it is wise to allow a 'safety factor' of at least 3 over the air breakdown value when a ceramic cylinder is placed between the plates. The maximum voltage that a VI is subjected to is the lightning impulse voltage. For standard test purposes, a lightning impulse voltage is simulated by a 1.2 x 50 microsecond voltage wave. The Basic Insulation Level (BIL) is the lightning impulse voltage that a device can withstand approximately 90% of the time. As we have already discussed in Section 2.2, it is imperative that an open VI in a circuit breaker does not flash over externally when subjected to its rated impulse voltage. The C-H experience of ceramic length required to completely satisfy the BIL requirements is also shown in Fig. 6. It shows that the design criterion C-H uses is somewhat conservative. The ceramic length for the VI is always more than the experiment of a right cylinder between two plates would suggest. Figure 7 shows examples of two VI's, one rated for 110kV BIL and the other rated for 150kV BIL.

The creep distance

The creep distance is the distance along the ceramic between the end plates. One way of expressing the creep distance is in mm/kV, where the total length L expressed in mm is divided by the rms line to line voltage. So in Fig. 7 the shorter VI with a ceramic length of 158 mm is suitable for use in a 17.5kV circuit, and thus has a creep value of 9 mm/kV. The longer VI with a ceramic length of 198mm can be used in a 27kV circuit, and thus has a creep value of 7.3mm/kV. These creep values have been found to be extremely reliable for use in both indoor and outdoor circuit breakers where there is very low probability of both water condensation and the deposit of atmospheric pollution on the ceramic surface. For applications where severe atmospheric pollution is common in urban and industrial areas and/or where water vapor condensation on the ceramic can occur, more conservative creep values can be used than has been the standard practice up until the present. For example, the Chinese creep values are about 2 times those calculated in the VI examples shown in Fig. 7. The new Chinese creep standard considers both the condensation effect and the pollution effect around metal enclosed switchgear. These effects are characterized as follows:

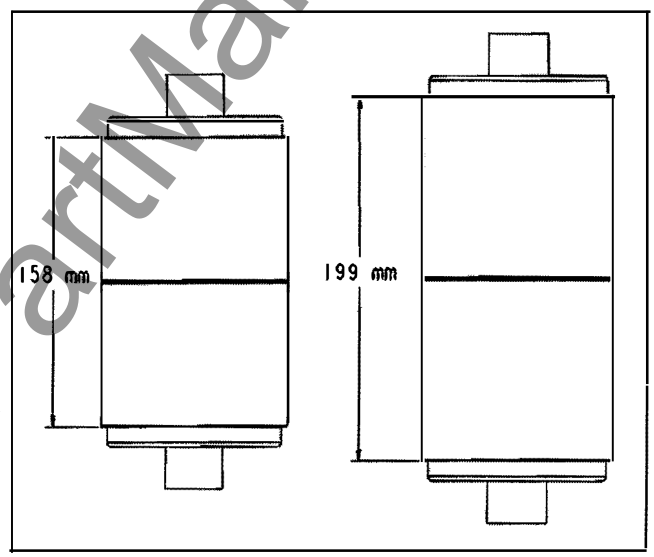

Fig. 7: Examples of Vacuum Interrupters With Two Ceramic Lengths, the Shorter VI has a BIL Rating of 110kV and the Longer One has a BIL Rating of 150kV.

Condensation Classification

Class	Description	Frequency
C_o	Condensation does not normally occur	$\leq$ 2 times / year
C_l	Condensation occurs with low frequency	< 2 times / month
C_h	Condensation occurs frequency	> 2 times / month

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Pollution Classification

Class	Description
P_o	No pollution
P_l	Light pollution
P_h	Heavy Pollution

Taking into account that in China P_o is unrealistic and that manufacturers should be conservative if the pollution deposit is corrosive, three degrees of service are defined as follows:

Degree 0 (D0): $C_o P_o$

Degree 1 (D1): $C_l P_l$ Or $C_o P_h$

Degree 2 (D2): $C_l P_h$ Or $C_h P_l$ Or $C_h P_h$

The desired creep values that correspond to these degrees of service are given in Table IV.

TABLE IV: Recommended Creep Values for Interrupters in Chinese switchgear

SERVICE CLASS	CREEP VALUE MM / KV	
	INSULATION TYPE	
	Ceramic	Organic
D0	14	16
D1	16	18
D2	18	20

Since an interrupter manufacturer has to respond to the worst case creep value, C-H uses 18mm/kV for ceramic envelopes and 20mm/kV for those that use organic insulation.

If the straight ceramic shown in Fig. 7 were used, then for 12kV service a ceramic length of 216mm would be required, and for 40.5kV service a length of 729mm would be needed. These lengths are impractical, however, because they do not address the advantage of compactness that the VI has to offer. The way to achieve the creep value and maintain a compact VI length is to use a contour-wave ceramic. Here grooves are cut into the ceramic that allow for a longer path along the ceramic surface, while at the same time permitting a compact length between the end plates. Figure 8 illustrates the C-H wave ceramic designs for 75mm, 102mm, and 135mm diameter VI's.

The dielectric medium

The vacuum medium inside the VI can withstand very high voltages with very small contact gaps. For example, a 10mm gap can satisfy a 1 minute withstand voltage of 50kV (rms) and a BIL level of 110kV, and a 18mm gap can satisfy a 95kV (rms) 1 minute withstand voltage and a 185kV BIL value. In order to manufacture compact switchgear it has been the practice to surround the VI with a dielectric medium such as oil or SF_6. The increase in the external dielectric insulation strength has two effects. The first effect is to permit the use of shorter VI's and the second effect is to allow a closer pole spacing. For example, a VI with a ceramic length of 150mm will only meet an external BIL value of about 120kV in atmospheric air. However, if it is placed in SF_6 or oil it will easily meet an external BIL value of 170kV.

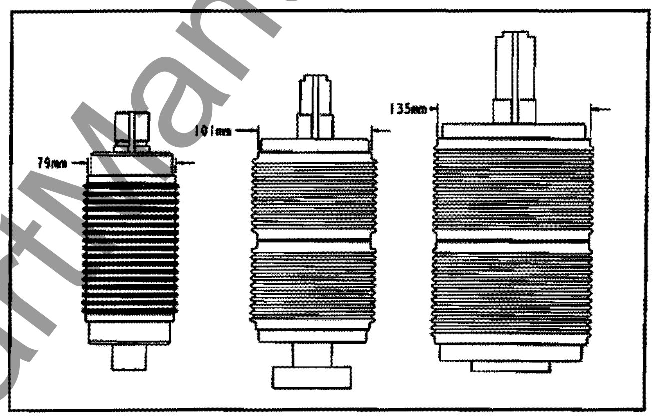

Fig. 8: Examples of Cutler-Hammer Contour Wave Ceramic Designs

Another approach for obtaining a higher external VI voltage rating is one that has been successfully used by C-H for more than 25 years. In this case a polyurethane material is used to surround the VI. Figure 9 illustrates an example with a ceramic length of 150mm. Without the potting this VI will meet a BIL voltage value externally of

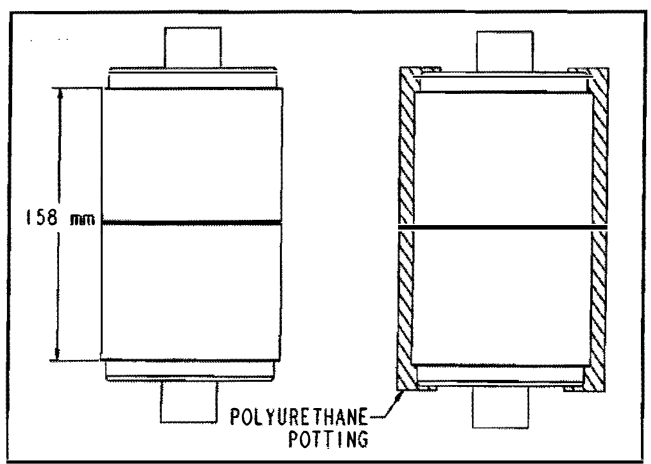

Fig. 9: Example of Using Polyurethane Potting to Increase the Voltage Withstand Rating for a mm Ceramic

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about 120kV, but with the potting, it is capable of a meeting a 170kV BIL value externally. It is also possible to use the "wave" approach with the potting material to give the required 20mm/kV required for the severe service class creep value. While potting the VI produces a compact VI, the whole circuit breaker surrounded by atmospheric air will still not be as compact as the designs surrounded by oil or SF_6.

Oil, because of its fire hazard, is slowly being phased out as an insulation on high-voltage switchgear. SF_6, while still being used, is recognized as a greenhouse gas. Accordingly, a number of new, compact vacuum circuit breaker and recloser designs are being developed using solid insulation. There are two approaches; these are illustrated in Fig. 10. The first takes a VI and encases the VI and its associated bus in a solid dielectric such as epoxy or hard polyurethane. The second takes a solid insulation housing connected to the bus, and the VI is attached to the fixed and moving bus assemblies. The space between the VI and the solid insulator is then filled with a material such as polyurethane which completely fills the void between the VI and solid insulator. In both cases the outside of the insulator will be designed to satisfy the required creep values. This type of structure in recent years has become popular for outdoor reclosers [22]. There has also been a gradual increase in interest for using this technique for compact indoor circuit breakers [23].

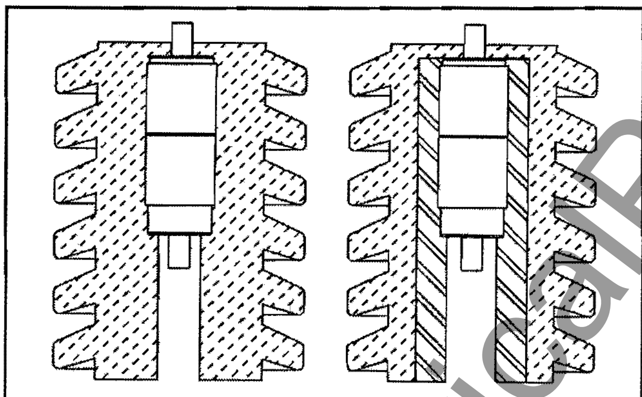

Fig. 10: Vacuum Interrupter Inside Solid Insulation (a) Potted Directly Into an Epoxy or Polyurethane Insulation, (b) Encapsulated in An Insulating Outer Shell With a Secondary Operation Using a Polyurethane or Other Insulating Material

3. CHOP CURRENT

Current chop is a subject that has been exhaustively investigated and discussed since the early 1960's and is often cited by advocates of competing technologies as a major disadvantage of the VI. It is, however, no longer a concern with state-of-the-art VI's using the latest developments in contact material and VI processing technology. In fact, the arc in all types of interrupters (oil, SF_6, air, and vacuum) becomes unstable just before the natural current zero in an AC circuit. The instability causes a sudden collapse of the current to zero. This phenomenon, known as current chop, is a function of the arc and the circuit parameters. It has been shown [24], for example, in oil, SF_6, and vacuum breakers that chop is predominantly governed by the effective capacitance in parallel with the circuit breaker. Figure 11 taken from [24] gives a comparison of chop current from these three different technologies. For a 12kV circuit, the typical capacitance value is between 0.001 and 0.01 μF.

Perhaps the concern about current chop levels of VI's results from the memory of the initial introduction of VI's which used a Cu-Bi contact material. This material did exhibit chop currents from 8 to 25 A. Since 1970, however, most VI manufacturers have come to use the Cu-Cr material first developed by Westinghouse for circuit breaker and recloser applications. The present Cu-Cr contact material used by C-H has an average chop current of about 3 A and a maximum value of about 5 A.

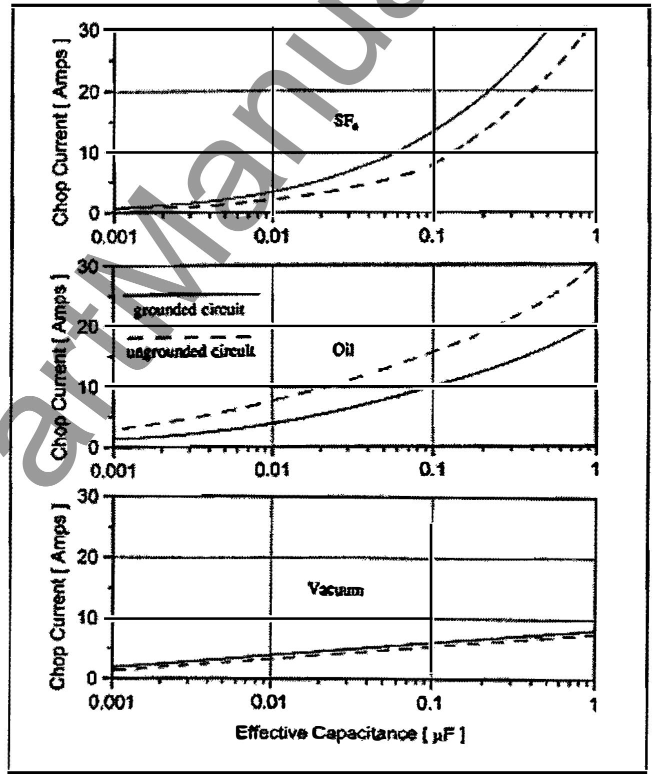

Fig. 11: Comparison of Chop Current Characteristics For Vacuum, SF_6, and Oil Interrupters

The effect of a current chop is mainly observed as a modification to the transient recovery voltage (TRV). As such, the voltage is a relatively slow transient reaching a crest voltage in many microseconds, rather that a fast transient with a short wavefront surge type of voltage that reaches its crest voltage in 1 microsecond or less. As an example, the effect of a 6 A current chop in an inductive circuit on the transient recovery voltage across an open interrupter is shown in Fig. 12 [25]. Here two realistic cases are drawn: the one line shows the TRV with a negligible chopping level and the other line shows the TRV with a 6 A chopping level. Note that in the case with no current chop, the TRV starts at zero and increases in a polarity opposite to that of the preceding current that was just interrupted. In contrast, in the case with current chopping, the TRV starts at zero but initially increases in a polarity that is the same as that of the preceding current that was just interrupted. Then the TRV changes to a polarity opposite to that of the preceding current that was just interrupted, and, moreover, that due to

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current chopping, the TRV peak then reached is higher than the case without current chopping. However, this first peak of TRV, even with this extreme level of chop current, is only 20% higher than the value expected with zero chop current. Such a modest increase in the peak voltage is not of concern for load insulation.

Thus, with the contact materials used in modem VI's, current chopping is not of concern when considering surge protection.

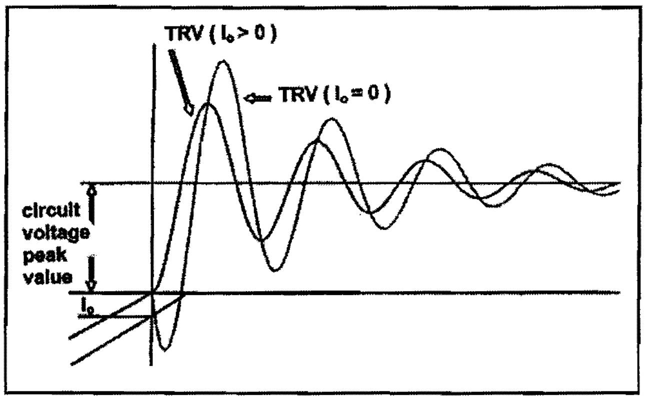

Fig. 12: Transient Recovery Voltage After Inductive Load Switching With and Without Current Chopping (I_o)

4. LOAD CURRENT SWITCHING

The performance of the VI for load switching is truly outstanding. For currents below about 5 kA, the diffuse vacuum arc is formed between the opening contacts [26]. This arc is characterized by multiple cathode spots moving randomly across the cathode contact and a passive anode contact collecting current uniformly across its entire surface [5]. This vacuum arc will always interrupt the AC current at the first current zero after a contact gap that will withstand the recovery voltage has been reached. Contact erosion is only observed on the cathode and is quite uniform over the cathode surface. For modern contact materials like Cu-Cr [27], the erosion is between 0.04×10^{-4} and 0.4×10^{-4}g.C^{-1} (grams/coulomb). In this case $C = \int I\,dt$ and the integral is taken over the complete arcing time, i.e., from the time the contacts part and the arc is initiated until the arc is extinguished at a current zero. The exact value depends upon the contact spacing and the fraction of material eroded from the cathode that is deposited upon the anode. In an AC circuit, the contact parting event occurs at random with respect to the current. Therefore, the contacts are a cathode on some switching operations and an anode on other switching operations, so that material eroded from one contact and deposited upon the other, would be redeposited on the original contact during a subsequent operation [27]. Using this erosion rate and knowing the size of the contacts of the VI, it is easy to show that the electrical switching life of the VI's used in circuit breakers and reclosers far exceeds the usual mechanical life of these devices. Indeed, VI's are now beginning to be used for electric railroad switching systems where electrical and mechanical lives of 250,000 operations are required. Of course, C-H has developed contactor VI's for motor control where switching lives in excess of 10^6 operations are regularly observed.

For the user of a very-long-life interrupter, it is essential for the contacts to maintain a low and constant contact resistance (R_c) for their whole life. The VI contact with its uniform erosion and with the lack of an ambient gas will, indeed, maintain a low and constant R_c in a manner that cannot be matched by any other interrupter technology. Users of SF_6 interrupters, for example, have experienced increases in the value of R_c as the interrupter is operated under load. This is a consequence of the chemical processes that take place on the contact surfaces, between the contact metal and the SF_6 gas, during and after arcing, each time the interrupter is operated. In addition, metal fluoride powders, which are insulating and are produced as arcing by-products, can in some designs interfere with contact mating and thereby cause an increase in contact resistance. So vacuum with its preserved clean interior is much better at preserving a low resistance, coolly operating contact interface.

5. SHORT CIRCUIT INTERRUPTION

In addition to outstanding performance in interrupting normal load currents, the C-H VI also has demonstrated superior performance in interrupting short circuit currents. VI designs are commercially available that interrupt short circuit currents from 2kA (rms) to 63kA (rms).

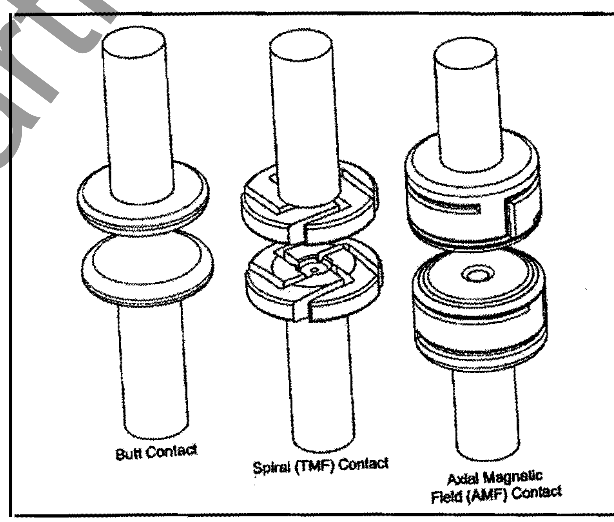

Fig. 13: Contact Structures Used In Vacuum Interrupters

The high current vacuum arc naturally tends to form a constricted column [5]. Thus in VI's designed to interrupt currents above approximately 5kA, this high current arc has to be controlled with a contact design. There are two main types of contact designs; one that causes the arc to rotate around the contact surfaces [3] by using a transverse magnetic field (TMF) and the other that forces the arc back into the diffuse mode by use of an axial magnetic field (AMF) [4], see Fig. 13. Figure 14 shows the present interrupting ability of the two contact structures as a contact function of contact diameter in a 12kV circuit. For 35kV-40.5kV applications C-H uses the axial magnetic field contact structure exclusively. The AMF structure is preferred because it is possible to shape it for the best possible high voltage performance and also because this shape is maintained even after short circuit interruption. Each contact design has its advantages and each has the ability to provide long life at the full short circuit rating of the device; VI designs are available that can perform up to 100 full short-circuit operations. For short-circuit operation of greater than 100 operations

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axial magnetic field contacts are usually required. In practice, even a fault that is 80% of the full fault rating is a rarity in normal distribution circuits, and most faults are of much lower value. Thus, the life of the VI will easily exceed the short-circuit life requirements of any practical distribution circuit. VI's also have no "blind spots" or "critical currents," i.e., there is no current from the smallest load current up to the full short-circuit current where the interrupter has difficulty interrupting. Beyond their full short-circuit rating, the probability of failure to interrupt gradually increases [28]. If a VI is forced to switch a current up to 125% of its rating and if a backup breaker removes the fault within a reasonable time, the VI will suffer little permanent damage and will subsequently interrupt currents up to its rating without difficulty. This distinguishes the VI from other technologies which have fairly well defined interruption levels and arcing times. When SF_6 or oil filled devices are operated at currents beyond these limits, they will, at the best, be permanently damaged and, at the worst, will cause an explosion in the switchgear housing.

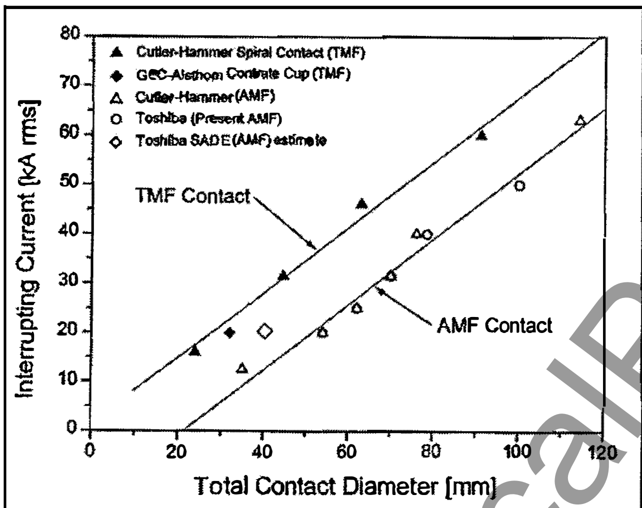
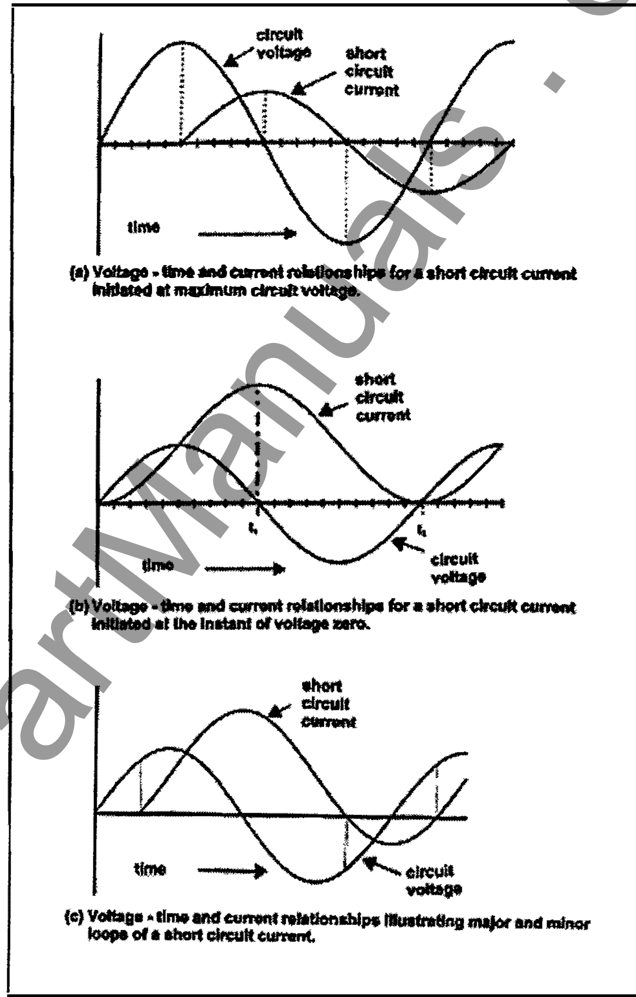


Fig. 14: Comparison of the Interruption Ability of Tansverse Magnetic Field and Axial Magnetic Field Contacts as a Function of Total Contact Diameter in a 12kV Circuit

When interrupting short circuits the interrupter must be able to deal with the asymmetric current that will occur on one or more of the phases in a three-phase fault. Figure 15 illustrates the asymmetric current wave in one phase [29] once the contacts in a circuit breaker open an arc is formed. The arc permits the flow of current in the circuit until a natural current zero occurs. If the conditions are favorable at the current zero the arc in the interrupter will be extinguished and the circuit will be interrupted. Traditionally, the arcing time for a circuit breaker has been characterized in terms of a minimum value and a maximum value. The concept of minimum and maximum arcing times are, however, highly dependent on the interruption technique and the interrupting conditions, especially the current magnitude and degree of asymmetry. Each interruption technology has its own unique requirement when arcing times are considered. When testing a circuit breaker to demonstrate its rating, it is required to demonstrate performance at the minimum arcing time, at the maximum arcing time and an average arcing time. For SF_6 or oil circuit breakers, the maximum arcing time is approximately equal to the minimum arcing time plus the time interval of ½ cycle of the power frequency. The time interval between the minimum and maximum arcing times is often referred to as the interrupting window. This window is an interval during which interruption



(a) Voltage - time and current relationships for a short circuit current initiated at maximum circuit voltage.

(b) Voltage - time and current relationships for a short circuit current initiated at the instant of voltage zero.

(c) Voltage - time and current relationships illustrating major and minor loops of a short circuit current.

Fig. 15: Examples of Short Circuit Current Waveforms For Short Circuits Initiated at Three Different Voltage Conditions

must successfully take place before the interruption effort is fully expended and interruptions after this time are no longer possible. If the arcing were to continue past this time, the SF_6 or oil breaker would fail. Demonstrating performance at the maximum arcing is especially important for interrupters such as SF_6 puffers that run out of the gas flow required to produce arc interruption when the full open position is reached. So the concept of an interrupting window during which interruption is possible is extremely important for some interrupter technologies. If the interrupting window is too small to cover the range from the minimum arcing time of the interrupter to the maximum that the system imposes, then the circuit breaker will not work successfully under all possible conditions.

For vacuum circuit breakers, on the other hand, the concept of the interrupting window is not as applicable since contact motion is not required for interruption to take place. Once some minimum contact gap is reached, arc interruption is affected by the geometry and materials of the contacts, the vapor shield and the degree of vacuum present inside the interrupter at current zero. Once the full open gap is reached, the arcing can continue for some time until an appropriate current zero

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arrives and interruption occurs. So the maximum limit on arcing time is not determined by the mechanical travel time, but is more a function of the amount of arc energy that can be absorbed within a particular interrupter. In fact, vacuum interrupters can be applied at quite low power frequencies such as 10 Hertz when the arcing times must be much longer since an ½ cycle is 50 milliseconds, provided the total arc energy is maintained within acceptable limits.

For vacuum circuit breakers, arcing times are generally short at normal power frequencies such as 50 or 60 Hertz. However, interruption at any one particular current zero is a statistical event, especially near the upper limit of current rating, and when the current wave is asymmetrical. The arcing times for a vacuum circuit breaker can range from very short values to much longer values. The minimum arcing time is generally about 3 or 4 milliseconds, but times as short as 1 or 2 milliseconds are occasionally observed. Maximum arcing times of 20 milliseconds or more have been observed. However, it is far more likely to observe an arcing time between 3 and 14 milliseconds with a value of 8 to 10 milliseconds (or ½ cycle) being the most common. It is no coincidence that the time required for the interrupter contacts to reach a value between 75% and 100% of full open point is also about ½ cycle. In addition, the distribution of arcing times tends to trend toward longer values as the current approaches the limit of performance for a particular interrupter.

One interesting characteristic of a VI when interrupting an asymmetric current wave is that the probability of interruption after the end of a major loop, where the current magnitude is at its highest, is about 50%. Interruption will usually occur at the end of the following minor loop where the current magnitude is much lower. As a result, if one attempts to demonstrate a maximum arcing time where the final current loop is a major loop, the interrupter may simply skip this current zero and a different pole will be the first to clear. Finally, the intended pole then will clear the remaining single-phase current in series with the third pole. This results in a maximum arcing time that is longer than the traditional value of the minimum arcing time plus the time interval of ½ cycle of the power frequency, however, this is perfectly acceptable as long as the circuit is in fact interrupted.

The three different methods of testing discussed below each present some challenges when attempting to demonstrate the maximum arcing time in a VCB.

- For 3-phase direct tests, the minimum and maximum arcing times are supposed to be demonstrated in the pole with the first pole to clear TRV. The TRV peak is appropriately reduced as a result of the phase shift of the current zero from being coincident with the peak of the system voltage by the effect of the current asymmetry. However, vacuum interrupters are non-deterministic in that they have a significant but definitely not 100% probability of interrupting with very short arcing times. So it is often observed that another pole will have a current zero with symmetrical current or a minor loop of current and will interrupt just before the pole with the asymmetry has its current zero. The non-deterministic nature of vacuum interrupters means that this behavior is not predictable. So in such tests, the pole with the required asymmetry may no longer be the first pole to clear and hence will have a lower TRV that the first pole to clear TRV. Such behavior is perfectly acceptable in the real world, because the VCB will behave this way in the actual power system. However, the non-deterministic nature of vacuum interrupters complicates the test demonstration by often requiring repeated tests in an effort to get one with the right combination of current asymmetry and first pole to clear TRV.

- For 1-phase direct tests, without the possibility of other phases complicating the situation, it is much easier to control the test conditions to provide the required asymmetry and the first pole to clear TRV in the same pole. Here again, the TRV peak is appropriately reduced due to the phase shift of the current zero from being coincident with the peak of the system voltage by the effect of the current asymmetry. The drawback is that this combination as noted above, may not actually occur in practice, and hence is really more severe test than is required in practice.

- For 1-phase synthetic tests, the test conditions can again be forced to provide the required asymmetry and appropriately reduced first pole to clear TRV in the same pole. However, the test engineer must choose at which current zero to apply the TRV. If the TRV is applied at the end of a major loop, then the interrupter may not interrupt. So a proper demonstration must then be to delay the application of the TRV to the next current zero which will be at the end of a minor loop. There can also be difficulty here in re-igniting the arc at the current zero after the major loop, because the TRV from the high current source is low and easily interrupted by the vacuum interrupter. However, in recent years test labs have been developing new systems to re-ignite the vacuum arc more reliably and efficiently. Also some test labs report that they can supply the proper TRV at more than one current zero. So with enough equipment, the real three-phase world can be simulated synthetically. In fact, some labs have even been able to perform 3 phase synthetic tests.

So demonstrating the maximum arcing time for a VCB can be a challenge.

VI's are capable of performing well for short-circuit situations where high degrees of asymmetry can produce long arcing times, e.g., small generator breakers and also for low-frequency transportation circuits of 16-2/3 Hz.

VI technology also has the outstanding ability to handle the developing fault. This is the situation where the value of the fault current suddenly increases during the time the breaker is opening to clear it. This can occur, for example, when a traveling arc changes a single line-to-ground fault into a double line-to-ground fault. Such events are easily handled by the VI, but they can destroy circuit breakers using other interruption technologies.

5.1 Voltages and Disturbances Observed During Interruption Testing

After the VI interrupts the current in a circuit during a test, the circuit imposes a voltage across the open contacts. In the first millisecond or so immediately following current zero, this voltage is called the Transient Recovery Voltage (TRV) and at later times this voltage is simply the Recovery Voltage. The TRV and Recovery Voltages are usually unaffected by the VI, however, occasionally, some disturbances are observed during tests that should be explained. Five TRV or Recovery Voltage conditions are described below ranging from the VI having no effect to the VI having a more significant on the circuit voltage.

(a) The TRV is withstood - At the first current zero after contact part, the TRV appears across the open VI contacts and is then withstood to successfully interrupt the circuit with no observed disturbances. This is the most typical condition seen during most tests.

(b) The TRV reignites the arc at the first current zero – Sometimes the gap at the first current zero is not large enough to sustain the interruption, and the TRV collapses at a time up to ¼ cycle of power frequency after the current zero. This is called a reignition. The current then flows to the next power frequency current zero where it is once again interrupted and this time the TRV is withstood. This too is a normal event and merely involves a longer arcing time.

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(c) The TRV is disturbed but withstood – Occasionally on a test, the TRV is seen to collapse and then instantaneously recover while no power frequency current is observed. If such a disturbance is observed at a time up to ¼ cycle of power frequency after the current zero, then this is referred to as a TRV disturbance that is considered a normal part of the arc interruption process.

(d) The Recovery Voltage is disturbed with no power current flow – Also on rare occasions during a test, the Recovery Voltage is seen to collapse and then instantaneously recover while again no power frequency current is observed. If such a disturbance is observed at a time later than ¼ cycle of power frequency after the current zero, then this is referred to as a Non-Sustained Disruptive Discharge or NSDD. These events seem to be unique to Vacuum Interrupters. When a few NSDDs are observed, this is considered as an event to record. NSDDs are, however, a rare, aspect of the interruption process in vacuum.

(e) The Recovery Voltage collapses and a power current flows – On even rarer occasions, a complete breakdown through the interrupter can occur that re-established the power frequency current. If this event is observed at a time later than ¼ cycle of power frequency after the current zero, then this is referred to as a restrike. The significance of a restrike we believe depends on whether or not the follow current is interrupted.

The subject of NSDDs is discussed below from the special perspective of interruption in vacuum to aid in the interpretation of the significance of observing such events during a test series.

The subject of Non-Sustained Disruptive Discharges (NSDDs) sometimes observed when testing vacuum circuit breakers continues to provide many opportunities for interesting discussions among short circuit test specialists. ***However, in real world applications NSDDs are not known to cause performance problems.*** Vacuum interrupters sometimes exhibit TRV disturbances and/or NSDDs during tests. NSDDs may be especially noted near the performance limits of the interrupter, e.g., when a VI is tested at or beyond its designed short circuit current rating. However, NSDDs have also been observed at lower currents as well, especially during capacitor switching tests. The voltage level is perhaps the most significant parameter affecting NSDDs. While NSDDs are sometimes observed while testing at the higher end of the medium voltage range, for example, at 24 kV and above, they are much less common at 17.5 kV and below. And below 12 kV, NSDDs are almost never observed. An NSDD can occur up to a few seconds after the circuit has been interrupted and is thought to be the result of a microparticle crossing the contact gap and initiating a small discharge within the VI. An NSDD does not result in a reestablishment of the power frequency current, but simply results in a very brief high frequency current flow as the parasitic capacitance local to the interrupter is discharged through the interrupter.

NSDDs are now considered to be benign curiosities occasionally observed during testing. This view was recently formulated by a CIGRE study committee working group and is being adopted by the IEC and IEEE standards writing committees and by the STL laboratory group. However, until this recent action, NSDDs were considered by some in the testing community as a "sign of distress" for the circuit breaker. The "sign of distress" interpretation then lead to the imposition of a limit of 3 as the allowable number NSDD events which were permitted in a single certification test series. This arbitrary limit of 3 NSDD events was specified at the insistence of the test laboratories whose test experience spans all types of interruption technologies. Since NSDDs have never been seen in other types of interrupters, they were therefore viewed with suspicion by the laboratories. However, the occurrence of a few NSDDs during certification testing, does not seem to be of any great significance for performance of VCBs in service. As experience has been gained in the testing of vacuum circuit breakers, it has now been recognized that NSDDs are not a "sign of distress". Therefore NSDDs are of no special consequence for the interpretation of performance during a test program and are no longer to be counted or considered during certification testing.

NSDDs will certainly remain of interest to the research community. An understanding of the mechanism that controls this phenomenon will continue to be sought. The role of micro-particles and contact phenomena in producing NSDDs is expected to be the primary focus of this research.

5.2 Interruption of Fault Currents With Very Fast Rates of Rise of Recovery Voltage

Vacuum interrupters using Cu-Cr contacts have an exceptional ability to withstand very rapidly rising Transient Recovery Voltages (TRVs). This is noted especially in two difficult switching duties of interrupting:

- Secondary Faults on Transformers, and

- Short Line Faults on overhead lines.

These fault conditions produce TRVs with very fast rates of rise of recovery voltage (RRRVs) that immediately stress the interrupter following a current zero.

Secondary faults on transformers are applications where VCBs are well suited. The high natural frequency of large power transformers results in a fast rising TRV with a 1-cosine wave shape. Moreover, large power transformers provide little damping, so the peak of the TRV is also high. While the 1-cosine wave shape results in a somewhat slower rate of rise in the first microsecond or two, the average rate of rise of recovery voltage (RRRV) is quite high. When the switchgear is placed a short distance from the transformer, the low capacitance of the connections together with the high natural frequency of the transformer results in a very fast TRV. For example, the rated (t_3) time of the TRV is about 60 ms for 12 kV indoor circuit breakers where typical cable connected circuits produce more slowly rising TRVs. However, t_3 can be less than 10 ms for a secondary fault on a large power transformer. In an extensive series of experiments [30], it has been shown that VI's using Cu-Cr contact material will reliably interrupt greater than 99.9% of transformer secondary faults that could be expected in the field without the need of TRV-modifying capacitors (see Fig. 16).

Overhead lines, in contrast, produce a sawtooth TRV when a fault is located a short distance from the breaker.

The sawtooth TRV wave of the short line fault (SLF) is the result of travelling voltage waves that go out on the line from the breaker and are reflected at the fault and are superimposed on the slower 1-cosine TRV of the source side circuit. Although the fault current value for a SLF is usually lower than the maximum fault interrupting capability of the breaker, the initial TRV of the sawtooth is then very fast in the first microseconds, immediately stressing the interrupter gap. Withstanding such initial fast RRRV stresses were first identified in the 1950's as difficult duties for gas interrupters where the decay rate of the gas temperature is in the same range as the increasing RRRV. However, tests have shown that the decay of the plasma temperature and cathode spot temperature in vacuum interrupters is faster than the typical SLF TRV and thus this duty is easily handled by the vacuum interrupter. So vacuum circuit breakers are also well suited for applications to protect overhead lines.

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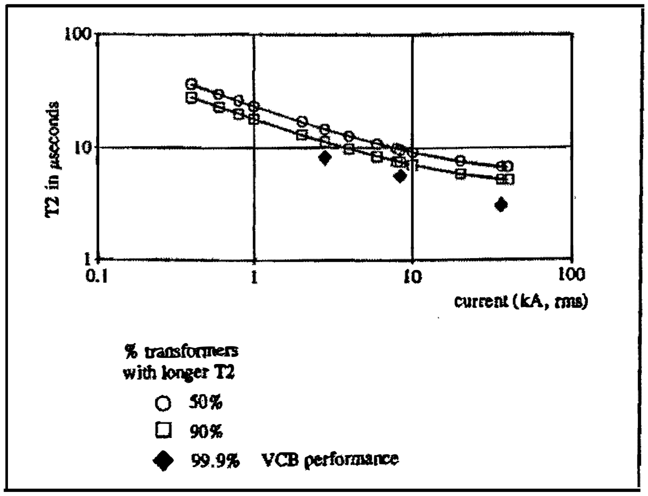

Fig. 16: Comparison of the Expected T2 Values for Transformer Secondary Faults With the Interruption Performance of a Vacuum Circuit Breaker Subjected to Very Fast TRV's

5.3 Developmental and Quality Testing of Cutler-Hammer Vacuum Interrupters

All C-H VI products are thoroughly tested for short circuit performance before being offered to a customer for designing into their circuit breaker or recloser [28]. These are described as pre-certification tests in that they provide a level of confidence to both C-H and our customers that the interrupter is capable of successfully passing a certification test series when installed in a properly design circuit breaker. A single-phase, high power test circuit is used which consists of a 5 MJ capacitor bank, several high-current inductors, and a Transient Recovery Voltage (TRV) wave-shaping network. The power frequency is typically tuned to 50 Hz or 60 Hz. A diagram of the circuit is shown in Figure 17 and current and arc voltage wave forms from a typical interruption experiment are shown in Figure 18. The circuit simulates the conditions in a power system during a short circuit by stressing the test VI with the rated values of short-circuit current and TRV (Note that for short circuits, the circuit power factor is very close to zero).

Single-Phase tests are used in the C-H, High Power Laboratory to predict Three-Phase capabilities

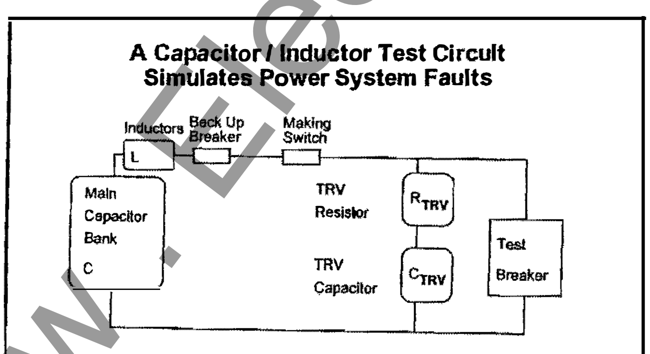

Fig. 17: Block Diagram of the Cutler-Hammer, Single-Phase, High Power, Test Circuit

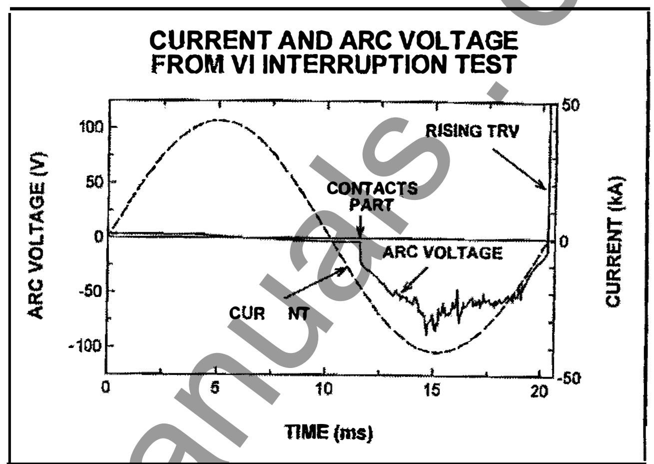

Fig. 18: Oscillograms of Arc Voltage and 50Hz Current From an Interruption Test of a TMF-Contact VI Using the High Power Circuit in Fig. 17

Single phase tests are well recognized [C37.09], [IEC62271-100] as an acceptable and conservative method of performing tests to demonstrate the interrupting rating of a circuit breaker. In such a test, the circuit must provide the rated symmetrical or asymmetrical short circuit current at the rated power frequency and with a TRV equal to that required for the first phase to clear a three phase ungrounded fault. This combination of current and voltage stress forms the basis of rating for the circuit breaker. It is also recognized that a single phase test with this combination of current and voltage provides a more severe stress than would be observed in an actual three phase ungrounded fault. This is so since only one of the 3 phases must actually clear at such as stress level in the 3 phase case. Moreover, in the single phase test, the TRV stress will be at the same high level at each successive current zero. In contrast, in the actual 3 phase circuit, if a particular pole attempts to be the first phase to clear at a short arcing time and then does not clear the circuit, it will then become one of the 2nd and 3rd phases to clear in series. The TRV for the 2nd and 3rd phases to clear is at a lower level and therefore the interrupting duty is easier on these poles. So the single phase test conditions used in the C-H lab are conservative in providing a somewhat higher test stress than would be experienced during a 3 phase ungrounded test or in actual service.

Despite the increasing use of sophisticated analysis in high power testing, the important result in certification tests is the pass/fail record. Based on over 30 years of experience, we have established a single-phase test program which allows us to predict the results of three-phase certification tests with high confidence. Three identical VI's are produced as prototypes or samples statistically from production and subjected to three levels of tests.

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(1) First Level: Interruption of Symmetrical Single-Phase Current

In a three-phase certification test series, the circuit breaker must perform several interruptions, where each of several currents expressed as percentages of the target rating as shown below.

The Number of Trials in a Certification Test Series	
Percent of Rated Short Circuit Current	Number of Interruptions Required
10	3
30	3
60	3
100 Symmetrical	3
100 Asymmetrical	3

In the C-H single-phase pre-certification test series of a new VI design, each VI is tested only at the targeted maximum 100% short circuit current, since experience has shown this to be the most severe test condition for vacuum interrupters. In addition, since the C-H test circuit is a capacitive / inductor discharge type, the test current produced is only a symmetrical current, so only symmetrical current interruption is possible. In the C-H test procedure, a total of 14 trials per VI are performed, as specified in Table V with a TRV of the first phase to clear for a three phase ungrounded fault. The total number of tests and accumulated arcing duty in the C-H series is approximately the same or greater than that experienced in the three-phase certification series. So the C-H test circuit provides all of the required conditions of rated symmetrical short circuit current, including the first phase to clear TRV. Experience has also shown that an acceptable level of interruption performance in the C-H single-phase test circuit at rated conditions is achieved when the arcing time to clear the circuit in at least 90% of the trails is within the typical normal range. The normal range of arcing times is approximately from a minimum of about 3ms up to a maximum of about 1 cycle + 3ms. That is, the VI can then be expected, with a high degree of confidence, to pass a series of certification trials in a three-phase circuit breaker with a three-phase ungrounded circuit at rated voltage and short circuit current stresses. Our 90% normal arcing time rate criterion is based on many years of experience that shows us that three-phase certification tests are less stressful. The three phase test is less stressful for two reasons. First, only one of the three poles must perform at the worst-case TRV, and, second, after the first phase clears, the other poles clear in series where each poles is at about 58% of the voltage stress seen by the first phase to clear. If we are testing at C-H to evaluate a single phase application, then an acceptable rate must of course be that 100% of all tests must clear within a normal arcing time range. This is also true for testing VI's that will be used in a three phase grounded systems. In this case, the peak TRV will be reduced to 2/3 of the values used in the first phase to clear ungrounded tests and an acceptable rate must also be that 100% of all tests must clear within a normal arcing time range.

TABLE V: Testing at a Targeted Current to Predict Certification Results

NO. OF TRIALS	TRIAL DESIGNATION	POINT OF CONTACT PART
5	CZ+	Near I = 0, positive wave
5	CZ-	Near I = 0, negative wave
2	CM+	Near I = I_p, positive wave
2	CM-	Near I = I_p, negative wave

(2) Second Level: Impulse Voltage Withstand (BIL).

The BIL of each VI is measured after the 14 interruptions to determine if it is still acceptable. The internal shields in the VI must adequately protect the ceramic insulation from condensation of metal vapor from the vacuum arc, which would degrade the dielectric strength.

(3) Third Level: A Simulation of an Asymmetric Current Tests

While the capacitor-inductor test circuit can only produce symmetrical currents, the circuit can be used to simulate the effects of asymmetric current as a means to assess the ability of an interrupter to operate under such conditions. The single-phase high-power circuit is first configured to provide a power frequency which is about 80% of the rated frequency. The lower frequency simulates the longer current loop duration of the asymmetric current when the contacts of the circuit breaker part about 2 cycles after the fault is initiated. The current magnitude is adjusted to include the required DC component that produces the asymmetric current. If the DC component is expressed in per unit of the symmetrical component, then the test current is then set at a value that is (1 + DC) times the rated amplitude (see Fig. 19).

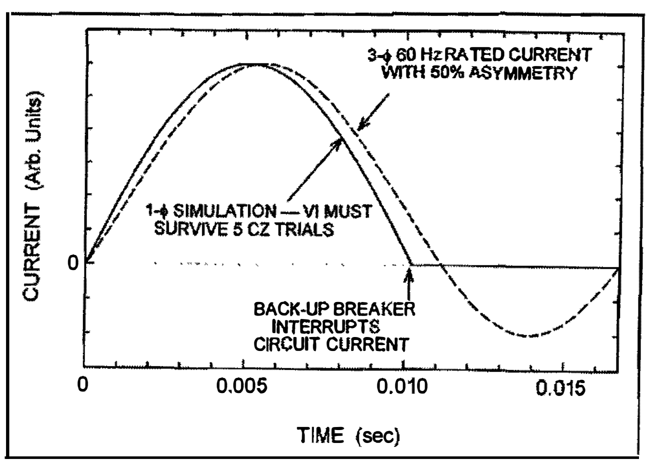

Fig. 19: Three Phase Current With 50% Asymmetry (Dashed) and the Single Phase Simulation With Symmetric Half-Cycle at 82% of the Power Frequency

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So if a 50% DC component is required, then the test current is set at 1.5 times the symmetrical value. Now in this simulated circuit, the first loop of current that is as large and as long as the major loop in a real circuit, is followed by another long loop that is only a few percent smaller. So attempting to interrupt such a current is like attempting to interrupt a current 50% greater and at a lower power frequency than the VIs rating. However, in a real circuit with asymmetric current, the large major current loop is followed by a small minor current loop and vacuum interrupters often interrupt after this minor current loop. So the main objective of this simulated test is to show that the VI can withstand the major current loop without significant arcing damage so it is ready to interrupt the following minor loop. The simulated test is then performed with a fresh tube which is subjected to five applications of one half-cycle of arcing with the larger, longer duration current. If this sample finishes this series without catastrophic damage (e.g., holes melted through the arc shield), our experience has shown that the VI will pass with actual asymmetric current trials during a certification test.

Other Design Considerations

Production of high quality VI's requires a successful integration of design, analysis, testing, and strict quality control over materials and manufacturing processes. Clearly, it is desirable to develop tools for reducing the testing required to develop new VI types and to monitor the production quality of existing types. Our production program emphasizes that a VI should be well designed initially, so that a limited number of relevant tests will validate the prototypes. We start with empirical design guidelines for different kinds of interrupters and applications, based on over 30 years of experience. These include correlations of the rated voltage withstand and current requirements with the design parameters of the internal arcing region. Adherence to the recommended opening speed and gap are also very important for given current and voltage ratings.

Testing for Quality Assurance (QA) or Performance Comparison

Our experience has shown that differences in the quality of alternative materials, or in the effects of design changes, may not be apparent from the interruption performance at a VI's rated current. For QA or comparative testing, we evaluate the decrease in performance above the maximum rated current, I_{rated}. Three identical VI's (one sample set) are first given 8 trials each at I_{rated}, three at each polarity for opening near current zero (CZ + and CZ-), and one each polarity for opening near current maximum (CM+ and CM-). The test current is then is then increased in steps to values such as 110%, 115% 120% and 125% of I_{rated}. At each new test current, the VI's are each given four trials; consisting of one trial at each condition of CZ+, CZ-, CM+ and CM-. These four trials are repeated on each VI at each increased current until the combined pass rate, defined as the rate of interruptions within a normal arcing time (3ms + 1 cycle), drops to $\leq$50%. Typically, a total of 24 trials are performed on each VI in a set of three samples. The point on the current wave at which the contacts part is varied consistently, because it affects the amount of arc motion [3].

An example of the results in such a test series is shown in Fig. 20, in which 4 sample sets of a 100mm OD VIs (I_{rated} = 36 kA) with different formulations of contact material were compared. One of these formulations was clearly inferior, so it was therefore rejected. The other formulations evaluated all performed well up to about 42 kA, or 115% of the rating. In fact, it is often not possible to differentiate among materials by merely testing only at the rating of the interrupter. It takes testing a currents above the rating to start to see differences in performance.

In this C-H test method, both the short circuit current and the TRV are increased in the same proportion by increasing the charge on the capacitor bank. So the combined interruption stress increases in a square relationship. So the fairly steep drop in the interruption success rate above about 42 kA (117% of I_{rated}) which is shown for the other three sets of samples is a result of this extreme increase in stress. The interrupter, however, can handle higher magnitude currents during asymmetrical current interruptions. For example, this same VI will interrupt its rated symmetrical current with a 50% dc offset for which the major loop has an rms value of 54 kA and a peak value of 77kA as required by ANSI standards. In this case, interruption often occurs on the following smaller minor loop.

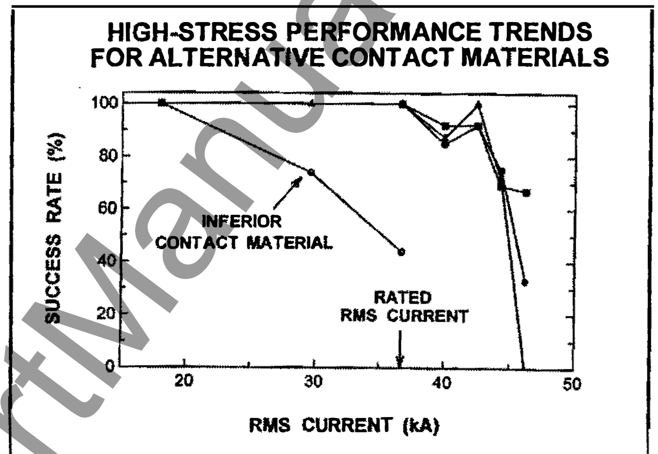

Fig. 20: Comparison of Statistical Interruption Performance Trends for Sets of Highly Stressed VI's With Four Different Formulations of Contact Material

6. SWITCHING INDUCTIVE CIRCUITS

Voltage surges at the terminals of inductive elements in distribution circuits (such as motors, shunt reactors and transformers) occur any time they are switched on or off by any kind of switching technology and their interaction with VI's in particular have been studied extensively [5]. The interactions are now well understood and, when the occasion arises palliative measures are easily applied. Surges can be produced in three ways [31-33].

(1) From lightning-induced or other surges on the line

(2) From closing the circuit to switch on the current.

(3) From opening the circuit to switch off the current.

Lightning-induced surges are not influenced by the interrupters and the established surge protection on the distribution circuit would be designed to prevent damage to the inductive element from lightning type impulse voltages.

The events that occur when closing a circuit are illustrated in Figure 21. It must be noted that this discussion applies to ALL interrupter technologies and not just to vacuum. It often occurs that the instant at which the circuit is energized coincides with the system voltage being at its maximum value since the rapidly reducing contact gap has a tendency to prestrike. If this happens, a travelling voltage wave will be applied to the cable linking the interrupter to the inductive element (in this illustration a non-energized motor). Since the surge impedance of cables is typically 25 to 50 ohms, and the surge impedance of inductive loads is typically much higher, then the voltage wave reaching the

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inductive element will be reflected. A voltage of about 2 per unit will then be impressed across the first few windings of the load. The traveling wave can reflect several times between circuit breaker and the load. Moreover, the returning wave can cause the interrupter to reignite and then initiate another traveling wave that could produce a voltage at the load that is even higher than 2 per unit. From testing, surge magnitudes are usually found to be from 1 to 3 per unit with occasional values as high as 4.6 per unit observed. If these voltage pulses are too severe, then the same measures should be used as will be discussed later for surges resulting from switching off the current.

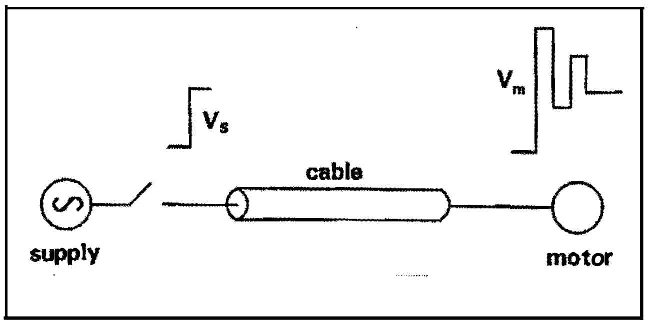

Fig. 21: When an Interrupter (Vacuum, SF_6, Oil, etc.) Closes an Inductive Circuit, the Resulting Voltage Wave Can Result in a Fast Rising Voltage At the Induction Terminals with Voltage Doubling

6.1 Multiple Reignitions

In general, multiple reignitions are a relatively infrequent phenomenon sometimes experienced by VI's and other interrupter technologies which may occur in circuits with certain combinations of circuit inductance, capacitance, and contact gap. Again, as with current chop, this topic has been researched exhaustively [10-12, 34-40]. Fig 22 shows a typical generic, inductive circuit with C_1 and C_2 being the stray capacitance to ground of the line-side and the load-side circuits. The development of multiple reignitions is as follows:

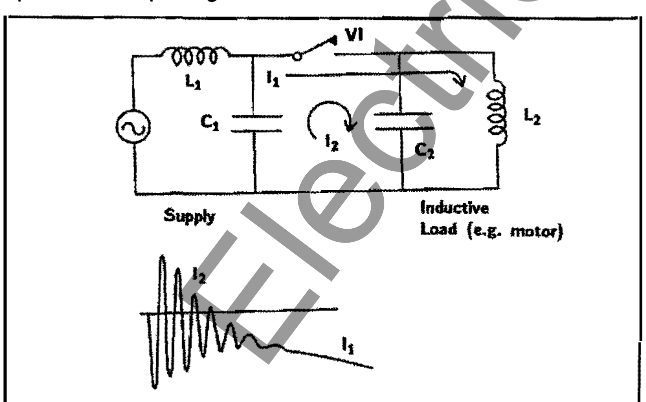

Fig. 22: An AC Circuit With an Inductive Load

(1) The VI contacts will open at a random point on the AC current wave, and as they continue to open, the current continues to flow, carried by the vacuum arc between the contacts, until current zero is reached. At current zero, the arc will extinguish.

(2) The contact gap in the VI recovers its dielectric strength extremely rapidly as soon as the arc is extinguished and the current flow in interrupted. The contact gap, in fact, assumes a dielectric breakdown value which is determined by the contact separation distance and, in VI's, is greater than 2 x 10^7 V/m^{-1}.

(3) Once the current has been interrupted, a transient recovery voltage (TRV) appears across the contact gap. This TRV is a function of the reactive components on the load and line side of the VI [38, 39].

(4) If the contact gap is not fully open and the TRV exceeds its breakdown strength, then the arc will be re-established. Once this happens, the charge from the two capacitors causes a high-frequency current I_2 to be superimposed upon the power frequency current I_1.

(5) There is a finite probability that the VI will extinguish this high-frequency current at one of its current zeroes because the vacuum is such an outstanding circuit interrupter. If this happens, the race between the TRV and the high-voltage strength of the contact gap begins again. The following three things can happen.

(a) The VI fails to extinguish the high-frequency cur rent and another half cycle of the power frequency current flows, at the end of which the contact gap will be large enough to withstand the circuit TRV (see Fig. 23).

(b) The contact gap will eventually become large enough to withstand the impressed TRV after a number of reignitions (see Fig. 24).

(c) The sequence of events will continue and the volt ages impressed across the VI will continue to increase [39] until a dielectric failure occurs, either in the breaker or some where else in the system.

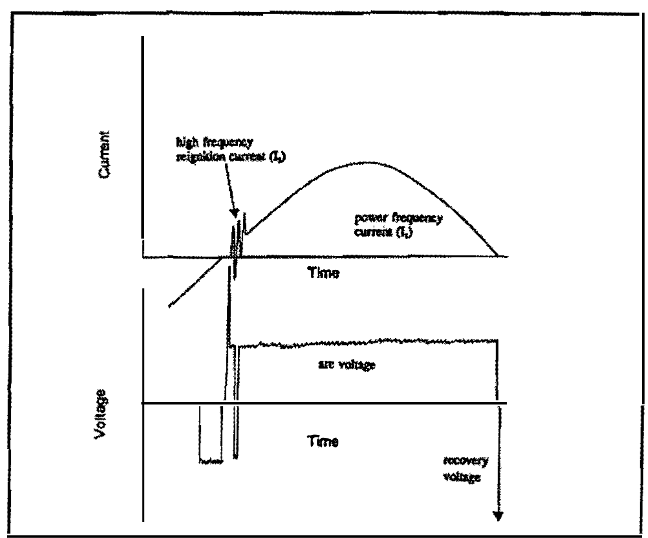

Fig. 23: If the High Frequency Reignition Current is Not Interrupted, An Extra Half Cycle of Power Frequency Current Follows

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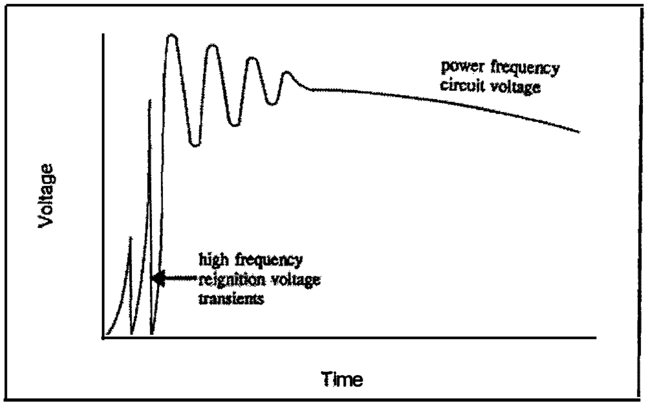

Fig. 24: If the Breakdown Strength of the Contact Gap Exceeds the Reignition Voltage Transient, the Circuit Will Be Interrupted

The VI has a probability of reignition only when very limited operating and circuit parameters are met [38]. These parameters are as follows:

(1) The circuit breaker must be attempting to interrupt moderate currents of more than 20-30A, and generally less than about 500-600A [38]. However, multiple reignitions have been observed at currents as high as 2000A in the C-H lab.

(2) The gap between the breaker contacts must be small. A gap of typically 3 millimeters or less at 27 kV is required to observe multiple reignitions, so contact part is therefore only 1 to 3 ms before the current zero when the contact opening speed is about 1 m/s.

(3) The TRV must rise slowly enough initially so that the breaker can extinguish the arc at the first power frequency 50 Hz/60 Hz current zero at this short gap.

(4) The TRV must rise faster than the increasing breakdown strength of the contact gap of the VI as the contacts continue to open.

If the load exceeds some upper limit such as 600A or 2000A, the vacuum arc will not extinguish at the first current zero with closely spaced contacts. Because the contacts continue to open during the ensuing half cycle of arcing, the dielectric strength of the contact gap at the next current zero is high enough to prevent a voltage breakdown. The breakdown strength of the VI depends almost entirely upon the contact gap. If a breaker operates with an opening speed of about 1 m/s and the contacts part at a time of about 0.5 ms before a current zero, then the gap will recover to about 10-20kV in at the first current zero. If the contacts open at a speed of 2 m/s, then the recovery will be to about 20-30 kV. Most vacuum circuit breakers and reclosers operate with opening speeds in this range. When the rate of rise of recovery voltage is less than the rate of increase in the dielectric strength of the contact gap, no reignitions will occur. The upper boundary has been observed of 900 Hz for 5kV circuits, 500 Hz for 15kV circuits and 250 Hz for 24kV circuits [38]. When the load current is below 20A, such as magnetizing currents of unloaded transformers, the overvoltages that can occur are limited by the core losses in the transformer.

The effects of multiple reignitions can be minimized and even eliminated by connecting a surge suppressor directly at the inductive load terminals to ground. In fact, multiple reignitions can be eliminated with a snubber consisting of a series-connected capacitor and resistor, R-C [36,37]; or special version of a snubber called a $ZORC_{tm}$ in which the R is paralleled by a ZnO varistor [41]. Lightning arresters such as a varistor [41] can keep the peak voltage within limits, but cannot eliminate multiple reignitions. It is also possible, but not nearly as effective, to apply a snubber at the breaker terminals [37]. The suppressor options of type and location are illustrated in Fig. 25.

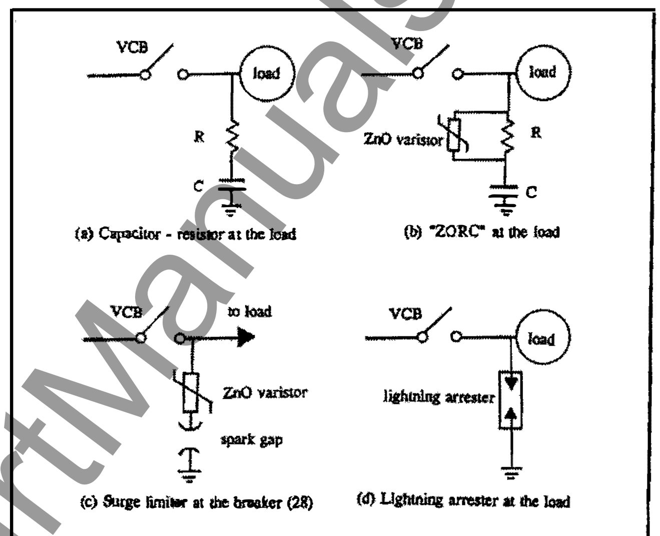

Fig. 25: Examples of Surge Suppression Circuits

6.2 High Voltage Motor Switching

For normal operation of HV motors, the same care has to be taken to reduce the effects of the three sources of voltage surge, no matter which interrupter technology is used, i.e., VCB's SF_6 breakers, oil or air magnetic circuit breakers. In fact, if the cost of the HV motor is significant or if the loss of service is critical, then surge protection is a very inexpensive and prudent step with very large potential benefits. Usual recommended practice is a surge capacitor or a surge arrester connected at the motor terminals IEEE updated to include a resistor (to match the cable surge impedance) in series with the capacitor and/or a Fig. 25)[41]. When a vacuum breaker is used to interrupt the loud comment after a motor has reacted its full running speed, no adverse effects are expected. This is because the back emt produced by the running motor opposes the source voltage resulting in a very small recovery voltage across the opening contacts immediately following current interruption [5, 32].

If the motor current is interrupted before the motor has attained its full operating speed (locked or stalled rotor conditions), the machine will have little or no back emf and, therefore, behaves like a reactor. In this case, it is possible to develop the multiple reignitions described in Section 6.1. Fortunately, the surge protection provided to protect against closing surges is equally effective in reducing the probability of multiple reignitions from occurring and, if they do occur, the surge protection will minimize their effects.

Table VI showed the effects of surge suppression on the observed surge voltages at a motor terminal and compares the VI with SF_6 and air interrupters [41].

The voltage withstand properties of motor insulation are different from those for air insulated devices. Motors windings are imbedded in the slots of the machine's magnetic structure and are insulated with solid materials. The material thickness is as small as possible while simul-

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taneously providing the necessary voltage withstand ability and good magnetic performance. As a result, the insulation does not have the higher resistance to fast wave front impulse surge voltages that other equipment can be designed to provide. Specifically, motors do not have ratings for lightning impulse voltages that are required for circuit breakers, switchgear and transformers. A typical curve of impulse voltage withstand versus the rise time of the voltage is show in Figure 26. Manufacturing methods are absolutely critical in producing a good voltage withstand ability in motor insulation. Large machines, typically purchased by utilities, tend to be better made with higher voltage withstand properties than smaller machines. Moreover, it has also been noted that a motor that has been rewound after a voltage breakdown, usually never experiences another problem. This is presumably because insulating quality of the rewound machine is better than it was on that particular machine when it was new. So it is natural that more care in providing overvoltage protection should be considered for motors.

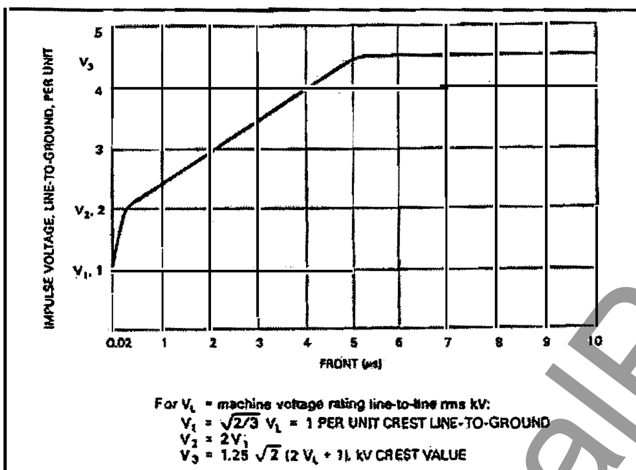

Fig. 26: Machine Impulse Voltage Withstand Envelope

TABLE VI: Effect of Surge Suppression on the Value and Duration of Voltage Surges at the Terminals of High Voltage Motors for Vacuum, SF6 and Air Interrupters

OPERATION	TYPE AND LOCATION OF SUPPRESSION	VACUUM		SF_6/AIR	
		V_{motor} (pu)	t_r µs	V_{motor} (pu)	t_r µs
CLOSING	None or Arrester	4	0.2 - 0.5	4	0.2 - 0.5
	Capacitor at Motor	4	3 - 7	4	3 - 7
	RC at Motor	2	0.2 - 0.5	2	0.2 - 0.5
	Zn0-RC at Motor	≤1	0.2 - 0.5	≤1	0.2 - 0.5
	Zn0-RC at Panel	≤2	0.2 - 0.5	≤2	0.2 - 0.5
OPENING STALLED MOTOR	None or Arrester	4 - 5	0.2 - 0.5	4 - 4.5	0.2 - 0.5
	Capacitor at Motor	6	3 - 7	4 - 4.5	3 - 7
	RC at Motor	3	0.2 - 0.5	2.2 - 2.8	0.2 - 0.5
	Zn0-RC at Motor	≤1.5	0.2 - 0.5	≤1.5	0.1 - 0.5
	Zn0-RC at Panel	≤3	0.2 - 0.5	≤2.5	0.2 - 0.5

There have been claims made that some SF_6 interrupters have a low surge characteristic on opening, and thus do not require special surge protection at the motor. Table VI, however, shows you should expect to obtain very similar surge voltages at the motor terminals with the use of SF_6 interrupters. Moreover, the table also shows that overvoltages on closing are nearly as high as on opening, so the advantage of producing a low surge on opening is of much reduced significance. The conclusion one has to draw from this data is that care must be exercised in protecting motors against overvoltages no matter which switching technology is used.

It is of course also possible to provide a low surge on opening operations performance using the VI. For at least 20 years VI's have been available for use in high voltage contactors which use low-surge contact material such as AgWC and CuCrBi. These materials have a very limited ability to interrupt high frequency currents and thus have a very low probability of initiating a voltage escalation sequence. These materials, however, also have a limited short circuit interruption capability and have traditionally been applied in series with fuses for short circuit protection. If a vacuum circuit breaker using CuCr contacts (a material that has an excellent ability to interrupt high frequency currents) is used to switch motors, it is prudent to use surge suppression at the motor terminals.

6.3 Transformer Switching

An unloaded transformer represents a highly inductive load with a magnetizing current ≤1% of the rated full-load current. On switching this current, a current chop is very likely to occur (see Section 3) which will trap energy proportional to the inductance and the square of the chop current value. The trapped energy manifests itself as a high frequency resonance, ringing between the inductance and the stray capacitance of the circuit. Fortunately, there is, however, considerable damping of the resultant voltage and current waveforms resulting from the losses in the transformer core. As the kilovoltampere rating of a transformer is reduced, the capacitance tends to be smaller and the magnetizing inductance becomes larger. This trend in C and L increases the impedance, but, as the magnetizing current is reduced, the maximum chop current is also reduced. Dry-type transformers with low-impulse voltage rating are more vulnerable. Overvoltage protection can be provided with a short cable of 20-50 m, plus a surge capacitor or an R-C network, (a surge capacitor and a resistor) at the load terminals of the transformer. Figures 27, 28 [12] illustrate effects of cable length and surge capacitors on the surge voltages seen at the transformer terminals. Table VII gives some recommendation guidelines on the use of surge protection for dry type and oil filled transformers [43].

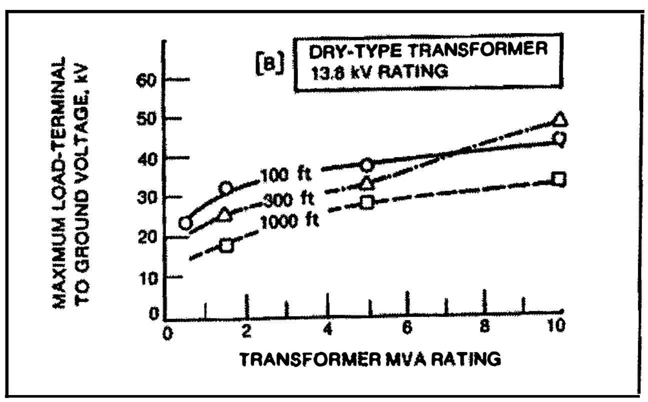

Fig. 27: Effect of Cable Length on Maximum Load-Terminal to Ground Surge Voltage

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It has been usual to assume that no surges will be generated or expected when switching a loaded transformer [5]. However, power transformer failures have been known to result when an internal resonance produces an overvoltage sufficient to cause an insulation breakdown. The transformer windings have a complicated internal structure that can be represented by a network of inductances and capacitances, which have natural resonant frequencies of oscillation. Under some conditions, a resonance can be excited to produce damaging overvoltages. Mechanisms that can excite a resonance can include:

1. multiple reignitions of a switching devices that occur at a frequency that matches the resonant frequency, or
2. large harmonic components present in the inrush current of the transformer that flows on energizing the transformer, or
3. inturruption with load capacitances.

A means of suppressing a resonance is therefore required to provide protection in such cases. R-C surge suppressors can damp or eliminate such internal resonance in power transformers and thereby reduce the risk of resonance induced overvoltages within the winding of a load.

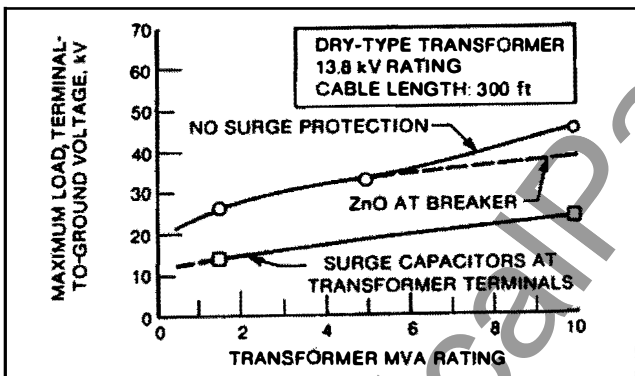

Fig. 28: Comparison of the Effects of Surge Capacitors At the Transformer and ZnO Surge Suppressors At the Breaker in Reducing the Maximum Load-Terminal to Ground Surge Voltage

TABLE VII: Transformer Protection

SWITCHING DEVICE	LOAD	
	Dry Type Transformer	Oil Filled Transformer
Vacuum Contactors 1kV - 7.2kV class	Protection not necessary for transformer rated more than 400 kVA: for small transformers use surge protection	Protection not necessary
Vacuum Circuit Breakers 5kV Class	Surge protection necessary, unless the transformer is rated for 60 kV BIL	Protection not necessary for transformers rated more than 300 kVA: for small transformers use surge protection
Vacuum Circuit Breakers 10kV - 40.5kV Class	Surge protection required unless the transformer is rated for the full BIL, e.g. Circuit V BIL V 10kV 75kV 15kV 95kV 24kV 125kV 36kV 170kV 40.5kV 185kV	Protectiuon recommended especially for transformers rated less than 3MVA, however, 0.2µF at the load terminals reduces maximum transient voltage and number of restrikes

An R-C suppressor consists of a resistor and capacitor in series; the capacitor is generally connected on the ground side and the resistor on the line side. The resistor value is approximately 25 to 50 ohms, which is approximately the surge impedance of high voltage cables which are often used to connect to the load. The capacitor should have a voltage rating appropriate to the system voltage and a capacitance value as recommended for surge capacitors listed in the IEEE Red Book [42]. These are:

Rules for Size of Surge Capacitors			
Voltage Rating in Volts	650 or less	2500 - 6900	11500 and higher
Capacitance in Microfarads	1.0	0.5	0.25

6.4 Virtual Chopping

Virtual chopping only occurs in rare cases. It is strongly dependent upon the circuit parameters, and, to a much lesser extent, the interrupter. Virtual chopping is a phenomenon that can occur in an ungrounded, three phase circuit with any interrupter type (SF_6, vacuum, oil, etc.). Virtual chopping can occur if the first phase to clear experiences a reignition before phases two and three interrupt. For example, if a reignition in one phase (say Phase A) causes a high-frequency current to flow which couples into the other two phases, virtual current chopping may occur. The circuit paths for the high-frequency current as shown in Fig. 29. The high-frequency current in phase A, i_T, due to a reignition in Phase A flows to ground via the terminal-to-ground capacitance at the load. If the three-phase system is balanced, i_T divides into two so that i_T / 2 enters phases B and C via the respective terminal-to-ground capacitance. The high-frequency current (i_T / 2) in phases B and C is shown to be capacitively coupled back into phases A on the source side of the breaker.

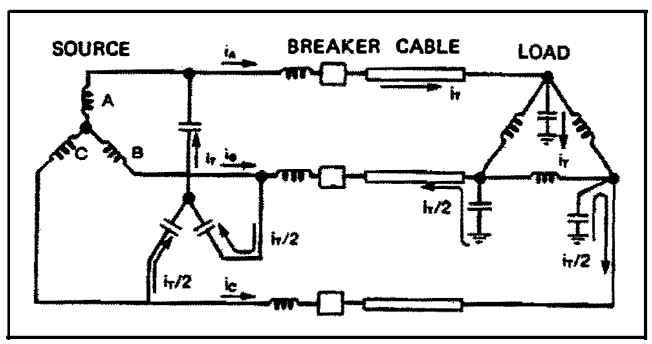

Fig. 29: Circuit Demonstrating How the High-Frequency Current Resulting From a Reignition in One Phase Couples Into the Other Two Phases to Produce the Conditions for Virtual Current Chopping.

At the instant of reignition in phase A, which occurs some tens to hundreds of microseconds after the power frequency current zero, the power frequency current in phases B and C is approximately 0.87 x the crest value of the power frequency current. If the magnitude of the high-frequency current in phases B and C (i_T / 2) is greater than 0.87 x

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the crest value of the power frequency current, the high-frequency current plus power frequency current add to zero: this appears to be a forced current-zero and the phenomenon is called virtual current chopping.

The high-frequency currents (i_T / 2) in phases B and C are of the same polarity and equal in magnitude to each other, but are of opposite polarity to i_T in phase A. Because the normal power frequency phase relationships cause the power frequency currents in phases B and C to be opposite polarities at the time of reignition in phase A, the forced current zeros are not time coincident. Also, the currents in phases B and C are of opposite polarities. Consequently, the surge overvoltage between phases B and C is twice the overvoltage from phase to ground on both phases, provided that the instantaneous voltages are significantly less than the virtual chop overvoltages.

Compared with normal current chopping, the effective level from which the load current is forced to zero (virtually chopped) can be much higher, typically several hundred amperes instead of 3 or 4 A. However, the effective surge impedance of the load (several hundred ohms) is much lower than it would be in switching an unloaded transformer without protection (typically 10 to 30 kΩ). The overall effect is to make the phase-to-ground overvoltage comparable with or larger than the overvoltage due to a normal current chop, but the important difference is that the surge overvoltage between phases B and C is approximately twice the overvoltage from phase-to-ground on these phases.

If a circuit is susceptible to this phenomenon an R-C surge suppressor at the load terminals will prevent this event from occurring.

7. CAPACITOR SWITCHING

For distribution systems, switching capacitor banks is the most severe capacitive switch duty. Unlike switching cables and overhead lines (see Section 7.3), switching capacitors is often a daily event, and sometimes occurs even more frequently. The reason for this is that capacitors are used to maintain the power factor in the distribution system when it is subjected to changing inductive loads. In some distribution circuits it is quite possible to have over 700 switching operations a year.

The VI has proven to be very effective for switching capacitor banks. Although capacitor switches specifically designed for capacitor switching have been developed that use VI's with W-Cu contact materials circuit breakers are also frequently required to perform this service. Fortunately, the Cu-Cr contact material now used in state-of-the-art VI's has excellent high-voltage properties and has shown an excellent ability to perform capacitor switching duty [44]. In the future, the combination of the VI with a magnetic actuator [45] operated separately on each pole will even make possible point on wave closing and opening. When this occurs the stresses that switching capacitors imposed upon the distribution system will be greatly reduced.

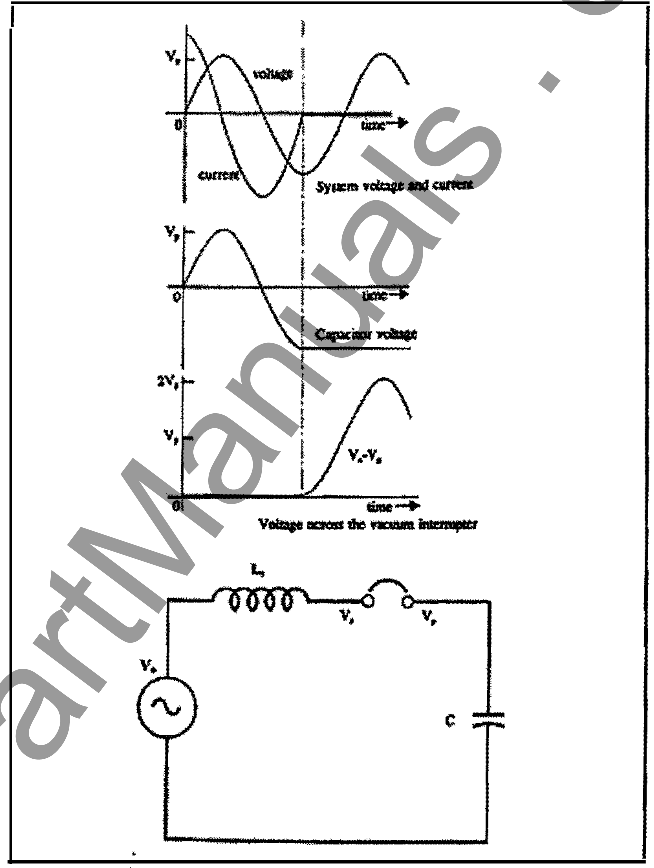

Fig. 30: An AC Circuit With a Single Capacitor Bank Load

7.1 Energizing a Capacitor Bank

Single Capacitor Bank

A schematic of a single capacitor is shown in Fig. 30. On closing the circuit there will be a large transient current given by [5]:

$$I_1 = (V_o / Z_1) \sin \omega_1 t \quad (7.1)$$

where Z_1 is the surge impedance of the circuit, equal to $(L_s/C)^{1/2}$, ω_1 is the angular natural frequency equal to $(L_sC)^{-1/2}$, and V_o is the voltage across the switch at the moment of energization. This current is usually much greater than the power-frequency current on which it is superimposed. For example, a capacitor bank rated 6 MVAR at 13.8kV will have a rated current of about 250A (rms), but can have a closing current of over 3kA. This high closing current stresses the whole electrical circuit, i.e. the upstream transformer, the bus or cable and the electrical connections.

During the closing sequence, the VI will have initiated the current flow a short time before the contacts actually touch. The reason for this is that as the contacts close there will be a time before they touch that the electric field across them is high enough to initiate a breakdown of the gap (a prestrike). The resulting short duration vacuum arc will allow current to flow in the circuit. It is possible that this prestrike arc would melt the contact surfaces and initiate tack-welding of the contacts once they touch. The mechanism for the VCB or vacuum ca-

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pacitor switch is designed to break such welds. The resulting projections left on the contact surfaces after breaking such welds are usually eroded away by the action of the arcing that occurs when opening the interrupter.

It can be seen from Eq. 7.1 that it would be extremely advantageous to close in on the circuit when V_o is close to zero (i.e. point on wave closing). Not only would the current I_1, be very small, but also the contacts would have to be practically touching before the field across them would be high enough to initiate the prestrike arc. However, a truly effective point on wave closing switch would have to have independently operated poles.

Back-to-Back Capacitor Banks

Increasingly, utilities are using a number of capacitor banks in parallel, which are switched into a power system as the inductive load builds up. They are then switched out when the inductive load declines. Figure 31 illustrates a back-to-back configuration. Here capacitor bank C_1 is closed and then capacitor bank C_2 is closed while C_1 is energized. In this situation the inrush current into C_2 is almost totally supplied by the neighboring bank C_1 because $L_s >> L_o$. In this case the inrush current is given by

$$I_2 = (V_2 / Z_2)\ \sin \omega_2 t \quad (7.2)$$

where Z_2 is the surge impedance of the loop containing the two capacitor banks C_1 and C_2 and L_0, and ω_2 is the angular natural frequency of this circuit. In this case if C_1 is at the peak voltage when C_2 is connected to the circuit the maximum current will flow. Again if the capacitor banks are 6 MVAR at 13.8kV a current between 11.5kA and 23kA can flow depending upon the initial charge trapped on C_2 and the value of the inductance between banks. Although the mechanical and electrical stress in this case only affects the local capacitor circuit, it is wise to limit this momentary high frequency current [46]. Equation (7.2) also indicates that if C_2 is switched in when V_2 is close to zero, i.e. point-on-wave closing, then again I_2 will have a low value.

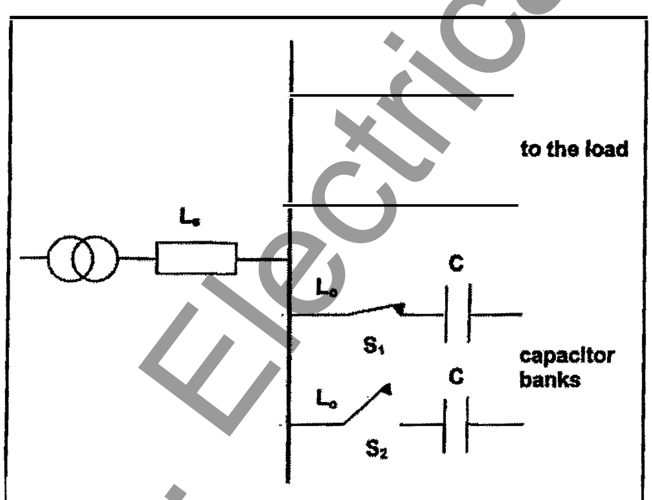

Fig. 31: Equivalent Circuit Diagram for Back to Back Capacitor Switching

7.2 De-energizing Capacitor Banks

Capacitor bank rated current is usually in the range of about 100A to 400A with the occasional large capacitor banks that can carry 2000A. In the current range up to and above 2000A the vacuum arc formed as the VI contacts part is in the diffuse mode and easily interrupts the circuit at current zero. At current zero, however, the peak circuit voltage V_p (see Fig. 30) trapped on the capacitor as the current passes through zero. This voltage remains on the capacitor for as long as it takes for the charge to bleed off through its internal discharge resistors. The voltage on the other side of the switch V_{a1} follows the power frequency source voltage and the voltage impressed across the VI's contacts ($V = V_a - V_p$) is given by:

$$V = V_p (1 - \cos \omega t) \quad (7.3)$$

as seen in Fig. 30. Te recovery voltage thus begins to rise very slowly, but will rise to a maximum value of $2V_p$. Note that in three phase systems, V_p would be the phase to neutral voltage

$$V_p = (V\ (\text{system}) \times \sqrt{2}) / \sqrt{3}$$

This value is usually designated as 1 PU. The peak voltages seen when switching various 3 phase capacitive loads are:

(a) grounded banks or cables

$$V_{max} = 2\ V_p$$

(b) cables with individual grounded sheaths

$$V_{max} = 2\ V_p$$

(c) cables with three conductors surrounded by one grounded sheath

$$V_{max} = 2.2 \text{ to } 2.3 \text{ times } V_p$$

(d) ungrounded banks

$$V_{max} = 2.5 \text{ times } V_p$$

The field E across the contacts will be

$$E\ (t) = V/d = V_p\ (1 - \cos \omega t)/d \quad (7.4)$$

Where d is the contact gap. Now, if the contacts are opening with a velocity v, then

$$E\ (t) = V_p\ (1 - \cos \omega t)/vt.$$

The VI has been designed so that the maximum field Ep for a fully open contact gap of $d=d_o$ is below that required to initiate vacuum breakdown. Thus, to insure that reignition does not occur as the contacts open

$$E\ (t) < E_p$$

Fig. 32 shows an example of the development of E(t) for a range of contact-opening speeds. In this example, Ep. is 6.17kV/9.65 mm = 6.4 V/mm, so the opening speed should be greater than 1.3 m/s if the opening is initiated just before current zero.

Even with the $2V_p$ impressed across the VI, switching a capacitor bank is usually a straight forward operation. Figs. 33 and 34 show data for a VCB undergoing 38kV capacitor switching certification at the Laboratory and Research Center, Arnheim, The Netherlands (KEMA), with inrush currents up to 24kA.

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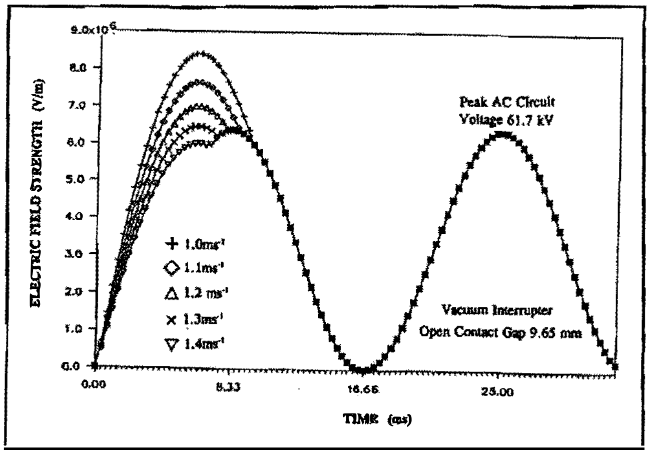

Fig. 32: Effect of Opening Speed of a Vacuum Circuit Breaker on the Electric Field Across the Opening Contacts of a Vacuum Interrupter if the Contacts Begin to Part Close to Current Zero

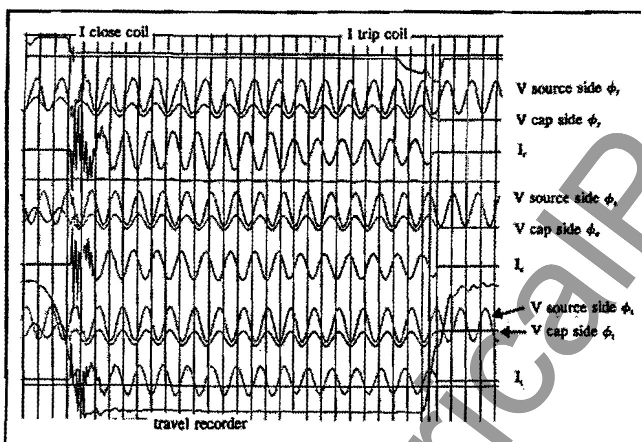

Fig. 33: Vacuum Circuit Breaker Switching Back-to-Back, Capacitor Banks in a 38kV Circuit

It has been increasingly recognized that when capacitor banks are switched a large number of times there is a finite probability of a restrike occurring during the life of the switching interrupter. This is true whether vacuum or SF_6 interrupters are used. When this restrike occurs, a high frequency current flows through the capacitor/switch circuit. If this current is interrupted at the first current zero it is possible for the voltage across the switch to increase from 2 to 3 per unit. This higher voltage can result in further restrikes and a further voltage escalation [47]. Thus even though the interrupter has a low probability of restriking it is prudent to protect the capacitor bank with a voltage-limiting device. It is interesting to note that using VI's specifically designed for capacitor switching with the WCu contact material, it is unlikely that voltage escalation will occur even after a restrike event. The reason for this is that WCu has very poor ability to switch power frequency currents much greater than 2.5kA and also has a poor ability to interrupt high frequency currents much greater than 1kA. So if a restrike does occur, the current will continue flowing until it rings down to a low enough value for the WCu material to interrupt it. When this happens, the charge left on the capacitor bank will be low enough that voltage escalation is unlikely. If, however, a vacuum circuit breaker is used to switch capacitor banks, the CrCu contact material which has an outstanding ability to interrupt high frequency, high currents, will interrupt the high frequency restrike current. When this occurs, voltage escalation may result. Care should thus be used to protect capacitor banks when vacuum circuit breakers are used to switch them.

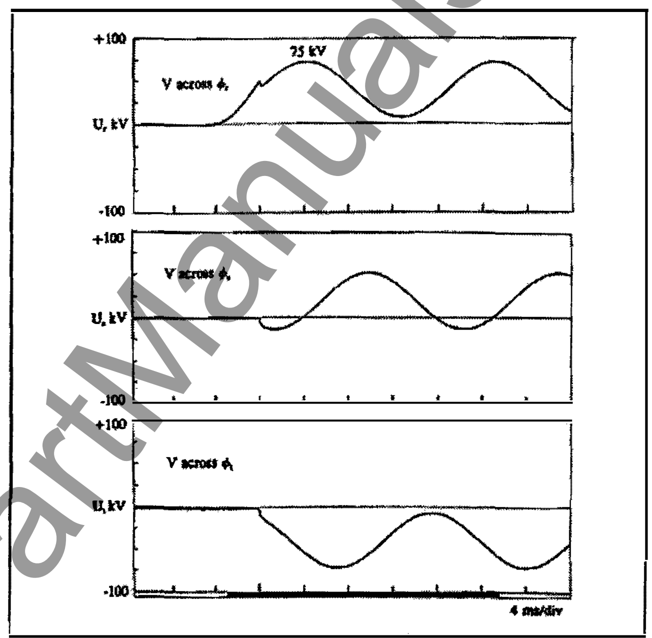

Fig. 34: Recovery Voltage Across the Individual Vacuum Interrupters Switching Back-to Back, Capacitor Banks in a 38kV Circuit; The Initial, High Frequency Closing Current Being 24kA (Peak), see Fig. 33.

7.3 Cable Switching and Line Dropping

When disconnecting cables or overhead distribution lines, the application considerations are similar to those previously discussed for switching capacitors. Although the current magnitudes are low, cables and lines have appreciable capacitance and interruption of the circuit current will trap charge on the cable or line. This results in a similar, slowly rising recovery voltage appearing across the VI contacts of the VCB which can reach a peak value of:

(a) screened cables with individual grounded sheaths

$$V_{max} = 2\ V_p$$

(b) belted cables with all three phase conductors surrounded by one ground sheeth

$$V_{max} = 2.2 \text{ to } 2.3 \text{ times } V_p$$

While other interrupting technologies have had difficulty with this duty, VCB's have performed this function very successfully for 30 years.

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It should be remembered when testing for this duty in a certification laboratory, that while the cable or line looks similar to a capacitor, it is not a single lumped capacitor, but contains a distributed capacitance. Figures 35 shows a circuit set up for testing a switch in a true capacitor bank or for screened cables when each phase conductor is surrounded by its own grounded sheath. Figure 36 shows a different circuit for testing a switch for belted cable overhead live switching, taking into account the distributed capacitor component of the line and series surge impedance.

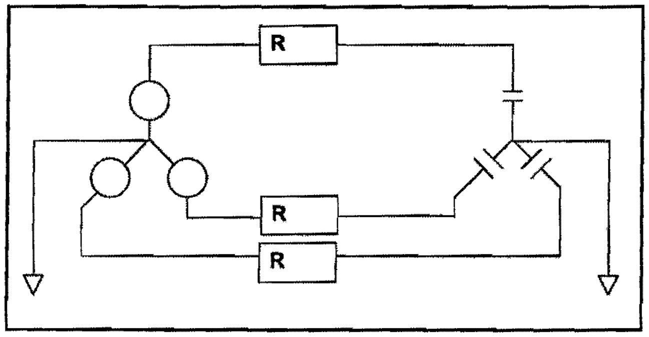

Fig. 35: Cable Charging Current Breaking Test Circuit

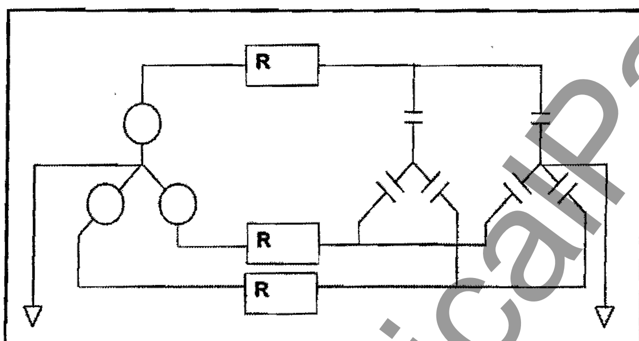

Fig. 36: Overhead Line Charging Current Breaking Test Circuit

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8. CONCLUSIONS

(a) Modem vacuum interrupters (VI's) that use state-of-the-art vacuum processing techniques to ensure an hermetically-sealed, vacuum-tight construction for the life of the VI and that use the Cu-Cr contact material are capable of providing maintenance-free operation for the full electrical life of the system.

(b) Vacuum interrupters have been successfully used in circuit breakers and reclosers over the whole distribution voltage range through 40.5kV.

(c) A state-of-the-art VI is capable of providing outstanding recloser performance far in excess of ANSI Standard C37.60. In fact, reclosers are now manufactured that will perform 300 fault operations with no maintenance, for use in applications where severe weather is frequent.

(d) The VI provides the longest switching life over the widest operating range, i.e.,

From less than 1 kV to 40.5kV,

From less than 100A to more than 3150A,

From less than 6kA to 63kA faults,

From power frequencies of 16 2/3 to 100 Hz, or higher

With transient recovery (TRV) voltages having the a fastest rate of rise of recovery voltage, and for resistive, capacitive and inductive load breaking

(e) If an open vacuum circuit breaker or recloser experiences a voltage surge greater than its design value, and the contact gap in the VI breaks down and allows current to flow, the current will be interrupted at the next current zero.

(f) The vacuum circuit breaker is used to reliably switch capacitor banks and motor circuits. If necessary, specialty VI's can be used that have been developed to operate only as capacitor switches. Also, for motor switching, specific VI's can provide low surge operation. These vacuum interrupters can be used in high-voltage motor contactors or low-surge vacuum circuit breakers.

(g) The fast TRV interrupting ability of the Cu-Cr contact material provides greatly enhanced transformer protection from secondary faults and overhead line protection from short-line faults.

(h) The versatility of VI design will see its continued application to an even wider role in the control and protection of distribution circuits. Present-day emerging examples are generator protection breakers and switches for electric trains.

9. REFERENCES

[1] M.B. Schulman and P.G. Slade, editors, *Research and Development of the Vacuum Interrupter and the Vacuum Circuit Breaker: 1929-1997,* (pub. Cutler-Hammer, Horseheads, NY) 1997.

[2] P.G. Slade, "Advance in Material Development for High Power Vacuum Interrupter Contacts," *IEEE Trans. Comp., Package., Manufact. Technol. A*, Vol. 17, pp 96-106, Mar. 1994.

[3] M.B. Schulman, "Separation of Spiral Contacts and the Motion of Vacuum Arcs at High AC Currents," *IEEE Trans. Plasma Sci.*, Vol. 16, pp. 342-347, June 1993.

[4] M.B. Schulman, P.G. Slade, and J.V.R. Heberlein, "Effect of an Axial Magnetic Field Upon the Development of the Vacuum Arc Between Opening Electric Contacts," *IEEE Trans. Components Hybrids and Manufacturing Technology,* Vol. 16, No. 2, pp. 180-189, March 1993.

[5] A. Greenwood, *Vacuum Switchgear,* London, U.K.: IEE, 1994.

[6] P. G. Slade, "Growth of Vacuum Interrupter Application in Distribution Switchgear," *Proc. 5th Intl. Conf. On Trends in Distribution Switchgear,* London, UK, IEE Conf. Pub. 459, pp. 155-160, Nov. 1998.

[7] L.G. Christophorou, J.K. Olthoff and R.J. VanBrunt, "Sulphur Hexafluoride and the Electric Power Industry," *IEEE Electrical Insulation Magazine,* Vol. 13, No. 5, pp. 2024, Sept. – Oct. 1997.

[8] M. Farber, S. P. Harris, D. E . Cooper, and M. Khazei, "Mass Spectrometric Determination of S2F10 resulting from high-voltage arcing of SF_6," *J. Phys. D. Appl. Phys.*, Vol. 22, pp. 233-234, 1989, and "Health Hazards That Lurk in Inert Gas," *New Scientist*, Feb. 16, 1991.

[9] Much of this work has been first presented at the International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), which began with the first conference in 1964 and has been held every two years since then.

[10] A.N. Greenwood, D.R. Kurtz, and J . C. Soflanek, "A Guide to the Application of Vacuum Circuit Breakers," IEEE *Trans. Power App. Syst.*, Vol. PAS-90, pp. 1589-1597, July/Aug. 1971.

[11] J. F. Perkins, "Evaluation of Switching Surge Overvoltages on Medium Voltage Power Systems," *IEEE Trans. Power App. Syst.*, Vol. PAS-101, pp. 1727-1734, June 1982.

[12] J. F. Perkins and D. Bhasavanich, "Vacuum Switchgear Application Study With Reference to Switching Surge Protection," *IEEE Trans. Ind. Applicat.*, Vol. IA-19, pp. 879-888, Sept./Oct. 1983.

[13] P. G. Slade, "The Vacuum Interrupter Contact," *IEEE Trans. Comp, Hybrids, Manufact. Technol.,* Vol. CHMT-7, pp. 25-32, Mar. 1984.

[14] A. Bereza, "Method of Sealing and Evacuating Vacuum Envelopes," U.S. Patent 3 656 255, Apr. 18, 1972, and Revisions 27 773, Aug. 14, 1973.

[15] M. Okawa, T. Tsutsumi, and T. Aiyoshi, "Reliability and Field Experience of Vacuum Interrupters," *IEEE Trans. Power Delivery*, Vol. PD-2, pp. 799-804, July 1987.

[16] R.E. Voshall, C. W. Kimblin, P.G. Slade, and J. G. Gorman, "Experiments on Vacuum Interrupters in High Voltage 72kV Circuits," *IEEE Trans. Power App. Syst.*, vol. PAS-99, 2, pp. 658-666, March/April 1980.

[17] Wang Zhongyi, Wang Jimei, "Theoretic Research and Design on High Voltage Vacuum Interrupter With Long Electrode Distance," *Proc. 17th ISDEIV,* (IEEE Catalog No. 96CH35939), pp. 258-262, July 1996.

[18] P. G. Slade, P. O. Wayland, G. McCracken, R. E. Voshall, A. Bamford, R. Yeckley, H. Spindle, "The Development of a Vacuum Interrupter Retrofit for the Upgrading and Life Extension of 121kV-145kV Oil Circuit Breakers," *IEEE Trans. Power Delivery,* Vol. 6, No. 3, pp.1124-1131, July 1991.

[19] Farrall, G.A., "Electrical Breakdown in Vacuum" *Vacuum Arcs: Theory and Application,* ed. J. M. Lafferty (John Wiley and Sons, NY), pp. 69-74, 1980.

[20] ANSI/IEEE Standard C37.09-1999, Test Procedures for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[21] IEC Publication 694, Common Clauses for High-Voltage Switchgear and Control Gear Standards, Clause 6. "Type Tests," Note 3.

[22] B. Southerlin, "An Environmentally Friendly, Maintenance Free, Universal Protection Device", *Proc. Int'l. Conf. On Trends in Distribution Switchgear*, IEE Conf. Pub. 459, pp. 7-12, Nov. 1998.

[23] M.B.J. Leusenkamp, J.H.L.A. Hilderink, and K. Lenstra, "Field Calculations on Epoxy Resin Insulated Vacuum Interrupters," *Proc. XVII Int'l. Symp. On Discharges and Insulation in Vacuum*, IEEE Catalog No. 96CH35939, pp. 1065-1069, July 1996.

[24] K. J. Cornick, "Current-Chopping Performance of Distribution Circuit Breakers," *Proc. 2nd IEE Conf. On Developments in Distribution Switchgear*, pp. 12-16, May 1986.

[25] R. P. P. Smeets, "Switching Inductive Current With Vacuum Switchgear," IEEE Tutorial on the Vacuum Switchgear, TP-150-0, 1999.

[26] M. B. Schulman and P. G. Slade, "Sequential Modes of Drawn Vacuum Arc Between Butt Contacts for Currents in the Range 1kA to 16kA," *IEEE Trans. Comp., Packag., Manufact. Technol.* A, vol. 18, pp. 417-422, June 1995.

[27] M. B. Schulman, P. G. Slade, L. D. Loud, and W. P. Li, "Influence of Contact Geometry and Current on Effective Erosion of Cu-Cr, Ag-WC and Ag-Cr Vacuum Contact Materials", *IEEE Trans. Components Packaging and Mfg. Tech.* Part A, Vol. 22, No. 3, Sept. 1999.

[28] M. B. Schulman and R. K. Smith, "Better Interpretation of Vacuum Interrupter Tests," *IEEE Industry Applications Magazine*, Vol. 5, No. 2, pp. 18-27, March/April 1999, with an "Erata" in Vol. 5, No. 4, p. 8, July/August 1999.

[29] R. D. Garzon, *High Voltage Circuit Breakers: Design and Applications*, Pub. Marcel Dekker, Inc., pp.29-75, 1997.

[30] R. K. Smith, "Tests Show Ability of Vacuum Circuit Breaker to Interrupt Fast Transient Recovery Voltage Rates of Rise of Transformer Secondary Faults," *IEEE Trans. On Power Delivery*, Vol. 10, No. 1, January 1995.

[31] B. K. Gupta, N. E. Nilsson, and D. K. Sharma, "Protection of Motors Against High Voltage Switching Surges, *IEEE Trans. Energy Conversion*, vol. 7, pp. 139-147, Mar. 1992.

[32] M.N. Jackson, G. M. Richards, D. Kadwa, and K. J. Cornick, "Transients Associated With Distribution Circuit Breakers During Induction Motor Switching," *Proc. IEE Conf. Developments in Distribution Switchgear*, May 1986.

[33] D. Paul and S. I. Venugopalan, "Power Distribution System Equipment Overvoltage Protection," *IEEE Trans. Ind. Applica.*, vol. 30, pp. 1290-1297, Sept./Oct. 1994.

[34] T. Itoh, Y. Murai, T. Ohkura, and T. Takani, "Voltage Escalation in Switching of Motor Control Circuit by Vacuum Contactor," *IEEE Trans. Power Appl. Syst.*, vol. PAS-91, pp. 1897-1903, Sept./Oct., 1972.

[35] M. Murano, T. Fujii, H. Nishikawa, S. Nishiwaki, and M. Okawa, "Three Phase Simultaneous Interruption in Interrupting Inductive Current Using Vacuum Switches," *IEEE Trans. Power App. Syst.*, vol. PAS-93, pp. 264-271, Jan./Feb. 1974.

[36] H. Ohashi, H. Koike, M. Okawa, and Y. Imajyo, "Switching Surge and Application of Vacuum Contactors and Vacuum Circuit Breakers," presented at the IEEE-PES Winter Meeting and Tesla Symp., New York, NY, Jan. 1076, Paper A76 173-5.

[37] Y. Murai, H. Toya, and T. Nitta, "Statistical Property of the Breakdown of Vacuum Circuit Breakers and Its Influence on the Surge Generation in Capacitive and Reactive Current Interruption," *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 232-238, Jan./Feb. 1979.

[38] S. H. Telander, M.R. Wilhelm, and K.B. Stump, "Surge Limiters for Vacuum Circuit Breaker," IEEE Trans. Ind. Applica., vol. 24, pp. 1672-1677, Oct. 1998.

[39] A. Greenwood and M. Glinkowski, "Voltage Escalation in Vacuum Switching Operations," *IEEE Trans. Power Delivery*, vol. PD-3, pp. 1698-1706, Oct. 1988.

[40] Y. Matsui, T. Yokoyama, and E. Nmeya, "Reignition Current Interruption Characteristics of the Vacuum Interrupter," *IEEE Trans. Power Delivery*, vol. 3, pp. 1672-1677, Oct. 1988.

[41] R. Pretorius, Guide for the Application f Switching Surge Suppressors to Medium Voltage Motors, South African Electric Power Coordinating Committee, 1992.

[42] IEEE Red Book, IEEE Recommend Practice for Electrical Power Distribution for Industrial Plants, IEEE Std. 141-1993, Chap. 6 – Surge Suppression.

[43] P. G. Slade, "Vacuum Interrupters: The New Technology for Switching and Protecting Distribution Circuits," *IEEE Transactions on Industry Applications*, vol. 33, No. 6, pp. 1501-1511, Nov./Dec. 1997.

[44] M. Glinkowski, A. Greenwood, J. Hill, R. Mauro, and V. Varneckes, "Capacitance Switching With Vacuum Circuit Breakers – A Comparative Study," *IEEE Trans. Power Delivery*, vol. 6, pp. 1088-1095, July 1991.

www.ElectricalPartManuals.com

[45] B.A.R. McKean and C. Reuber, "Magnets and Vacuum – The Perfect Match," *Proc. 5th Int'l. Conf. On Trends in Distribution Switchgear*, IEE Pub. No. 459, pp. 73-79, Nov. 1998.

[46] A. Sabot, C. Morin, C. Guillaume, A. Pons, J. P. Taisne G. LoPizzo, and H. U. Morf, "A Unique Multipurpose Damping Circuit for Shunt Capacitor Bank Switching," *IEEE Trans. Power Delivery*, vol. 8, pp. 1173-1183, July 1993.

[47] A. Greenwood, *Electrical Transients in Power Systems*, 2nd ed. New York, Wiley 1991.

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THE APPLICATION OF THE CUTLER-HAMMER VACUUM INTERRUPTER TO SWITCH, CONTROL AND PROTECT THE WORLD'S DISTRIBUTION CIRCUITS

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Dr. R. Kirkland Smith. Senior Member IEEE
Cutler-Hammer

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ABSTRACT

This white paper provides application guidelines for, and will show the advantages of, applying vacuum interrupters (VI's) to switch and to protect a wide variety of power distribution circuits. The high voltage design and testing of the VI is discussed with special reference to both the internal and external requirements including the external creep distance. The performance of VI's for load switching and for short-circuit interruption is discussed with reference to long-term switching life and low maintenance costs. During this discussion, the special advantages of the VI are presented as well as operating parameters to consider while short circuit testing. Transformer secondary protection, short line fault switching, non-sustained, destructive discharges and quality testing are also presented. The effects of current chop, virtual current chop and voltage escalation on the components in a distribution circuit are examined and straightforward methods to minimize them are presented. The advantages of using VI's for long life, maintenance-free performance for capacitor switching, and for motor switching are discussed. The white paper shows how the special characteristics of VI's can be used to produce a circuit breaker that will reliably protect all types of distribution circuit.

1. INTRODUCTION

Cutler-Hammer (C-H) (formerly Westinghouse Distribution and Control Business) has had close to 40 years experience in research, development, design and application of the Vacuum Interrupter (VI) [1]. There are over two million C-H VI's in the field controlling a wide variety of circuits in over 40 countries around the world. Research and development of the C-H VI began in 1960 at the then Westinghouse Research Laboratories in Pittsburgh, Pa., U.S.A. By the mid-sixties, the technology had been transferred to the Horseheads Operation in New York State where the first commercial VI's were produced. From the mid-sixties to 1994 the Westinghouse Horseheads Operation and the Westinghouse Central R&D Center worked together to extend the range of current and voltage interrupted and to extend the application of the VI. In 1994 when Eaton/Cutler-Hammer took over the Distribution and Control Business from Westinghouse, the R&D department with its High Power Laboratory was moved to the Horseheads Operation. All VI activities were thus aligned in one facility. This has not only accelerated the development of the VI product, but has also allowed C-H to maintain the tradition of continuous development, product improvement, and application extension. The C-H VI has now found wide application not only in C-H circuit breakers and contactors, but also with many OEM customers: e.g. in circuit breakers, reclosers, load break switches, contactors, capacitor switches, sectionalizers, and ring main units.

The R & D we have undertaken has led to a continually improved VI product; for example the size of our modern VI is markedly smaller than ones built in the 1960's and the capability is greatly increased. Figure 1

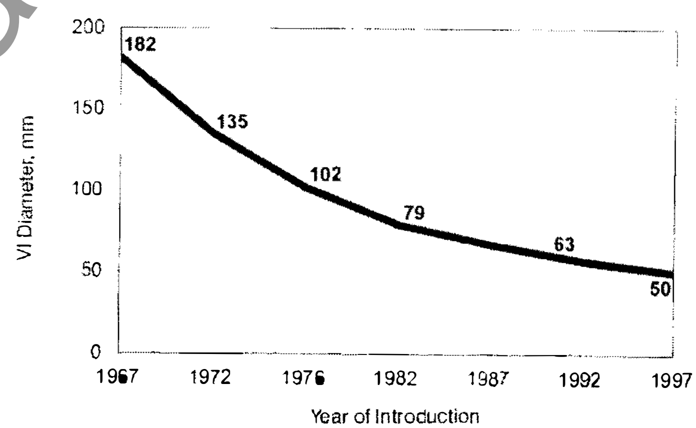

Fig. 1: Vacuum Interrupter Size Reduction for the 15kV, 12kA Function: Cutler-Hammer's Experience

shows an example for the 15kV, 12kA function. Here it can be seen that the diameter of the VI has been reduced from 180 mm in 1967 to 50 mm in 1997. This size reduction has resulted from our increased knowledge of vacuum technology, vacuum processing, vacuum contact materials [2], vacuum arc control [3,4] and VI design [5, 6].

The application of the VI to protect power distribution circuits has also grown in this time period as shown in

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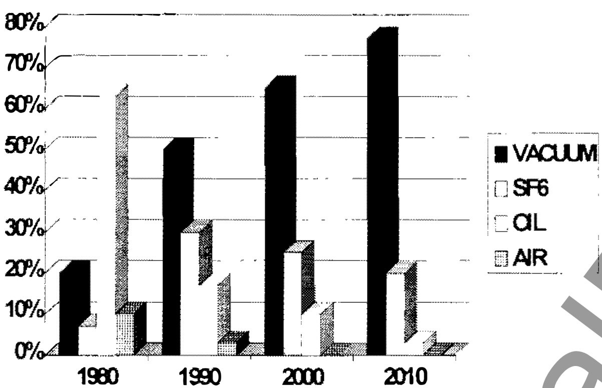
Fig. 2. In fact, the acceptance of the vacuum circuit breaker (VCB) has been such that it is now recognized as having the highest level of reliable performance and the lowest level of required maintenance of all technologies available to control and protect distribution circuits. The design philosophy at C-H has always been and continues to be the application of the VI to the widest possible range of international application. This means that we have developed a thorough knowledge of all certification testing standards. When C-H works with an OEM in a given country, we make sure that the VI we supply will perform satisfactorily during that country's certification test series. C-H has VI's that can be applied in equipment designed to meet Chinese (DL & GB), IEC, ANSI, BS, VDE, and other standards. This does, of course complicate our development process, but we are proud to say that there is a C-H VI design that will meet any of the international certification tests in the voltage range from <1kV to 40.5V.



- **Year 2000 Vacuum/SF_6 Ratio: 2.6/1**
- **KEMA 1991-1996 Certification Ratio: 3.2/1**

Fig. 2: World Wide Trend for Interrupters Used In Medium Voltage Circuit Breakers And Reclosers

The present worldwide consensus is that the VCB and the vacuum recloser will be the dominant technology in the first two decades of the twenty-first century, even though the SF_6 gas technology, primarily developed for transmission circuits (≥72kV), has been downsized to compete for the distribution protection market. There are three major areas where it is becoming increasingly difficult for SF_6 to compete with vacuum.

(1) Long life – it is now possible to produce cost-effective VI designs having electrical lives that exceed the required mechanical life of the circuit breakers, and will even be able to satisfy a recent IEC requirement of extended short-circuit operating life;

(2) Environmentally benign – VI's are constructed from environmentally benign materials. They do not provide a potential source of greenhouse gas (SF_6) that can enhance global warming [7]. The VI does not pose the potential health risk that exposure to arced SF_6 gas does [8], nor does it need the special hazardous waste handling that SF_6 interrupters require when routine maintenance is performed or when the SF_6 interrupter is disposed of at the end of its life; and

(3) Overall superior performance – this is a direct result of the extensive research and development that has been and continues to be performed by the universities and by the manufacturers of VI's [9].

This paper provides a background to the reader for the application of the VI to the protection and the control of power distribution circuits. It will also provide the potential user of this technology with a broad guide to the literature on these applications [5, 10-12]. The purpose is twofold: firstly, to provide the user with knowledge of the ability of the VI to satisfy all distribution circuit switching requirements, and secondly, to address some misconceptions of VI performance.

2. HIGH VOLTAGE VACUUM INTERRUPTER DESIGN

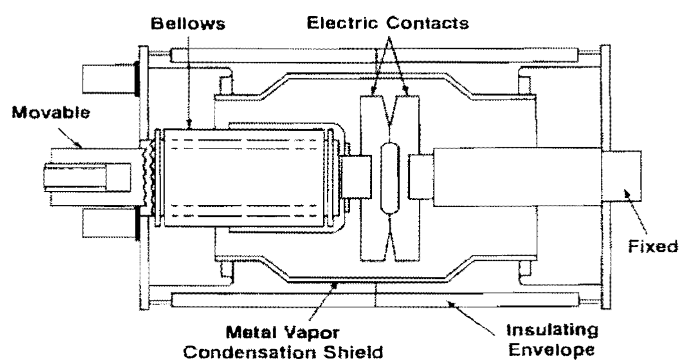


Fig. 3: Cross Section of a Vacuum Interrupter

A cross section of a vacuum interrupter is shown in Fig. 3. The contact material development and the design of the contacts have been well documented [2, 13]. Modern VI's using state-of-the-art vacuum-sealing techniques, such as vacuum furnace brazing [14], are built to retain their state of high vacuum for their entire lives: typically at least 30 years. One characteristic of vacuum brazing is that seal leaks are usually evident very early in the life of the VI. Cutler-Hammer therefore

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performs extensive quality assurance testing to identify those few VI's that have defective seals. Examples of this testing are high-pressure gas storage, vacuum measurement, and voltage withstand. This testing ensures that VI's reaching the field have an extremely high probability of maintaining their high vacuum condition. Table I shows another manufacturer's experience of VI reliability from 1970 to 1975 [15]. In our experience, once a VI has been in the field from three to four years, it will continue to be vacuum tight for life. Also, in these first few years, there is less than one chance in 100,000 of a vacuum leak occurring.

TABLE I:
Statistics of Vacuum Life

YEAR OF MANUFACTURE	NUMBER	VACUUM LIFE, YEARS		
		<80	80-160	>160
1970-1971	9000	0%	19.3%	80.7%
1972	500	0%	1.6%	98.4%
1973-1975	3000	0%	1.5%	98.5%

There are two major aspects to VI design: (a) the high voltage design, and (b) the current interruption design. In this section we will consider the high voltage design and in the following sections we will consider current interruption under different circuit conditions. C-H VI's are designed to operate at the normal system voltages listed as preferred in the applicable standards. In addition, they are designed to satisfy the overvoltage withstand requirements for these system voltages, i.e.

(a) Rated ac power frequency withstand voltage.
(b) Rated lightning impulse withstand voltage.

These ratings establish a conservative safety factor in the design to provide for an ability to withstand occasional overvoltages that can occur in a power system from normal switching operations, or from more abnormal natural causes such as lightning. These overvoltage withstand ratings can be expressed as multiples of the rated system voltage. At distribution levels of 3 to 72 kV these multiples are as follows:

Rated Overvoltage	Multiple Of The Rated System Voltage Or Normal Operating Voltage
Rated AC Power Frequency Withstand Voltage	2 to 4 times
The Rated Lightning Impulse Withstand Voltage	4 to 12 times

The test to demonstrate the ability to withstand the rated ac power frequency withstand voltage (sometimes called a Hipot test) is a deterministic test, that is, the test voltage must be withstood for 1 minute with no breakdowns. This is a simple pass or fail definition and at the stress level of 2 to 4 times the normal operating voltage, the ac hipot test is readily passed by properly designed and conditioned VI's. In contrast, the test to demonstrate the ability to withstand rated lightning impulse withstand voltage is a statistical test, that is, 1 or 2 breakdowns are permitted in a group of a certain number of tests. The impulse test is also readily passed by properly designed and conditioned VI's, but this test's criteria are tolerant of the occasional breakdown at the rated impulse voltage. In fact, according to the testing standards, a component satisfies the lightning impulse requirement when it withstands the rated impulse voltage about 90% of the time. The values of these two test overvoltages do not ensure that all possible overvoltages will be withstood, but the requirements do provide that the power circuit will be protected from the most typical overvoltages that can occur in service.

2.1 High-Voltage, Vacuum Interrupter Design – Internal Design

The development of C-H VI's that satisfy the voltage withstand requirements has been greatly assisted by the advent of powerful, comparatively low cost, personal computers, and user-friendly finite element analysis (FEA) software. This has enabled Cutler-Hammer design engineers to routinely perform FEA on both electrical and magnetic fields, with the result that changes in design can be rapidly analyzed and compared to design rules established over the years by empirical methods. Figure 4 shows a typical two-dimensional potential plot for an experimental vacuum interrupter. As the computers have become more powerful, it is now possible to perform three-dimensional analysis. This type of analysis has been instrumental in optimizing the spacing between the vacuum interrupter components so that the development of vacuum interrupters capable of operating in sub-transmission circuits at 72kV [16] and at transmission voltages [17] has become possible. Using VI's in series we have, in fact, already demonstrated effective circuit breaker performance at 145kV [18]. We show in Table II C-H VI designs that have been successfully tested for operation at the distribution voltage range, 35kV – 40.5kV.

TABLE II:
CUTLER-HAMMER VACUUM INTERRUPTERS FOR CIRCUIT BREAKER APPLICATION AT 35KV – 40.5KV

VI DIA	CONTINUOUS CURRENT RANGE	SHORT CIRCUIT CURRENT RANGE	AC WITH-STAND VOLTAGE	IMPULSE WITH-STAND VOLTAGE
Mm	Amps	kA	kV,rms	KV
63	630 – 800	8 – 10	80	170
75	630 – 1250	12.5 – 16	80	170
102	630 – 1600	16 – 25	95	170 – 200
135	1250 – 3150	25 – 40	95	170 – 250

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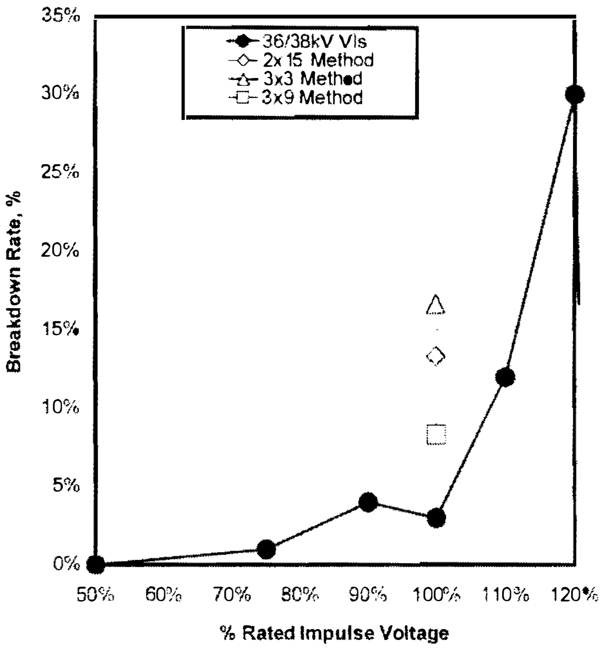

Fig. 5: Breakdown Rate in % vs % of Rated Impulse Voltage for 36/38kV VI's With 170kV BIL

2.3 High-Voltage, Vacuum Interrupter Design – External Design

FEA has evolved into an extremely useful design tool for optimizing the internal design of high-voltage vacuum interrupters. It has also been useful in developing VI's with a more uniform stress across the outside of the VI as is shown in Figure 4. It is essential to consider the external stress on the VI, because it is imperative that once the VI has opened that any circuit voltage impressed on the VI does not cause a breakdown across the outside of the VI's body. Looking at Figure 4, there are three things to consider in the external design.

(1) The length of the ceramic between the two end plates.
(2) The creep distance along the ceramic.
(3) The dielectric medium in which the VI will be housed.

The ceramic length

Figure 6 shows the breakdown strength of an air gap between two shaped plates. At 10 mm the breakdown is 31kV (or 3.1kV/mm), and at 300 mm the breakdown is 735kV (or 2.54kV/mm). If a right cylinder of ceramic if placed between the shaped plates, then the

TABLE III: Recommended Voltage Steps for Impulse Testing

TEST CONDITION	VOLTAGE POLARITY	TEST VOLTAGE APPLIED	NO. OF TRIALS
INITIAL	**POLARITY**	**% OF RATED**	
Preliminary	Positive	50%	3 Note 1
	Positive	75%	3 Note 1
	Positive	90%	3 Note 1
Certification	Positive	100%	N Note 2
REVERSE	POLARITY		
Preliminary	Negative	50%	3 Note 1
	Negative	75%	3 Note 1
	Negative	90%	3 Note 1
Certification	Negative	100%	N Note 2

Notes to TABLE III

Note 1: If a disruptive discharge occurs in one of these Trials, then use the 3x3 method at this voltage or, for more conditioning, perform additional trials at the same voltage until 3 to 5 impulses are withstood in a row.

Note 2: The number of trials performed at the rated impulse withstand voltage depends on the standard used.

For IEC tests to IEC standard 56 and 694 and 60:
N = 15 and Pass ≤ 2 breakdowns in 15 trials., i.e. <13.3%.

For ANSI tests to C37.09 and IEEE Standard 4:
N = 3 or 6 and Pass ≤ 1 breakdown in 6 trials, i.e. <16.6%.

For both ANSI and IEC Standards, recent revisions: N = 3 or 12 and Pass ≤ 1 breakdown in 12 trials, i.e. <8.3%.

breakdown voltage is decreased dramatically. Now a 10mm gap will only have a breakdown voltage of 16kV(1.6 kV/mm), and at 300mm the breakdown voltage will be only 270kV (or 0.9 kV/mm). The lowering of the breakdown voltage results from a number of effects: collection of charge on the ceramic surface, higher field stresses at the ceramic to metal interface, condensation on the ceramic surfaces, etc. From these data it is wise to allow a 'safety factor' of at least 3 over the air breakdown value when a ceramic cylinder is placed between the plates. The maximum voltage that a VI is subjected to is the lightning impulse voltage. For standard test purposes, a lightning impulse voltage is simulated by a 1.2 x 50 microsecond voltage wave. The Basic Insulation Level (BIL) is the lightning impulse voltage that a device can withstand approximately 90% of the time. As we have already

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discussed in Section 2.2, it is imperative that an open VI in a circuit breaker does not flash over externally when subjected to its rated impulse voltage. The C-H experience of ceramic length required to completely satisfy the BIL requirements is also shown in Fig. 6. It shows that the design criterion C-H uses is somewhat conservative. The ceramic length for the VI is always more than the experiment of a right cylinder between two plates would suggest. Figure 7 shows examples of two VI's, one rated for 110kV BIL and the other rated for 150kV BIL.

condensation and the deposit of atmospheric pollution on the ceramic surface. For applications where severe atmospheric pollution is common in urban and industrial areas and/or where water vapor condensation on the ceramic can occur, more conservative creep values can be used than has been the standard practice up until the present. For example, the Chinese creep values are about 2 times those calculated in the VI examples shown in Fig. 7. The new Chinese creep standard considers both the condensation effect and the pollution effect around metal enclosed switchgear. These effects are characterized as follows:

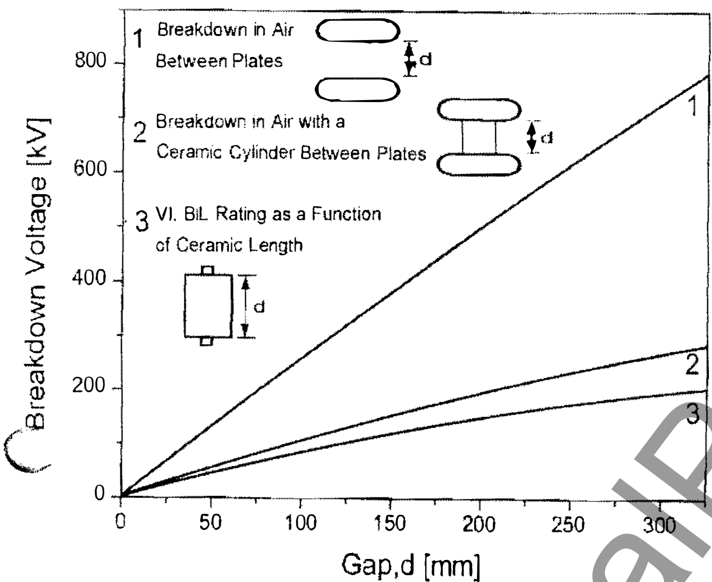

Fig. 6: Comparison of the Voltage Breakdown As a Function of Gap of Parallel Plates In Air, Parallel Plates With a Right Ceramic Cylinder Between Them, and the Length of VI Ceramic Used to Withstand a Given BIL Rating in Air.

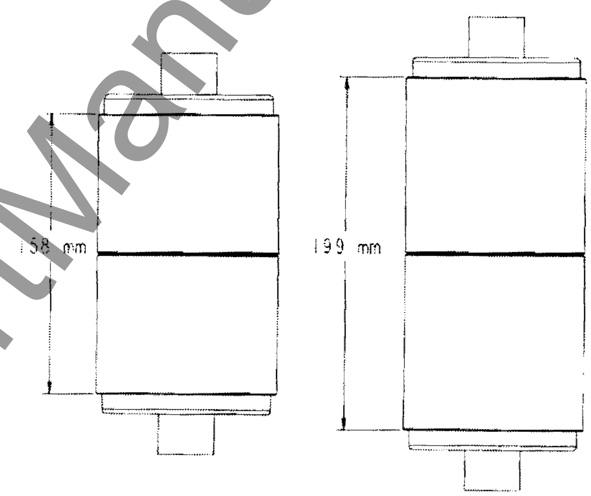

Fig. 7: Examples of Vacuum Interrupters With Two Ceramic Lengths, the Shorter VI has a BIL Rating of 110kV and the Longer One has a BIL Rating of 150kV.

The creep distance

The creep distance is the distance along the ceramic between the end plates. One way of expressing the creep distance is in mm/kV, where the total length L expressed in mm is divided by the rms line to line voltage. So in Fig. 7 the shorter VI with a ceramic length of 158 mm is suitable for use in a 17.5kV circuit, and thus has a creep value of 9 mm/kV. The longer VI with a ceramic length of 198mm can be used in a 27kV circuit, and thus has a creep value of 7.3mm/kV. These creep values have been found to be extremely reliable for use in both indoor and outdoor circuit breakers where there is very low probability of both water

Condensation classification		
Class	**Description**	**Frequency**
C_o	Condensation does not normally occur	≤ 2 times/year
C_l	Condensation occurs with low frequency	< 2 times/month
C_h	Condensation occurs frequently	> 2 times/month

Pollution Classification	
Class	**Description**
P_o	No pollution
P_l	Light pollution
P_h	Heavy pollution

Taking into account that in China P_o is unrealistic and that manufacturers should be conservative if the

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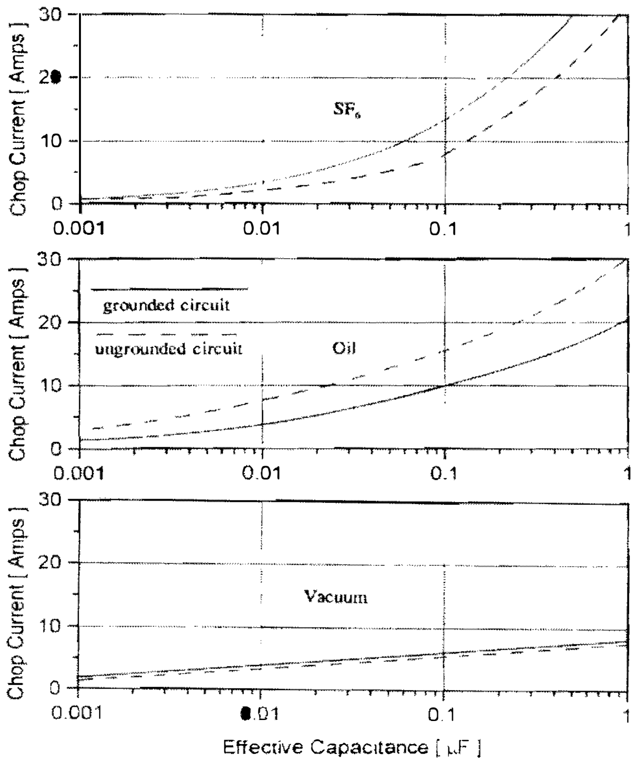

Fig. 11: Comparison of Chop Current Characteristics For Vacuum, SF_6, and Oil Interrupters

as that of the preceding current that was just interrupted. Then the TRV changes to a polarity opposite to that of the preceding current that was just interrupted, and, moreover, that due to current chopping, the TRV peak then reached is higher than the case without current chopping. However, this first peak of TRV, even with this extreme level of chop current, is only 20% higher than the value expected with zero chop current. Such a modest increase in the peak voltage is not of concern for load insulation.

Thus, with the contact materials used in modern VI's, current chopping is not of concern when considering surge protection.

4. LOAD CURRENT SWITCHING

The performance of the VI for load switching is truly outstanding. For currents below about 5 kA, the diffuse vacuum arc is formed between the opening contacts [26]. This arc is characterized by multiple cathode spots moving randomly across the cathode contact and a passive anode contact collecting current uniformly

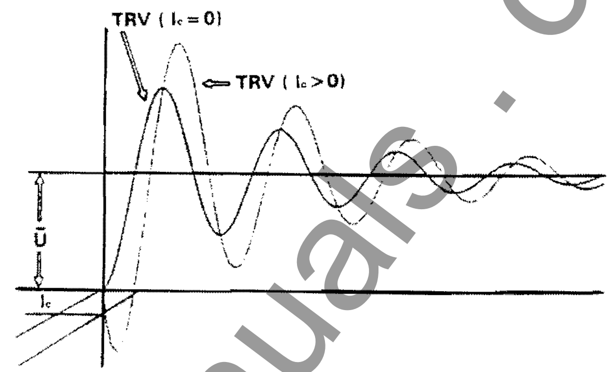

Fig. 12: Transient Recovery Vol.tage After Inductive Load Switching With and Without Current Chopping (I_c)

across its entire surface [5]. This vacuum arc will always interrupt the ac current at the first current zero after a contact gap that will withstand the recovery voltage has been reached. Contact erosion is only observed on the cathode and is quite uniform over the cathode surface. For modern contact materials like Cu-Cr [27], the erosion is between 0.04×10^{-4} and $0.4 \times 10^{-4} g.C^{-1}$ (grams/coulomb). In this case $C = \int I\,dt$ and the integral is taken over the complete arcing time, i.e., from the time the contacts part and the arc is initiated until the arc is extinguished at a current zero. The exact value depends upon the contact spacing and the fraction of material eroded from the cathode that is deposited upon the anode. In an ac circuit, the contact parting event occurs at random with respect to the current. Therefore, the contacts are a cathode on some switching operations and an anode on other switching operations, so that material eroded from one contact and deposited upon the other, would be redeposited on the original contact during a subsequent operation [27]. Using this erosion rate and knowing the size of the contacts of the VI, it is easy to show that the electrical switching life of the VI's used in circuit breakers and reclosers far exceeds the usual mechanical life of these devices. Indeed, VI's are now beginning to be used for electric railroad switching systems where electrical and mechanical lives of 250,000 operations are required. Of course, C-H has developed contactor VI's for motor control where switching lives in excess of 10^6 operations are regularly observed.

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For the user of a very-long-life interrupter, it is essential for the contacts to maintain a low and constant contact resistance (R_c) for their whole life. The VI contact with its uniform erosion and with the lack of an ambient gas will, indeed, maintain a low and constant R_c in a manner that cannot be matched by any other interrupter technology. Users of SF_6 interrupters, for example, have experienced increases in the value of R_c as the interrupter is operated under load. This is a consequence of the chemical processes that take place on the contact surfaces, between the contact metal and the SF_6 gas, during and after arcing, each time the interrupter is operated. In addition, metal fluoride powders, which are insulating and are produced as arcing by-products, can in some designs interfere with contact mating and thereby cause an increase in contact resistance. So vacuum with its preserved clean interior is much better at preserving a low resistance, coolly operating contact interface.

5. SHORT CIRCUIT INTERRUPTION

In addition to outstanding performance in interrupting normal load currents, the C-H VI also has demonstrated superior performance in interrupting short circuit currents. VI designs are commercially available that interrupt short circuit currents from 2kA (rms) to 63kA (rms).

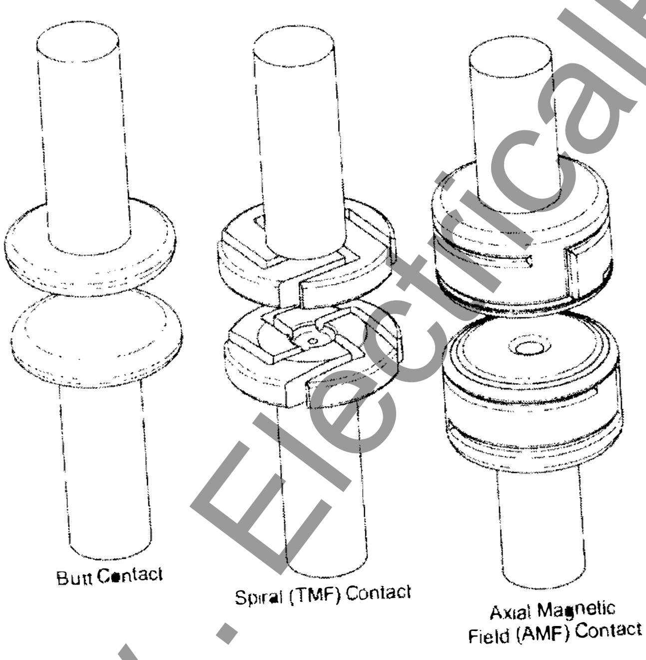

Fig. 13: Contact Structures Used In Vacuum Interrupters

The high current vacuum arc naturally tends to form a constricted column [5]. Thus in VI's designed to interrupt currents above approximately 5kA, this high current arc has to be controlled with a contact design. There are two main types of contact designs; one that causes the arc to rotate around the contact surfaces [3] by using a transverse magnetic field (TMF) and the other that forces the arc back into the diffuse mode by use of an axial magnetic field (AMF) [4], see Fig. 13. Figure 14 shows the present interrupting ability of the two contact structures as a contact

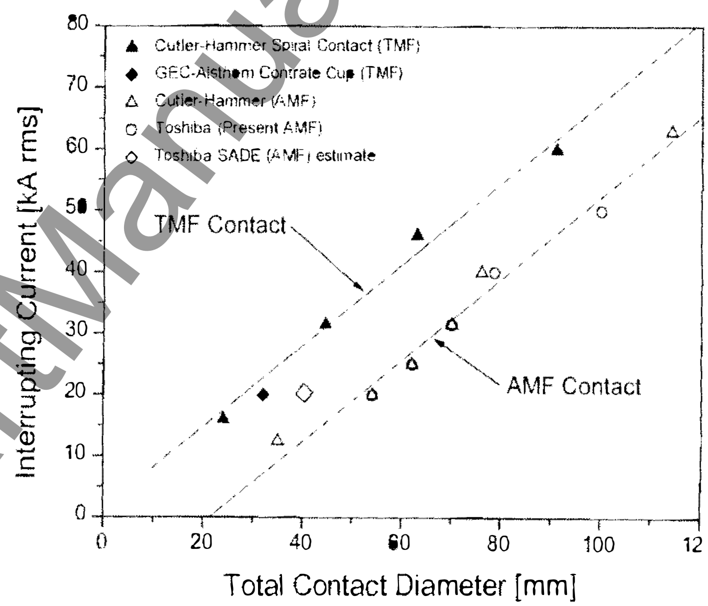

Fig. 14: Comparison of the Interruption Ability of Tansverse Magnetic Field and Axial Magnetic Field Contacts as a Function of Total Contact Diameter in a 12kV Circuit

function of contact diameter in a 12kV circuit. For 35kV-40.5kV applications C-H uses the axial magnetic field contact structure exclusively. The AMF structure is preferred because it is possible to shape it for the best possible high voltage performance and also because this shape is maintained even after short circuit interruption. Each contact design has its advantages and each has the ability to provide long life at the full short circuit rating of the device; VI designs are available that can perform up to 100 full short-circuit operations. For short circuit operation of greater than 100 operations axial magnetic field contacts are usually required. In practice, even a fault that is 80% of the full fault rating is a rarity in normal distribution circuits, and most faults are of much lower value. Thus, the life of the VI will easily exceed the short-circuit life requirements of any practical distribution circuit. VI's also have no "blind spots" or "critical currents," i.e., there is no current from the smallest load current up to the full short-circuit current

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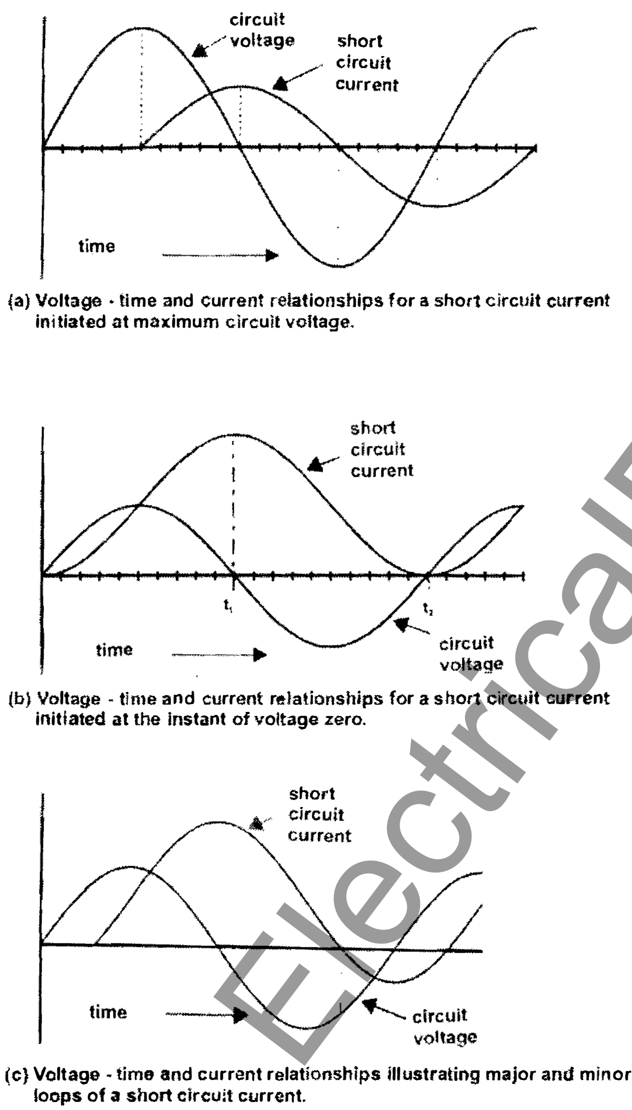
where the interrupter has difficulty interrupting. Beyond their full short-circuit rating, the probability of failure to interrupt gradually increases [28]. If a VI is forced to switch a current up to 125% of its rating and if a backup breaker removes the fault within a reasonable time, the VI will suffer little permanent damage and will subsequently interrupt currents up to its rating without difficulty. This distinguishes the VI from other technologies which have fairly well defined interruption levels and arcing times. When SF_6 or oil filled devices are operated at currents beyond these limits, they will, at the best, be permanently damaged and, at the worst, will cause an explosion in the switchgear housing.



(a) Voltage - time and current relationships for a short circuit current initiated at maximum circuit voltage.

(b) Voltage - time and current relationships for a short circuit current initiated at the instant of voltage zero.

(c) Voltage - time and current relationships illustrating major and minor loops of a short circuit current.

Fig. 15: Examples of Short Circuit Current Waveforms For Short Circuits Initiated at Three Different Voltage Conditions

When interrupting short circuits the interrupter must be able to deal with the asymmetric current that will occur on one or more of the phases in a three-phase fault. Figure 15 illustrates the asymmetric current wave in one phase [29] once the contacts in a circuit breaker open and an arc is formed. The arc permits the flow of current in the circuit until a natural current zero occurs. If the conditions are favorable at the current zero the arc in the interrupter will be extinguished and the circuit will be interrupted. Traditionally, the arcing time for a circuit breaker has been characterized in terms of a minimum value and a maximum value. The concept of minimum and maximum arcing times are, however, highly dependent on the interruption technique and the interrupting conditions, especially the current magnitude and degree of asymmetry. Each interruption technology has its own unique requirement when arcing times are considered. When testing a circuit breaker to demonstrate its rating, it is required to demonstrate performance at the minimum arcing time, at the maximum arcing time and an average arcing time. For SF_6 or oil circuit breakers, the maximum arcing time is approximately equal to the minimum arcing time plus the time interval of ½ cycle of the power frequency. The time interval between the minimum and maximum arcing times is often referred to as the interrupting window. This window is an interval during which interruption must successfully take place before the interruption effort is fully expended and interruptions after this time are no longer possible. If the arcing were to continue past this time, the SF_6 or oil breaker would fail. Demonstrating performance at the maximum arcing is especially important for interrupters such as SF_6 puffers that run out of the gas flow required to produce [illegible] interruption when the full open position is reached. So the concept of an interrupting window during which interruption is possible is extremely important for some interrupter technologies. If the interrupting window is too small to cover the range from the minimum arcing time of the interrupter to the maximum that the system imposes, then the circuit breaker will not work successfully under all possible conditions.

For vacuum circuit breakers, on the other hand, the concept of the interrupting window is not as applicable since contact motion is not required for interruption to take place. Once some minimum contact gap is reached, arc interruption is affected by the geometry and materials of the contacts, the vapor shield and the degree of vacuum present inside the interrupter at current zero. Once the full open gap is reached, the arcing can continue for some time until an appropriate current zero arrives and interruption occurs. So the maximum limit on arcing time is not determined by the mechanical travel time, but is more a function of the amount of arc energy that can be absorbed within a particular interrupter. In fact, vacuum interrupters can be applied at quite low power frequencies such as 10 Hertz when the arcing times must be much longer since ½ cycle is 50 milliseconds, provided the total arc energy is maintained within acceptable limits.

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For vacuum circuit breakers, arcing times are generally short at normal power frequencies such as 50 or 60 Hertz. However, interruption at any one particular current zero is a statistical event, especially near the upper limit of current rating, and when the current wave is asymmetrical. The arcing times for a vacuum circuit breaker can range from very short values to much longer values. The minimum arcing time is generally about 3 or 4 milliseconds, but times as short as 1 or 2 milliseconds are occasionally observed. Maximum arcing times of 20 milliseconds or more have been observed. However, it is far more likely to observe an arcing time between 3 and 14 milliseconds with a value of 8 to 10 milliseconds (or ½ cycle) being the most common. It is no coincidence that the time required for the interrupter contacts to reach a value between 75% and 100% of full open point is also about ½ cycle. In addition, the distribution of arcing times tends to trend toward longer values as the current approaches the limit of performance for a particular interrupter.

One interesting characteristic of a VI when interrupting an asymmetric current wave is that the probability of interruption after the end of a major loop, where the current magnitude is at its highest, is about 50%. Interruption will usually occur at the end of the following minor loop where the current magnitude is much lower. As a result, if one attempts to demonstrate a maximum arcing time where the final current loop is a major loop, the interrupter may simply skip this current zero and a different pole will be the first to clear. Finally, the intended pole then will clear the remaining single-phase current in series with the third pole. This results in a maximum arcing time that is longer than the traditional value of the minimum arcing in time plus the time interval of ½ cycle of the power frequency, however, this is perfectly acceptable as long as the circuit is in fact interrupted.

The three different methods of testing discussed below each present some challenges when attempting to demonstrate the maximum arcing time in a VCB.

- For 3-phase direct tests, the minimum and maximum arcing times are supposed to be demonstrated in the pole with the first pole to clear TRV. The TRV peak is appropriately reduced as a result of the phase shift of the current zero from being coincident with the peak of the system voltage by the effect of the current asymmetry. However, vacuum interrupters are non-deterministic in that they have a significant but definitely not 100% probability of interrupting with very short arcing times. So it is often observed that another pole will have a current zero with symmetrical current or a minor loop of current and will interrupt just before the pole with the asymmetry has its current zero. The non-deterministic nature of vacuum interrupters means that this behavior is not predictable. So in such tests, the pole with the required asymmetry may no longer be the first pole to clear and hence will have a lower TRV that the first pole to clear TRV. Such behavior is perfectly acceptable in the real world, because the VCB will behave this way in the actual power system. However, the non-deterministic nature of vacuum interrupters complicates the test demonstration by often requiring repeated tests in an effort to get one with the right combination of current asymmetry and first pole to clear TRV.

- For 1-phase direct tests, without the possibility of other phases complicating the situation, it is much easier to control the test conditions to provide the required asymmetry and the first pole to clear TRV in the same pole. Here again, the TRV peak is appropriately reduced due to the phase shift of the current zero from being coincident with the peak of the system voltage by the effect of the current asymmetry. The drawback is that this combination as noted above, may not actually occur in practice, and hence is really more severe test than is required in practice.

- For 1-phase synthetic tests, the test conditions can again be forced to provide the required asymmetry and appropriately reduced first pole to clear TRV in the same pole. However, the test engineer must choose at which current zero to apply the TRV. If the TRV is applied at the end of a major loop, then the interrupter may not interrupt. So a proper demonstration must then be to delay the application of the TRV to the next current zero which will be at the end of a minor loop. There can also be difficulty here in re-igniting the arc at the current zero after the major loop, because the TRV from the high current source is low and easily interrupted by the vacuum interrupter. However, in recent years test labs have been developing new systems to re-ignite the vacuum arc more reliably and efficiently. Also some test labs report that they can supply the proper TRV at more than one current zero. So with enough equipment, the real three-phase world can be simulated synthetically. In fact, some labs have even been able to perform 3 phase synthetic tests.

So demonstrating the maximum arcing time for a VCB can be a challenge.

VI's are capable of performing well for short-circuit situations where high degrees of asymmetry can produce long arcing times, e.g., small generator breakers and also for low-frequency transportation circuits of 16-2/3 Hz.

VI technology also has the outstanding ability to handle the developing fault. This is the situation where the value of the fault current suddenly increases during the time the breaker is opening to clear it. This can occur, for example, when a traveling arc changes a single line-to-ground fault into a double line-to-ground fault. Such events are easily handled by the VI, but they can destroy circuit breakers using other interruption technologies.

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5.1 Voltages and Disturbances Observed During Interruption Testing

After the VI interrupts the current in a circuit during a test, the circuit imposes a voltage across the open contacts. In the first millisecond or so immediately following current zero, this voltage is called the Transient Recovery Voltage (TRV) and at later times this voltage is simply the Recovery Voltage. The TRV and Recovery Voltages are usually unaffected by the VI, however, occasionally, some disturbances are observed during tests that should be explained. Five TRV or Recovery Voltage conditions are described below ranging from the VI having no effect to the VI having a more significant effect on the circuit voltage.

(a) The TRV is withstood - At the first current zero after contact part, the TRV appears across the open VI contacts and is then withstood to successfully interrupt the circuit with no observed disturbances. This is the most typical condition seen during most tests.

(b) The TRV reignites the arc at the first current zero – Sometimes the gap at the first current zero is not large enough to sustain the interruption, and the TRV collapses at a time up to ¼ cycle of power frequency after the current zero. This is called a reignition. The current then flows to the next power frequency current zero where it is once again interrupted and this time the TRV is withstood. This too is a normal event and merely involves a longer arcing time.

(c) The TRV is disturbed but withstood – Occasionally on a test, the TRV is seen to collapse and then instantaneously recover while no power frequency current is observed. If such a disturbance is observed at a time up to ¼ cycle of power frequency after the current zero, then this is referred to as a TRV disturbance that is considered a normal part of the arc interruption process.

(d) The Recovery Voltage is disturbed with no power current flow – Also on rare occasions during a test, the Recovery Voltage is seen to collapse and then instantaneously recover while again no power frequency current is observed. If such a disturbance is observed at a time later than ¼ cycle of power frequency after the current zero, then this is referred to as a Non-Sustained Disruptive Discharge or NSDD. These events seem to be unique to Vacuum Interrupters. When a few NSDDs are observed, this is considered as an event to record. NSDDs are, however, a rare, aspect of the interruption process in vacuum.

(e) The Recovery Voltage collapses and a power current flows – On even rarer occasions, a complete breakdown through the interrupter can occur that re-established the power frequency current. If this event is observed at a time later than ¼ cycle of power frequency after the current zero, then this is referred to as a restrike. The significance of a restrike we believe depends on whether or not the following current is interrupted.

The subject of NSDDs is discussed below from the special perspective of interruption in vacuum to aid in the interpretation of the significance of observing such events during a test series.

The subject of Non-Sustained Disruptive Discharges (NSDDs) sometimes observed when testing vacuum circuit breakers continues to provide many opportunities for interesting discussions among short circuit test specialists. In fact, ***NSDDs are not known to cause performance problems in real world applications***. Certain types of vacuum interrupter sometimes exhibit TRV disturbances and/or NSDDs during tests, especially near the performance limits of the interrupter, e.g., when a VI is tested at or beyond its designed short circuit current rating. An NSDD can occur up to a few seconds after the circuit has been interrupted and is thought to be the result of a microparticle crossing the contact gap and initiating a small discharge within the VI. An NSDD does not result in reestablishment of the power frequency current, but simply results in a very brief high frequency current from the local parasitic capacitance being discharged through the interrupter. The allowable number of trials in which 1 or more NSDD events may occur in a single certification test series has been arbitrarily limited to 3 events in IEC 60056 for high voltage circuit breakers.

This arbitrary limit of 3 NSDD events has been specified at the insistence of the test laboratories whose test experience spans all types of interruption technologies. NSDDs have never been seen in other types of interrupters, and have therefore been viewed with suspicion by the laboratories. However, the occurrence of a few NSDDs during certification testing, does not seem to be of any great significance for performance of VCBs in service. It is therefore a source of continuing controversy over how much importance should be ascribed to the observation of NSDDs when evaluating a circuit breaker for certification. As the significance of NSDDs observed in the testing of vacuum circuit breakers is understood and their affect on VCB performance develops, then we would expect the certification testing standards to evolve and be modified.

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5.2 Interruption of Fault Currents With Very Fast Rates of Rise of Recovery Voltage

Vacuum interrupters using Cu-Cr contacts have an exceptional ability to withstand very rapidly rising Transient Recovery Voltages (TRVs). This is noted especially in two difficult switching duties of interrupting:

- Secondary Faults on Transformers, and
- Short Line Faults on overhead lines.

These fault conditions produce TRVs with very fast rates of rise of recovery voltage (RRRVs) that immediately stress the interrupter following a current zero.

Secondary faults on transformers are applications where VCBs are well suited. The high natural frequency of large power transformers results in a fast rising TRV with a 1-cosine wave shape. Moreover, large power transformers provide little damping, so the peak of the TRV is also high. While the 1-cosine wave shape results in a somewhat slower rate of rise in the first microsecond or two, the average rate of rise of recovery voltage (RRRV) is quite high. When the switchgear is placed a short distance from the transformer, the low capacitance of the connections together with the high natural frequency of the transformer results in a very fast TRV. For example, the rated (T3) time of the TRV is about 60 μs for 12 kV indoor circuit breakers where typical cable connected circuits produce more slowly rising TRVs. However, T3 can be less than 10 μs for a secondary fault on a large power transformer. In an extensive series of experiments [30], it has been shown that VI's using Cu-Cr contact material will reliably interrupt greater than 99.9% of transformer secondary faults that could be expected in the field without the need of TRV-modifying capacitors (see Fig. 16).

Overhead lines, in contrast, produce a sawtooth TRV when a fault is located a short distance from the breaker. The sawtooth TRV wave of the short line fault (SLF) is the result of travelling voltage waves that go out on the line from the breaker and are reflected at the fault and are superimposed on the slower 1-cosine TRV of the source side circuit. Although the fault current value for a SLF is usually lower than the maximum fault interrupting capability of the breaker, the initial TRV of the sawtooth is then very fast in the first microseconds, immediately stressing the interrupter gap. Withstanding such initial fast RRRV stresses were first identified in the 1950's as difficult duties for gas interrupters where the decay rate of the gas temperature is in the same range as the increasing RRRV. However, tests have shown that the decay of the plasma temperature and cathode spot temperature in vacuum interrupters is faster than the typical SLF TRV and thus this duty is easily handled by the vacuum interrupter. So vacuum circuit breakers are also well suited for applications to protect overhead lines.

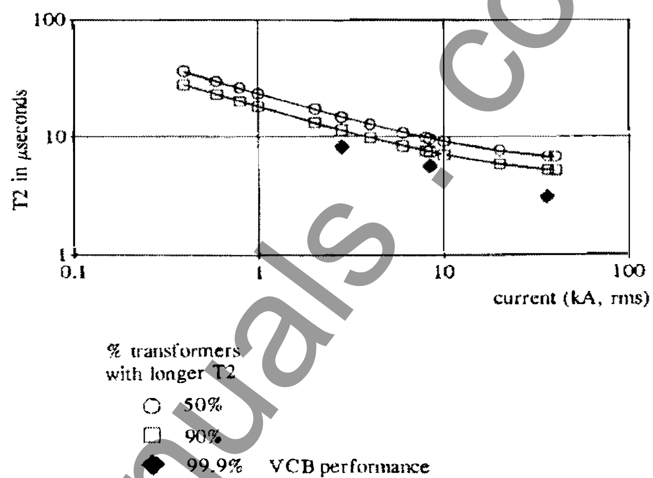

Fig. 16: Comparison of the Expected T2 Values for Transformer Secondary Faults With the Interruption Performance of a Vacuum Circuit Breaker Subjected to Very Fast TRV's

5.3 Developmental and Quality Testing of Cutler-Hammer Vacuum Interrupters

All C-H VI products are thoroughly tested for short circuit performance before being offered to a customer for designing into their circuit breaker or recloser [28]. These are described as pre-certification tests in that they provide a level of confidence to both C-H and our customers that the interrupter is capable of successfully passing a certification test series when installed in a properly design circuit breaker. A single-phase, high power test circuit is used which consists of a 5 MJ capacitor bank, several high-current inductors, and a Transient Recovery Voltage (TRV) wave-shaping network. The power frequency is typically tuned to 50 Hz or 60 Hz. A diagram of the circuit is shown in Figure 17 and current and arc voltage wave forms from a typical interruption experiment are shown in Figure 18. The circuit simulates the conditions in a power system during a short circuit by stressing the test VI with the rated values of short-circuit current and TRV (Note that for short circuits, the circuit power factor is very close to zero).

Single-Phase tests are used in the C-H, High Power Laboratory to predict Three-Phase capabilities

Single phase tests are well recognized [C37.09], [IEC56] as an acceptable and conservative method of performing tests to demonstrate the interrupting rating of a circuit breaker. In such a test, the circuit must provide the rated symmetrical or asymmetrical short circuit current at the rated power frequency and with a TRV equal to that required for the first phase to clear a three phase ungrounded fault. This combination of current and voltage stress forms the basis of

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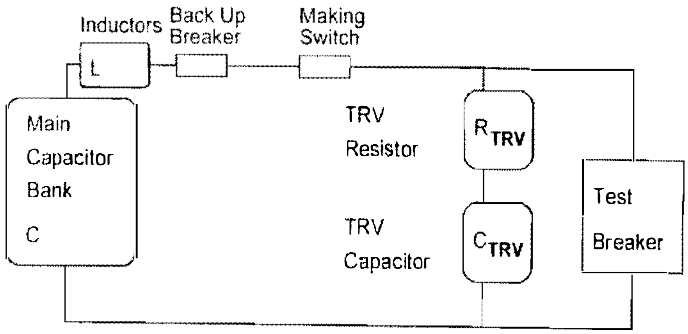

Fig. 17: Block Diagram of the Cutler-Hammer, Single-Phase, High Power, Test Circuit

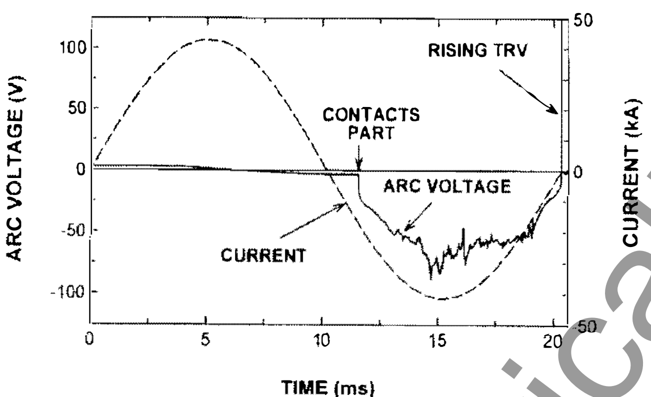

Fig. 18: Oscillograms of Arc Voltage and 50Hz Current From an Interruption Test of a TMF-Contact VI Using the High Power Circuit in Fig. 17

rating for the circuit breaker. It is also recognized that a single phase test with this combination of current and voltage provides a more severe stress than would be observed in an actual three phase ungrounded fault. This is so since only one of the 3 phases must actually clear at such a stress level in the 3 phase case. Moreover, in the single phase test, the TRV stress will be at the same high level at each successive current zero. In contrast, in the actual 3 phase circuit, if a particular pole attempts to be the first phase to clear at a short arcing time and then does not clear the circuit, it will then become one of the 2nd and 3rd phases to clear in series. The TRV for the 2nd and 3rd phases to clear is at a lower level and therefore the interrupting duty is easier on these poles. So the single phase test conditions used in the C-H lab are conservative in providing a somewhat higher test stress than would be experienced during a 3 phase ungrounded test or in actual service.

Despite the increasing use of sophisticated analysis in high power testing, the important result in certification tests is the pass/fail record. Based on over 30 years of experience, we have established a single-phase test program which allows us to predict the results of three-phase certification tests with high confidence. Three identical VI's are produced as prototypes or statistically chosen as samples from production and subjected to three levels of tests.

(1) First Level: Interruption of Symmetrical Single-Phase Current

In a three-phase certification test series, the circuit breaker must perform several interruptions, where each of several currents expressed as percentages of the target rating as shown below.

The Number of Trials in a Certification Test Series	
Percent of Rated Short Circuit Current	Number of Interruptions Required
10	3
30	3
60	3
100 Symmetrical	3
100 Asymmetrical	3

In the C-H single-phase pre-certification test series of a new VI design, each VI is tested only at the targeted maximum 100% short circuit current, since experience has shown this to be the most severe test condition for vacuum interrupters. In addition, since the C-H test circuit is a capacitor / inductor discharge type, the test current produced is only a symmetrical current, so only symmetrical current interruption is possible. In the C-H test procedure, a total of 14 trials per VI are performed, as specified in Table V with a TRV of the first phase to clear for a three phase ungrounded fault. The total number of tests and accumulated arcing duty in the C-H test series is approximately the same or greater than that experienced in the three-phase certification series. So the C-H test circuit provides all of the required conditions of rated symmetrical short circuit current, including the first phase to clear TRV. Experience has also shown that an acceptable level of interruption performance in the C-H single-phase test circuit at rated conditions is achieved when the arcing time to clear the circuit in at least 90% of the trails is within the typical normal range. The normal range of arcing time is approximately from a minimum of about 3ms up to a

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maximum of about 1 cycle + 3ms. That is, the VI can then be expected, with a high degree of confidence, to pass a series of certification trials in a three-phase circuit breaker with a three-phase ungrounded circuit at rated voltage and short circuit current stresses. Our 90% normal arcing time rate criterion is based on many years of experience that shows us that three-phase certification tests are less stressful. The three phase test is less stressful for two reasons. First, only one of the three poles must perform at the worst-case TRV, and, second, after the first phase clears, the other poles clear in series where each poles is at about 58% of the voltage stress seen by the first phase to clear. If we are testing at C-H to evaluate a single phase application, then an acceptable rate must of course be that 100% of all tests must clear within a normal arcing time range. This is also true for testing VI's that will be used in a three phase grounded systems. In this case, the peak TRV will be reduced to 2/3 of the values used in the first phase to clear ungrounded tests and an acceptable rate must also be that 100% of all tests must clear within a normal arcing time range.

TABLE V:
Testing at a Targeted Current to Predict Certification Results

NO. OF TRIALS	TRIAL DESIGNATION	POINT OF CONTACT PART
5	CZ+	Near I = 0, positive wave
5	CZ-	Near I = 0, negative wave
2	CM+	Near I = I_p, positive wave
2	CM-	Near I = I_p, negative wave

(2) Second Level:
Impulse Voltage Withstand (BIL).

The BIL of each VI is measured after the 14 interruptions to determine if it is still acceptable. The internal shields in the VI must adequately protect the ceramic insulation from condensation of metal vapor from the vacuum arc, which would degrade the dielectric strength.

(3) Third Level:
A Simulation of an Asymmetric Current Tests

While the capacitor-inductor test circuit can only produce symmetrical currents, the circuit can be used to simulate the effects of asymmetric current as a means to assess the ability of an interrupter to operate under such conditions. The single-phase high-power circuit is first configured to provide a power frequency which is about 80% of the rated frequency. The lower frequency simulates the longer current loop duration of the asymmetric current when the contacts of the circuit breaker part about 2 cycles after the fault is initiated. The current magnitude is adjusted to include the required DC component that produces the asymmetric current. If the DC component is expressed in per unit of the symmetrical component, then the test current is then set at a value that is (1 + DC) times the rated amplitude (see Fig. 19).

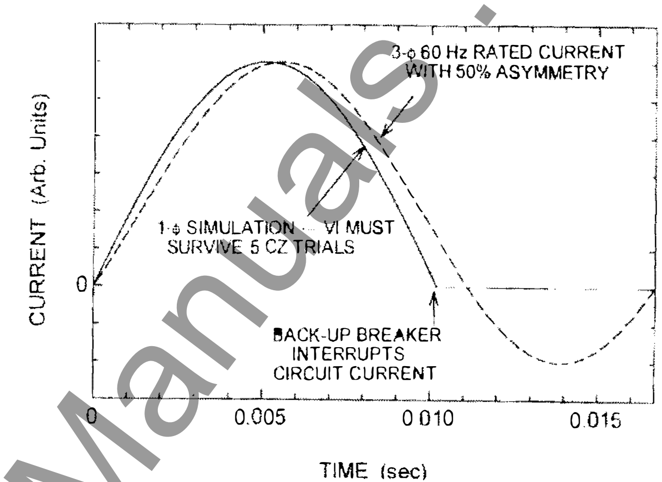

Fig. 19: Three Phase Current With 50% Asymmetry (Dashed) and the Single Phase Simulation With Symmetric Half-Cycle at 82% of the Power Frequency

So if a 50% DC component is required, then the test current is set at 1.5 times the symmetrical value. Now in this simulated circuit, the first loop of current that is as large and as long as the major loop in a real circuit, is followed by another long loop that is only a few percent smaller. So attempting to interrupt such a current is like attempting to interrupt a current 50% greater and at a lower power frequency than the VIs rating. However, in a real circuit with asymmetric current, the large major current loop is followed by a small minor current loop and vacuum interrupters often interrupt after this minor current loop. So the main objective of this simulated test is to show that the VI can withstand the major current loop without significant arcing damage so it is ready to interrupt the following minor loop. The simulated test is then performed with a fresh tube which is subjected to five applications of one half-cycle of arcing with the larger, longer duration current. If this sample finishes this series without catastrophic damage (e.g., holes melted through the arc shield), our experience has shown that the VI will pass with actual asymmetric current trials during a certification test.

Other Design Considerations

Production of high quality VI's requires a successful integration of design, analysis, testing, and strict quality control over materials and manufacturing processes. Clearly, it is desirable to develop tools for reducing the

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testing required to develop new VI types and to monitor the production quality of existing types. Our production program emphasizes that a VI should be well designed initially, so that a limited number of relevant tests will validate the prototypes. We start with empirical design guidelines for different kinds of interrupters and applications, based on over 30 years of experience. These include correlations of the rated voltage withstand and current requirements with the design parameters of the internal arcing region. Adherence to the recommended opening speed and gap are also very important for given current and voltage ratings.

Testing for Quality Assurance (QA) or Performance Comparison

Our experience has shown that differences in the quality of alternative materials, or in the effects of design changes, may not be apparent from the interruption performance at a VI's rated current. For QA or comparative testing, we evaluate the decrease in performance above the maximum rated current, I_{rated}. Three identical VI's (one sample set) are first given 8 trials each at I_{rated}, three at each polarity for opening near current zero (CZ + and CZ-), and one each polarity for opening near current maximum (CM+ and CM-). The test current is then increased in steps to values such as 110%, 115% 120% and 125% of I_{rated}. At each new test current, the VI's are each given four trials; consisting of one trial at each condition of CZ+, CZ-, CM+ and CM-. These four trials are repeated on each VI at each increased current until the combined pass rate, defined as the rate of interruptions within a normal arcing time (3ms + 1 cycle), drops to ≤50%. Typically, a total of 24 trials are performed on each VI in a set of three samples. The point on the current wave at which the contacts part is varied consistently, because it affects the amount of arc motion [3].

An example of the results in such a test series is shown in Fig. 20, in which 4 sample sets of a 100mm OD VIs (I_{rated} = 36 kA) with different formulations of contact material were compared. One of these formulations was clearly inferior, so it was therefore rejected. The other formulations evaluated all performed well up to about 42 kA, or 115% of the rating. In fact, it is often not possible to differentiate among materials by merely testing only at the rating of the interrupter. It takes testing at currents above the rating to start to see differences in performance.

In this C-H test method, both the short circuit current and the TRV are increased in the same proportion by increasing the charge on the capacitor bank. So the combined interruption stress increases in a square relationship. So the fairly steep drop in the interruption success rate above about 42 kA (117% of I_{rated}) which is shown for the other three sets of samples is a result of this extreme increase in stress. The interrupter, however, can handle higher magnitude currents during asymmetrical current interruptions. For example, this same VI will interrupt its rated symmetrical current with a 50% dc offset for which the major loop has an rms value of 54 kA and a peak value of 77kA as required by ANSI standards. In this case, interruption often occurs on the following smaller minor loop.

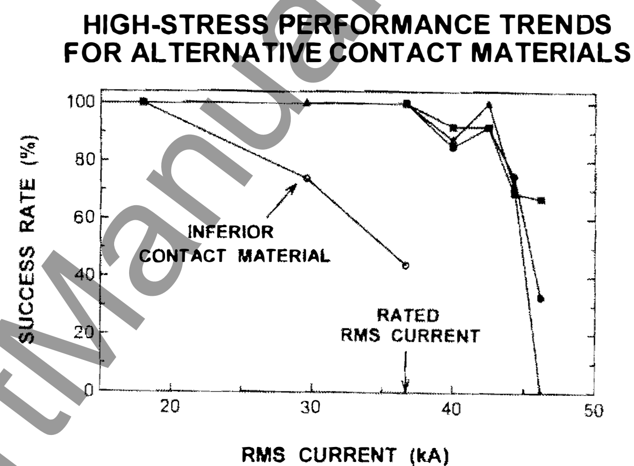

Fig. 20: Comparison of Statistical Interruption Performance Trends for Flow Sets of Highly Stressed VI's With Four Different Formulations of Contact Material

6. SWITCHING INDUCTIVE CIRCUITS

Voltage surges at the terminals of inductive elements in distribution circuits (such as motors, shunt reactors and transformers) occur any time they are switched on or off by any kind of switching technology and their interaction with VI's in particular have been studied extensively [5]. The interactions are now well understood and, when the occasion arises palliative measures are easily applied. Surges can be produced in three ways [31-33]:

(1) From lightning-induced or other surges on the line
(2) From closing the circuit to switch on the current.
(3) From opening the circuit to switch off the current.

Lightning-induced surges are not influenced by the interrupters and the established surge protection on the distribution circuit would be designed to prevent damage to the inductive element from lightning type impulse voltages.

The events that occur when closing a circuit are illustrated in Figure 21. It must be noted that this discussion applies to ALL interrupter technologies and not just to vacuum. It

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often occurs that the instant at which the circuit is energized coincides with the system voltage being at its maximum value since the rapidly reducing contact gap has a tendency to prestrike. If this happens, a travelling voltage wave will be applied to the cable linking the interrupter to the inductive element (in this illustration a non-energized motor). Since the surge impedance of cables is typically 25 to 50 ohms, and the surge impedance of inductive loads is typically much higher, then the voltage wave reaching the inductive element will be reflected. A voltage of about 2 per unit will then be impressed across its first few windings of the load. The traveling wave can reflect several times between circuit breaker and the load. Moreover, the returning wave can cause the interrupter to reignite and then initiate another traveling wave that could produce a voltage at the load that is even higher than 2 per unit. From testing, surge magnitudes are usually found to be from 1 to 3 per unit with occasional values as high as 4.6 per unit observed. If these voltage pulses are too severe, then the same measures should be used as will be discussed later for surges resulting from switching off the current.

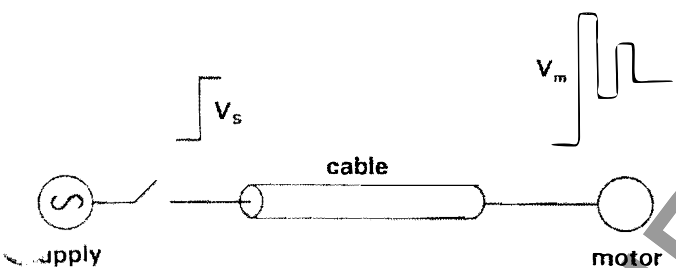

Fig. 21: When an Interrupter (Vacuum, SF_6, Oil, etc.) Closes an Inductive Circuit, the Resulting Voltage Wave Can Result in a Fast Rising Voltage At the Induction Terminals with Voltage Doubling

6.1 Multiple Reignitions

In general, multiple reignitions are a relatively infrequent phenomenon sometimes experienced by VI's and other interrupter technologies which may occur in circuits with certain combinations of circuit inductance, capacitance, and contact gap. Again, as with current chop, this topic has been researched exhaustively [10-12, 34-40]. Fig 22 shows a typical generic, inductive circuit with C_1 and C_2 being the stray capacitance to ground of the line-side and the load-side circuits. The development of multiple reignitions is as follows:

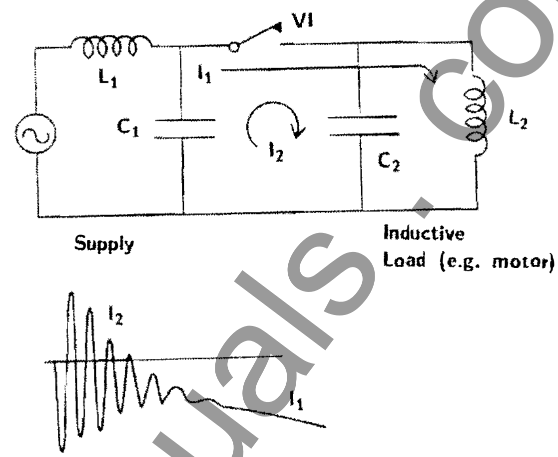

Fig. 22: An AC Circuit With an Inductive Load

(1) The VI contacts will open at a random point on the ac current wave, and as they continue to open, the current continues to flow, carried by the vacuum arc between the contacts, until current zero is reached. At current zero, the arc will extinguish.

(2) The contact gap in the VI recovers its dielectric strength extremely rapidly as soon as the arc is extinguished and the current flow is interrupted. The contact gap, in fact, assumes a dielectric breakdown value which is determined by the contact separation distance and, in VI's, is greater than 2×10^7 V/m^{-1}

(3) Once the current has been interrupted, a transient recovery voltage (TRV) appears across the contact gap. This TRV is a function of the reactive components on the load and line side of the VI [38, 39].

(4) If the contact gap is not fully open and the TRV exceeds its breakdown strength, then the arc will be re-established. Once this happens, the charge from the two capacitors causes a high-frequency current I_2 to be superimposed upon the power frequency current I_1.

(5) There is a finite probability that the VI will extinguish this high-frequency current at one of its current zeroes because the vacuum is such an outstanding circuit interrupter. If this happens, the race between the TRV and the high-voltage strength of the contact gap begins again. The following three things can happen.
   (a) The VI fails to extinguish the high-frequency current and another half cycle of the power frequency current flows, at the end of which the contact gap will be large enough to withstand the circuit TRV (see Fig. 23).
   (b) The contact gap will eventually become large enough to withstand the impressed TRV after a number of reignitions (see Fig. 24).
   (c) The sequence of events will continue and the voltages impressed across the VI will continue to increase [39] until a dielectric failure occurs, either in the breaker or somewhere else in the system.

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The VI has a probability of reignition only when very limited operating and circuit parameters are met [38]. These parameters are as follows:

(1) The circuit breaker must be attempting to interrupt moderate currents of more than 20-30A, and generally less than about 500-600A [38]. However, multiple reignitions have been observed at currents as high as 2000A in the C-H lab.
(2) The gap between the breaker contacts must be small. A gap of typically 3 millimeters or less at 27 kV is required to observe multiple reignitions, so contact part is therefore only 1 to 3 ms before the current zero when the contact opening speed is about 1 ms-1.
(3) The TRV must rise slowly enough initially so that the breaker can extinguish the arc at the first power frequency 50 Hz/60 Hz current zero at this short gap.
(4) The TRV must rise faster than the increasing breakdown strength of the contact gap of the VI as the contacts continue to open.

If the load exceeds some upper limit such as 600A or 2000A, the vacuum arc will not extinguish at the first current zero with closely spaced contacts. Because the contacts continue to open during the ensuing half cycle of arcing, the dielectric strength of the contact gap at the next current zero is high enough to prevent a voltage breakdown. The breakdown strength of the VI depends almost entirely upon the contact gap. If a breaker operates with an opening speed of about 1 m/s and the contacts part at a time of about 0.5 ms before a current zero, then the gap will recover to about 10-20kV at the first current zero. If the contacts open at a speed of 2 m/s, then the recovery will be to about 20-30 kV. Most vacuum circuit breakers and reclosers operate with opening speeds in this range. When the rate of rise of recovery voltage is less than the rate of increase in the dielectric strength of the contact gap, no reignitions will occur. The upper boundary has been observed of 900 Hz for 5kV circuits, 500 Hz for 15kV circuits and 250 Hz for 24kV circuits [38]. When the load current is below 20A, such as magnetizing currents of unloaded transformers, the overvoltages that can occur are limited by the core losses in the transformer.

The effects of multiple reignitions can be minimized and even eliminated by connecting a surge suppressor directly at the inductive load terminals to ground. In fact, multiple reignitions can be eliminated with a snubber consisting of a series-connected capacitor and resistor, R-C [36,37]; or special version of a snubber called a $ZORC_{tm}$ in which the R is paralleled by a ZnO varistor [41]. Lightning arresters such as a varistor [41] can keep the peak voltage within limits, but cannot eliminate multiple reignitions. It is also possible, but not nearly as effective, to apply a snubber at the breaker terminals [37]. The suppressor options of type and location are illustrated in Fig. 25.

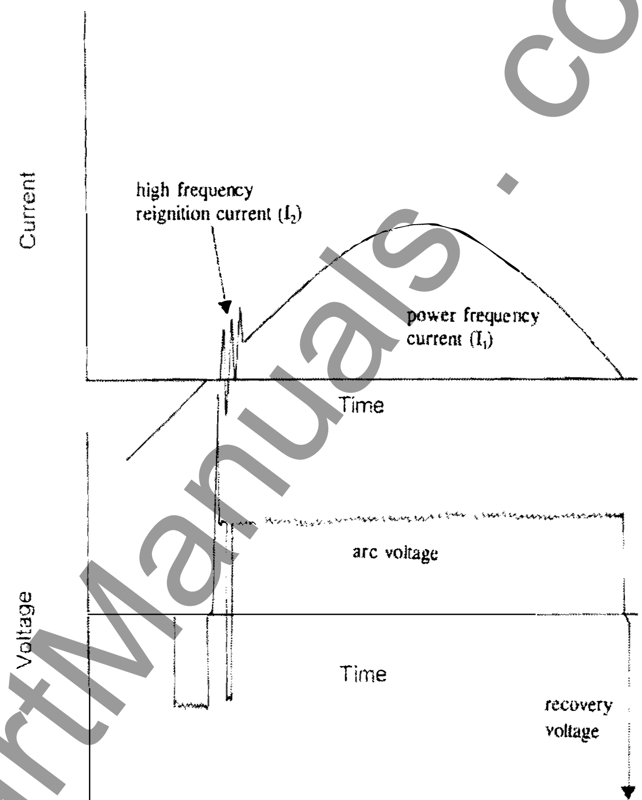

Fig. 23 If the High Frequency Reignition Current is not Interrupted, An Extra Half Cycle of Power Frequency Current Follows

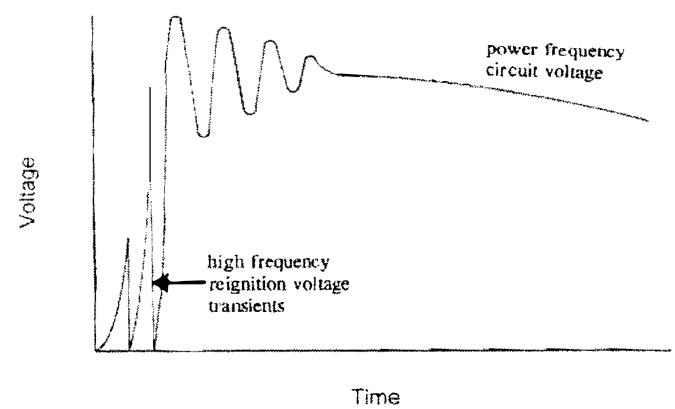

Fig. 24 If the Breakdown Strength of the Contact Gap Exceeds the Reignition Voltage Transient, the Circuit Will Be Interrupted

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6.2 High Voltage Motor Switching

For normal operation of HV motors, the same care has to be taken to reduce the effects of the three sources of voltage surge, no matter which interrupter technology is used, i.e., VCB's, SF_6 breakers, oil or air magnetic circuit breakers. In fact, if the cost of the HV motor is significant or if the loss of service is critical, then surge protection is a very inexpensive and prudent step with very large potential benefits. Usual recommended practice is a surge capacitor or a surge arrester connected at the motor terminals IEEE Red Book [42]. In recent years, this practice has been updated to include a resistor (to match the cable surge impedance) in series with the capacitor and/or a combination of this R-C network and a ZnO varistor (see Fig. 25)[41]. When a vacuum breaker is used to interrupt the load current after a motor has reached its full running speed, no adverse effects are expected. This is because the back emf produced by the running motor opposes the source voltage resulting in a very small recovery voltage across the opening contacts immediately following current interruption [5, 32].

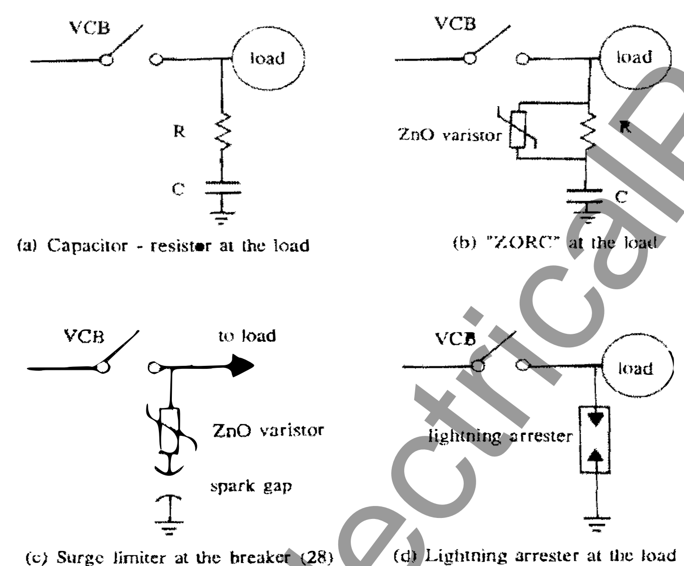
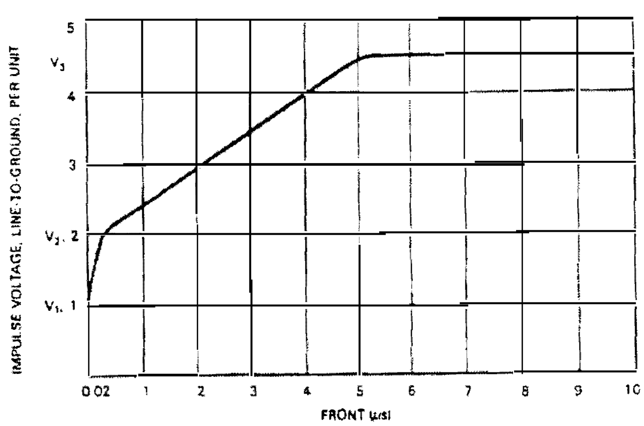


Fig. 25: Examples of Surge Suppression Circuits

If the motor current is interrupted before the motor has attained its full operating speed (locked or stalled rotor conditions), the machine will have little or no back emf and, therefore, behaves like a reactor. In this case, it is possible to develop the multiple reignitions described in Section 6.1. Fortunately, the surge protection provided to protect against closing surges is equally effective in reducing the probability of multiple reignitions from occurring and, if they do occur, the surge protection will minimize their effects.

Table VI showed the effects of surge suppression on the observed surge voltages at a motor terminal and compares the VI with SF_6 and air interrupters [41].

The voltage withstand properties of motor insulation are different from those for other air insulated devices. Motors windings are imbedded in the slots of the machine's magnetic structure and are insulated with solid materials. The material thickness is as small as possible while simultaneously providing the necessary voltage withstand ability and good magnetic performance. As a result, the insulation does not have the higher resistance to fast wave front impulse surge voltages that other equipment can be designed to provide. Specifically, motors do not have ratings for lightning impulse voltages that are required for circuit breakers, switchgear and transformers. A typical curve of impulse voltage withstand versus the rise time of the voltage is show in Figure 26. Manufacturing methods are absolutely critical in producing a good voltage withstand ability in motor insulation. Large machines, typically purchased by utilities, tend to be better made with higher voltage withstand properties than smaller machines. Moreover, it has also been noted that a motor that has been rewound after a voltage breakdown, usually never experiences another problem. This is presumably because insulating quality of the rewound machine is better than it was on that particular machine when it was new. So it is natural that more care in providing overvoltage protection should be considered for motors.



For V_L = machine voltage rating line-to-line rms kV:
$V_1 = \sqrt{2/3}\, V_L$ = 1 PER UNIT CREST LINE-TO-GROUND
$V_2 = 2\, V_1$
$V_3 = 1.25\sqrt{2}\,(2\, V_L + 1)$, kV CREST VALUE

Fig. 26: Machine Impulse Voltage Withstand Envelope

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TABLE VI: Effect of Surge Suppression on the Value and Duration of Voltage Surges at the Terminals of High Voltage Motors for Vacuum, SF6 and Air Interrupters					
OPERATION	TYPE AND LOCATION OF SUPPRESSION	VACUUM		SF_6/AIR	
		V_{motor} (pu)	t_r µs	V_{motor} (pu)	t_r µs
CLOSING	None or Arrester	4	0.2-0.5	4	0.2-0.5
	Capacitor at Motor	4	3-7	4	3-7
	RC at Motor	2	0.2-0.5	2	0.2-0.5
	Zn0-RC at Motor	≤1	0.2-0.5	≤1	0.2-0.5
	Zn0-RC at Panel	≤2	0.2-0.5	≤2	0.2-0.5
OPENING STALLED MOTOR	None or Arrester	4-5	0.2-0.5	4-4.5	0.2-0.5
	Capacitor at Motor	6	3-7	4-4.5	3-7
	RC at Motor	3	0.2-0.5	2.2-2.8	0.2-0.5
	Zn0-RC at Motor	≤1.5	0.2-0.5	≤1.5	0.1-0.5
	Zn0-RC at Panel	≤3	0.2-0.5	≤2.5	0.2-0.5

There have been claims made that some SF_6 interrupters have a low surge characteristic on opening, and thus do not require special surge protection at the motor. Table VI, however, shows you should expect to obtain very similar surge voltages at the motor terminals with the use of SF_6 interrupters. Moreover, the table also shows that overvoltages on closing are nearly as high as on opening, so the advantage of producing a low surge on opening is of much reduced significance. The conclusion one has to draw from this data is that care must be exercised in protecting motors against overvoltages no matter which switching technology is used.

It is of course also possible to provide a low surge on opening operations using the VI. For at least 20 years VI's have been available for use in high voltage contactors which use low-surge contact material such as AgWC and CuCrBi. These materials have a very limited ability to interrupt high frequency currents and thus have a very low probability of initiating a voltage escalation sequence. These materials, however, also have a limited short circuit interruption capability and have traditionally been applied in series with fuses for short circuit protection. If a vacuum circuit breaker using CuCr contacts (a material that has an excellent ability to interrupt high frequency currents) is used to switch motors, it is prudent to use surge suppression at the motor terminals.

6.3 Transformer Switching

An unloaded transformer represents a highly inductive load with a magnetizing current ≤1% of the rated full-load current. On switching this current, a current chop is very likely to occur (see Section 3) which will trap energy proportional to the inductance and the square of the chop current value. The trapped energy manifests itself as a high frequency resonance, ringing between the inductance and the stray capacitance of the circuit. Fortunately, there is, however, considerably damping of the resultant voltage and current waveforms resulting from the losses in the transformer core. As the kilovoltampere rating of a transformer is reduced, the capacitance tends to be smaller and the magnetizing inductance becomes larger. This trend in C and L increases the impedance, but, as the magnetizing current is reduced, the maximum chop current is also reduced. Dry-type transformers with low-impulse voltage rating are more vulnerable. Overvoltage protection can be provided with a short cable of 20-50 m, plus a surge capacitor or an R-C network, (a surge capacitor and a resistor) at the load terminals of the transformer. Figures 27, 28 [12] illustrate effects of cable length and surge capacitors on the surge voltages seen at the transformer terminals. Table VII gives some recommendation guidelines on the use of surge protection for dry type and oil filled transformers [43].

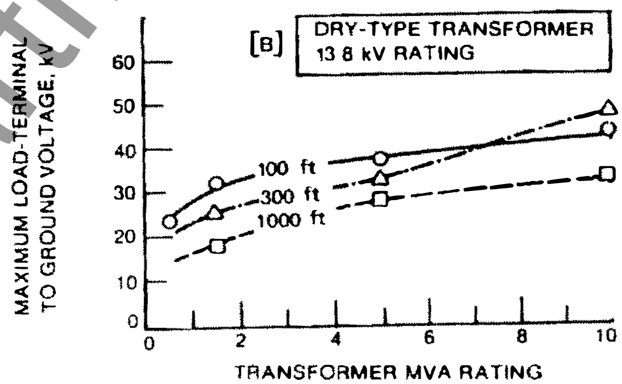

Fig. 27: Effect of Cable Length on Maximum Load-Terminal to Ground Surge Voltage

It has been usual to assume that no surges will be generated or expected when switching a loaded transformer [5]. However, power transformer failures have been known to result when an internal resonance produces an overvoltage sufficient to cause an insulation breakdown. The transformer windings have a complicated internal structure that can be represented by a network of inductances and capacitances, which have natural resonant frequencies of oscillation. Under some conditions, a resonance can be excited to produce damaging overvoltages. Mechanisms that can excite a resonance can include:

1. multiple reignitions of a switching devices that occur at a frequency that matches the resonant frequency , or
2. large harmonic components present in the inrush current of the transformer that flows on energizing the transformer

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A means of suppressing a resonance is therefore required to provide protection in such cases. R-C surge suppressors can damp or eliminate such internal resonance in power transformers and thereby reduce the risk of resonance induced overvoltages within the winding of a load.

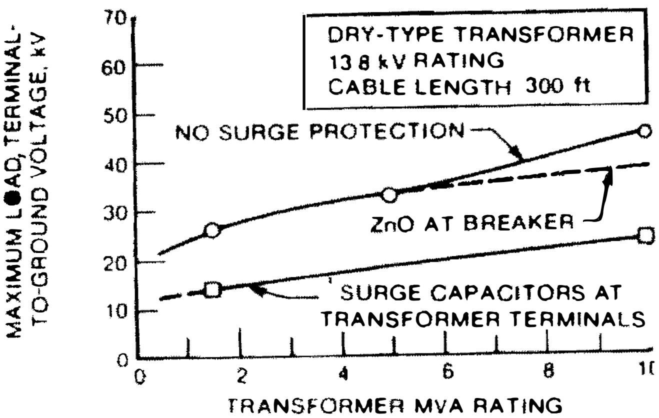

Fig. 28: ***Comparison of the Effects of Surge Capacitors At the Transformer and ZnO Surge Suppressors At the Breaker in Reducing the Maximum Load-Terminal to Ground Surge Voltage***

TABLE VII: Transformer Protection		
SWITCHING DEVICE	**LOAD**	
	Dry Type Transformer	**Oil Filled Transformer**
Vacuum Contactors 1kV ~ 7.2kV class	Protection not necessary for transformer rated more than 400 kVA: for small transformers use surge protection	Protection not necessary
Vacuum Circuit Breakers 5kV Class	Surge protection necessary, unless the transformer is rated for 60 kV BIL	Protection not necessary for transformers rated more than 300 kVA: for small transformers use surge protection
Vacuum Circuit Breakers 10kV-40.5kV Class	Surge protection required, unless the transformer is rated for full BIL, e.g. Circuit V — BIL V 10kV — 75kV 15kV — 95kV 24kV — 125kV 36kV — 170kV 40.5kV — 185kV	Protection recommended especially for transformers rated less than 3MVA, however, 0.2μF at the load terminals reduces maximum transient voltage and number of restrikes

An R-C suppressor consists of a resistor and capacitor in series; the capacitor is generally connected on the ground side and the resistor on the line side. The resistor value is approximately 25 to 50 ohms, which is approximately the surge impedance of high voltage cables which are often used to connect to the load. The capacitor should have a voltage rating appropriate to the system voltage and a capacitance value as recommended for surge capacitors listed in the IEEE Red Book [42]. These are:

Rules for Size of Surge Capacitors			
Voltage Rating in Volts	650 or Less	2500-6900	11500 and Higher
Capacitance in Microfarads	1.0	0.5	0.25

6.4 Virtual Chopping

Virtual chopping only occurs in rare cases. It is strongly dependent upon the circuit parameters, and, to a much lesser extent, the interrupter. Virtual chopping is a phenomenon that can occur in an ungrounded, three phase circuit with any interrupter type (SF_6, vacuum, oil, etc.). Virtual chopping can occur if the first phase to clear experiences a reignition before phases two and three interrupt. For example, if a reignition in one phase (say Phase A) causes a high-frequency current to flow which couples into the other two phases, virtual current chopping may occur. The circuit paths for the high-frequency current as shown in Fig. 29. The high-frequency current in phase A, i_T, due to a reignition in Phase A flows to ground via the terminal-to-ground capacitance at the load. If the three-phase system is balanced, i_T divides into two so that $i_T / 2$ enters phases B and C via the respective terminal-to-ground capacitance. The high-frequency current ($i_T / 2$) in phases B and C is shown to be capacitively coupled back into phase A on the source side of the breaker.

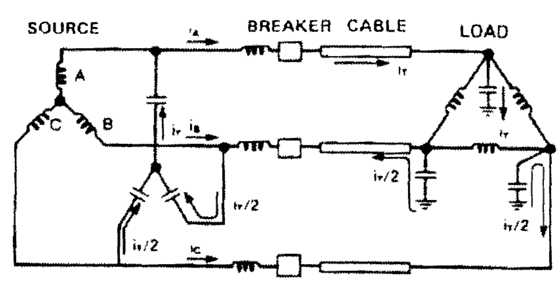

Fig. 29: Circuit Demonstrating How the High-Frequency Current Resulting From a Reignition in One Phase Couples Into the Other Two Phases to Produce the Conditions for Virtual Current Chopping

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At the instant of reignition in phase A, which occurs some tens to hundreds of microseconds after the power frequency current zero, the power frequency current in phases B and C is approximately 0.87 x the crest value of the power frequency current. If the magnitude of the high-frequency current in phases B and C (i_T / 2) is greater than 0.87 x the crest value of the power frequency current, the high-frequency current plus power frequency current add to zero: this appears to be a forced current-zero and the phenomenon is called virtual current chopping.

The high-frequency currents (i_T / 2) in phases B and C are of the same polarity and equal in magnitude to each other, but are of opposite polarity to i_T in phase A. Because the normal power frequency phase relationships cause the power frequency currents in phases B and C to be of opposite polarities at the time of reignition in phase A, the forced current zeros are not time coincident. Also, the currents in phases B and C approach zero from different polarities, which means that the resulting transient voltages in phases B and C are of opposite polarities. Consequently, the surge overvoltage between phases B and C is twice the overvoltage from phase to ground on both phases, provided that the instantaneous voltages are significantly less than the virtual chop overvoltages.

Compared with normal current chopping, the effective level from which the load current is forced to zero (virtually chopped) can be much higher, typically several hundred amperes instead of 3 or 4 A. However, the effective surge impedance of the load (several hundred ohms) is much lower than it would be in switching an unloaded transformer without protection (typically 10 to 30 kΩ). The overall effect is to make the phase-to-ground overvoltage comparable with or larger than the overvoltage due to a normal current chop, but the important difference is that the surge overvoltage between phases B and C is approximately twice the overvoltage from phase-to-ground on these phases.

If a circuit is susceptible to this phenomenon an R-C surge suppressor at the load terminals will prevent this event from occurring.

7. CAPACITOR SWITCHING

For distribution systems, switching capacitor banks is the most severe capacitive switch duty. Unlike switching cables and overhead lines (see Section 7.3), switching capacitors is often a daily event, and sometimes occurs even more frequently. The reason for this is that capacitors are used to maintain the power factor in the distribution system when it is subjected to changing inductive loads. In some distribution circuits it is quite possible to have over 700 switching operations a year.

The VI has proven to be very effective for switching capacitor banks. Although capacitor switches specifically designed for capacitor switching have been developed that use VI's with W-Cu contact materials circuit breakers are also frequently required to perform this service. Fortunately, the Cu-Cr contact material

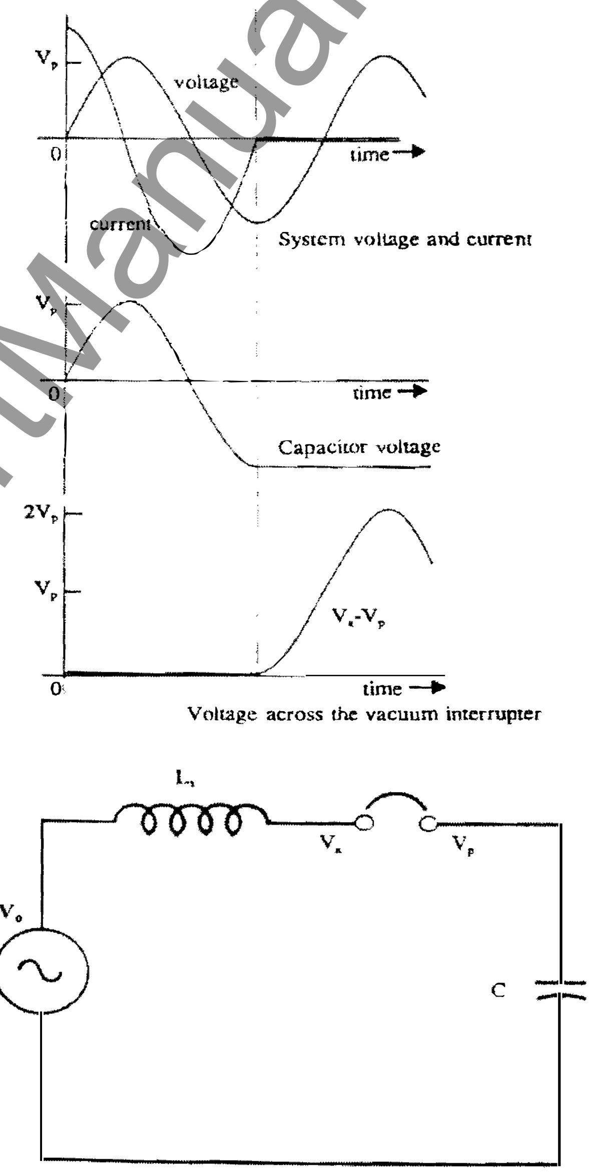

Fig. 30: An AC Ciccuit With a Single Capacitor Bank Load

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now used in state-of-the-art VI's has excellent high-voltage properties and has shown an excellent ability to perform capacitor switching duty [44]. In the future, the combination of the VI with a magnetic actuator [45] operated separately on each pole will even make possible point on wave closing and opening. When this occurs the stresses that switching capacitors imposed upon the distribution system will be greatly reduced.

7.1 Energizing a Capacitor Bank

Single Capacitor Bank

A schematic of a single capacitor is shown in Fig. 30. On closing the circuit there will be a large transient current given by [5]:

$$I_1 = (V_o / Z_1) \sin \omega_1 t \quad (7.1)$$

where Z_1 is the surge impedance of the circuit, equal to $(L_s/C)^{½}$, ω_1 is the angular natural frequency equal to $(L_sC)^{-½}$, and V_o is the voltage across the switch at the moment of energization. This current is usually much greater than the power-frequency current on which it is superimposed. For example, a capacitor bank rated 6 MVAR at 13.8kV will have a rated current of about 250A (rms), but can have a closing current of over 3kA. This high closing current stresses the whole electrical circuit, i.e. the upstream transformer, the bus or cable and the electrical connections.

During the closing sequence, the VI will have initiated the current flow a short time before the contacts actually touch. The reason for this is that as the contacts close there will be a time before they touch that the electric field across them is high enough to initiate a breakdown of the gap (a prestrike). The resulting short duration vacuum arc will allow current to flow in the circuit. It is possible that this prestrike arc would melt the contact surfaces and initiate tack-welding of the contacts once they touch. The mechanism for the VCB or vacuum capacitor switch is designed to break such welds. The resulting projections left on the contact surfaces after breaking such welds are usually eroded away by the action of the arcing that occurs when opening the interrupter.

It can be seen from Eq. 7.1 that it would be extremely advantageous to close in on the circuit when V_o is close to zero (i.e. point on wave closing). Not only would the current I_1, be very small, but also the contacts would have to be practically touching before the field across them would be high enough to initiate the prestrike arc. However, a truly effective point on wave closing switch would have to have independently operated poles.

Back-to-Back Capacitor Banks

Increasingly, utilities are using a number of capacitor banks in parallel, which are switched into a power system as the inductive load builds up. They are then switched out when the inductive load declines. Figure 31 illustrates a back-to-back configuration. Here capacitor bank C_1 is closed and then capacitor bank C_2 is closed while C_1 is energized. In this situation the inrush current into C_2 is almost totally supplied by the neighboring bank C_1 because $L_s >> L_o$. In this case the inrush current is given by

$$I_2 = (V_2 / Z_2) \sin \omega_2 t \quad (7.2)$$

where Z_2 is the surge impedance of the loop containing the two capacitor banks C_1 and C_2 and L_0, and ω_2 is the angular natural frequency of this circuit. In this case if C_1 is at the peak voltage when C_2 is connected to the circuit the maximum current will flow. Again if the capacitor banks are 6 MVAR at 13.8kV a current between 11.5kA and 23kA can flow depending upon the initial charge trapped on C_2 and the value of the inductance between banks. Although the mechanical and electrical stress in this case only affects the local capacitor circuit, it is wise to limit this momentary high frequency current [46]. Equation (7.2) also indicates that if C_2 is switched in when V_2 is close to zero, i.e. point-on-wave closing, then again I_2 will have a low value.

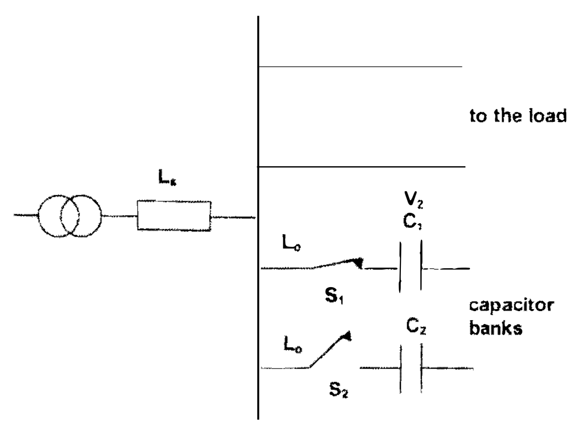

Fig. 31: Equivalent Circuit Diagram for Back to Back Capacitor Switching

7.2 De-energizing Capacitor Banks

Capacitor bank rated current is usually in the range of about 100A to 400A with the occasional large capacitor banks that can carry 2000A. In the current range up to and above 2000A the vacuum arc formed as the VI contacts part is in the diffuse mode and easily interrupts the circuit at current zero. At current zero, however, the

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peak circuit voltage V_p (see Fig. 30) is trapped on the capacitor as the current passes through zero. This voltage remains on the capacitor for as long as it takes for the charge to bleed off through its internal discharge resistors. The voltage on the other side of the switch V_a, follows the power frequency source voltage and the voltage impressed across the VI's contacts ($V = V_a - V_p$) is given by:

$$V = V_p (1 - \cos \omega t) \quad (7.3)$$

as seen in Fig. 30. The recovery voltage thus begins to rise very slowly, but will rise to a maximum value of $2V_p$. Note that in three phase systems, V_p would be the phase to neutral voltage

$$V_p = (V (\text{system}) \times \sqrt{2}) / \sqrt{3}$$

This value is usually designated as 1 PU. The peak voltages seen when switching various 3 phase capacitive loads are:

(a) grounded banks or cables
$V_{max} = 2\ V_p$
(b) cables with individual grounded sheaths
$V_{max} = 2\ V_p$
(c) cables with individual ungrounded sheaths or overhead lines $V_{max} = 2.2$ to $2.3\ V_p$
(d) ungrounded banks $V_{max} = 2.5\ V_p$

The field E across the contacts will be

$$E = V/d = V_p (1 - \cos \omega t)/d \quad (7.4)$$

Where d is the contact gap. Now, if the contacts are opening with a velocity v, then

$$E\ (t) = V_p (1 - \cos \omega t)/vt.$$

The VI has been designed so that the maximum field Ep for a fully open contact gap of $d=d_o$ is below that required to initiate vacuum breakdown. Thus, to insure that reignition does not occur as the contacts open

$$E\ (t) < E_p$$

Fig. 32 shows an example of the development of E(t) for a range of contact-opening speeds. In this example, Ep. is 6.17kV/9.65 mm = 6.4 V/mm, so the opening speed should be greater than 1.3 m/s if the opening is initiated just before current zero.

Even with the $2V_p$ impressed across the VI, switching a capacitor bank is usually a straight forward operation. Figs. 33 and 34 show data for a VCB undergoing 38kV capacitor switching certification at the Laboratory and Research Center, Arnheim, The Netherlands (KEMA), with inrush currents up to 24kA.

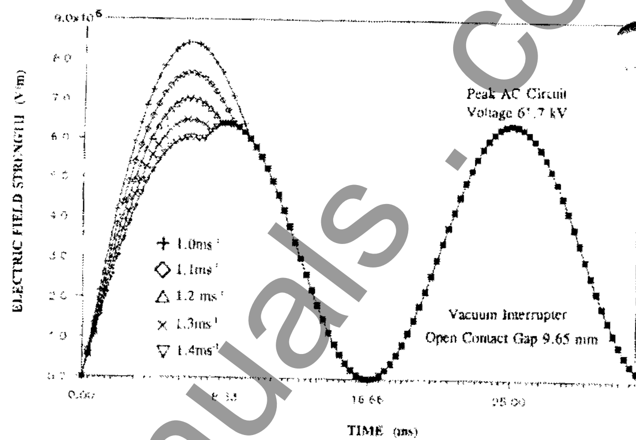

Fig. 32: Effect of Opening Speed of a Vacuum Circuit Breaker on the Electric Field Across the Opening Contacts of a Vacuum Interrupter if the Contacts Begin to Part Close to Current Zero

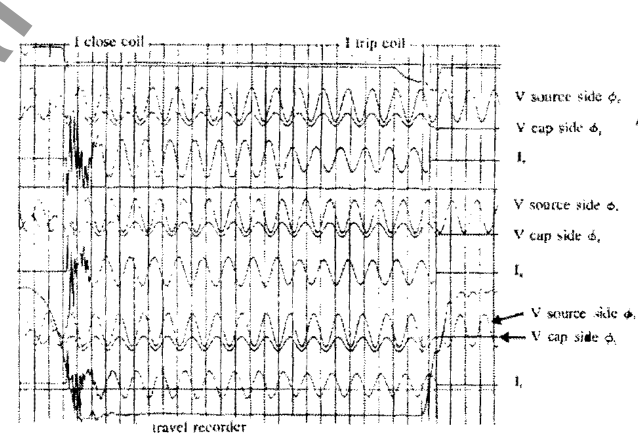

Fig. 33: Vacuum Circuit Breaker Switching Back-to Back, Capacitor Banks in a 38kV Circuit

It has been increasingly recognized that when capacitor banks are switched a large number of times there is a finite probability of a restrike occurring during the life of the switching interrupter. This is true whether vacuum or SF_6 interrupters are used. When this restrike occurs, a high frequency current flows through the capacitor/switch circuit. If this current is interrupted at the first current zero it is possible for the voltage across the switch to increase from 2 to 3 per unit. This higher voltage can result in further restrikes and a further voltage escalation [47]. Thus even though the interrupter has a low probability of restriking it is prudent to protect the capacitor bank with a voltage-

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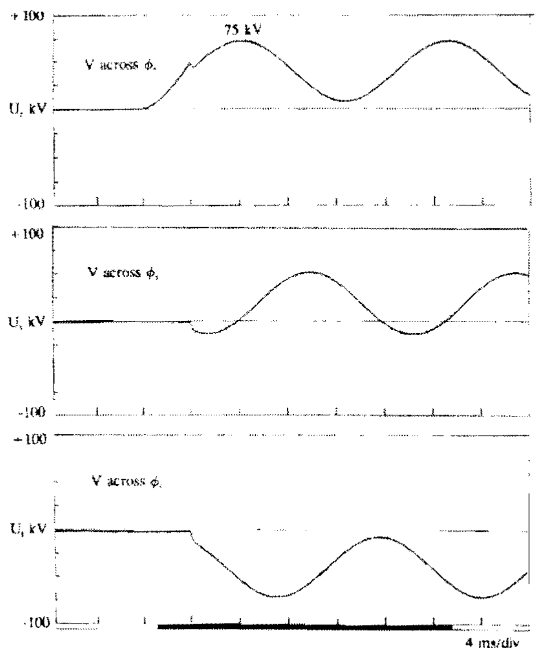

Fig. 34: Recovery Voltage Across the Individual Vacuum Interrupters Switching Back-to Back, Capacitor Banks in a 38kV Circuit; The Initial, High Frequency Closing Current Being 24kA (Peak), see Fig. 33.

limiting to protect the capacitor bank with a voltage-limiting device. It is interesting to note that using VI's specifically designed for capacitor switching with the WCu contact material, it is unlikely that voltage escalation will occur even after a restrike event. The reason for this is that WCu has very poor ability to switch power frequency currents much greater than 2.5kA and also has a poor ability to interrupt high frequency currents much greater than 1kA. So if a restrike does occur, the current will continue flowing until it rings down to a low enough value for the WCu material to interrupt it. When this happens, the charge left on the capacitor bank will be low enough that voltage escalation is unlikely. If, however, a vacuum circuit breaker is used to switch capacitor banks, the CrCu contact material which has an outstanding ability to interrupt high frequency, high currents, will interrupt the high frequency restrike current. When this occurs, voltage escalation may result. Care should thus be used to protect capacitor banks when vacuum circuit breakers are used to switch them.

7.3 Cable Switching and Line Dropping

When disconnecting cables or overhead distribution lines, the application considerations are similar to those previously discussed for switching capacitors. Although the current magnitudes are low, cables and lines have appreciable capacitance and interruption of the circuit current will trap charge on the cable. This results in a similar, slowly rising recovery voltage appearing across the VI contacts of the VCB which can reach a peak value of:

(a) cables with individual grounded sheaths

$$V_{max} = 2\ V_p$$

(b) cables with individual ungrounded sheaths or overhead lines

$$V_{max} = 2.2 \text{ to } 2.3 \text{ times } V_p$$

While other interrupting technologies have had difficulty with this duty, VCB's have performed this function very successfully for 30 years.

It should be remembered when testing for this duty in a certification laboratory, that while the cable or line looks similar to a capacitor, it is not a single lumped capacitor, but contains a distributed capacitance. Figures 35 and 36 compare a circuit set up for testing a switch in a true capacitor and an equivalent circuit for testing a switch for cable switching or overhead line switching, taking into account the distributed capacitor component of the line and series surge impedance.

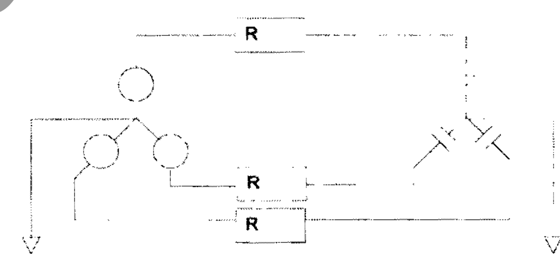

Fig. 35: Cable Charging Current Breaking Test Circuit

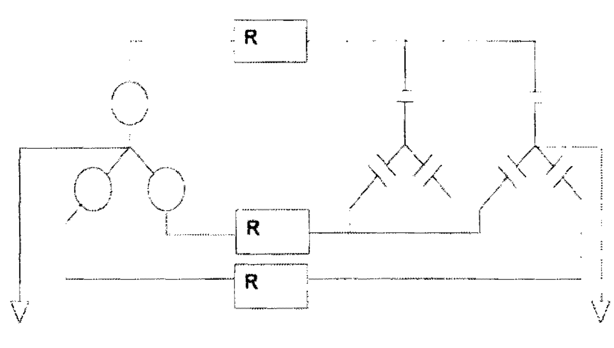

Fig. 36: Overhead Line Charging Current Breaking Test Circuit

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8. CONCLUSIONS

(a) Modern vacuum interrupters (VI's) that use state-of-the-art vacuum processing techniques to ensure an hermtically-sealed, vacuum-tight construction for the life of the VI and that use the Cu-Cr contact material are capable of providing maintenance-free operation for the full electrical life of the system.
(b) Vacuum interrupters have been successfully used in circuit breakers and reclosers over the whole distribution voltage range through 40.5kV.
(c) A state-of-the-art VI is capable of providing outstanding recloser performance far in excess of ANSI Standard C37.60. In fact, reclosers are now manufactured that will perform 300 fault operations with no maintenance, for use in applications where severe weather is frequent.
(d) The VI provides the longest switching life over the widest operating range, i.e.,
    From less than 1 kV to 40.5kV,
    From less than 100A to more than 3150A,
    From less than 6kA to 63kA faults,
    From power frequencies or 16 2/3 to100 Hz,
    With transient recovery (TRV) voltages having the a fastest rate of rise of recovery voltage, and for
    Resistive, capacitive and inductive load breaking
(e) The VI provides a unique ability to quickly restore an open circuit condition even if an open vacuum circuit breaker or recloser experiences a voltage surge greater than its design value, and the contact gap in the VI breaks down and allows current to flow, since the current will be interrupted at the next current zero.
(f) The vacuum circuit breaker is used to reliably switch capacitor banks and motor circuits. If necessary, specialty VI's can be used that have been developed to operate only as capacitor switches. Also, for motor switching, specific VI's can provide low surge operation. These vacuum interrupters can be used in high-voltage motor contactors or low-surge vacuum circuit breakers.
(g) The fast TRV interrupting ability of the Cu-Cr contact material provides greatly enhanced transformer protection from secondary faults and overhead line protection from short-line faults.
(h) The versatility of VI design will see its continued application to an even wider role in the control and protection of distribution circuits. Present-day emerging examples are generator protection breakers and switches for electric trains.

9. REFERENCES

[1] M.B. Schulman and P.G. Slade, editors, *Research and Development of the Vacuum Interrupter and the Vacuum Circuit Breaker: 1929-1997,* (pub. Cutler-Hammer, Horseheads, NY) 1997.

[2] P.G. Slade, "Advance in Material Development for High Power Vacuum Interrupter Contacts," *IEEE Trans. Comp., Package., Manufact. Technol. A*, Vol. 17, pp 96-106, Mar. 1994.

[3] M.B. Schulman, "Separation of Spiral Contacts and the Motion of Vacuum Arcs at High AC Currents," *IEEE Trans. Plasma Sci.*, Vol. 16, pp. 342-347, June 1993.

[4] M.B. Schulman, P.G. Slade, and J.V.R. Heberlein, "Effect of an Axial Magnetic Field Upon the Development of the Vacuum Arc Between Opening Electric Contacts," *IEEE Trans. Components Hybrids and Manufacturing Technology,* Vol. 16, No. 2, pp. 180-189, March 1993.

[5] A. Greenwood, *Vacuum Switchgear,* London, U.K.: IEE, 1994.

[6] P. G. Slade, "Growth of Vacuum Interrupter Application in Distribution Switchgear," *Proc. 5th Intl. Conf. On Trends in Distribution Switchgear,* London, UK, IEE Conf. Pub. 459, pp. 155-160, Nov. 1998.

[7] L.G. Christophorou, J.K. Olthoff and R.J. VanBrunt, "Sulphur Hexafluoride and the Electric Power Industry," *IEEE Electrical Insulation Magazine,* Vol. 13, No. 5, pp. 2024, Sept. – Oct. 1997.

[8] M. Farber, S. P. Harris, D. E . Cooper, and M. Khazei, "Mass Spectrometric Determination of S2F10 resulting from high-voltage arcing of SF_6," *J. Phys. D. Appl. Phys.*, Vol. 22, pp. 233-234, 1989, and "Health Hazards That Lurk in Inert Gas," *New Scientist*, Feb. 16, 1991.

[9] Much of this work has been first presented at the International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), which began with the first conference in 1964 and has been held every two years since then.

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[10] A.N.Greenwood, D.R. Kurtz, and J . C. Sofianek, "A Guide to the Application of Vacuum Circuit Breakers," IEEE *Trans. Power App. Syst.*, Vol. PAS-90, pp. 1589-1597, July/Aug. 1971.

[11] J. F. Perkins, "Evaluation of Switching Surge Overvoltages on Medium Voltage Power Systems," *IEEE Trans. Power App. Syst.*, Vol. PAS-101, pp. 1727-1734, June 1982.

[12] J. F. Perkins and D. Bhasavanich, "Vacuum Switchgear Application Study With Reference to Switching Surge Protection," *IEEE Trans. Ind. Applicat.*, Vol. IA-19, pp. 879-888, Sept./Oct. 1983.

[13] P. G. Slade, "The Vacuum Interrupter Contact," *IEEE Trans. Comp, Hybrids, Manufact. Technol.*, Vol. CHMT-7, pp. 25-32, Mar. 1984.

[14] A. Bereza, "Method of Sealing and Evacuating Vacuum Envelopes," U.S. Patent 3 656 255, Apr. 18, 1972, and Revisions 27 773, Aug. 14, 1973.

[15] M. Okawa, T. Tsutsumi, and T. Aiyoshi, "Reliability and Field Experience of Vacuum Interrupters," *IEEE Trans. Power Delivery*, Vol. PD-2, pp. 799-804, July 1987.

[16] R.E. Voshall, C. W. Kimblin, P.G. Slade, and J. G. Gorman, "Experiments on Vacuum Interrupters in High Voltage 72kV Circuits," *IEEE Trans. Power App. Syst.*, vol. PAS-99, 2, pp. 658-666, March/April 1980.

[17] Wang Zhongyi, Wang Jimei, "Theoretic Research and Design on High Voltage Vacuum Interrupter With Long Electrode Distance," *Proc. 17th ISDEIV,* (IEEE Catalog No. 96CH35939), pp. 258-262, July 1996.

[18] P. G. Slade, P. O. Wayland, G. McCracken, R. E. Voshall, A. Bamford, R. Yeckley, H. Spindle, "The Development of a Vacuum Interrupter Retrofit for the Upgrading and Life Extension of 121kV-145kV Oil Circuit Breakers," *IEEE Trans. Power Delivery,* Vol. 6, No. 3, pp.1124-1131, July 1991.

[19] Farrall, G.A., "Electrical Breakdown in Vacuum" *Vacuum Arcs: Theory and Application,* ed. J. M. Lafferty (John Wiley and Sons, NY), pp. 69-74, 1980.

[20] ANSI/IEEE Standard C37.09-1999, Test Procedures for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[21] IEC Publication 694, Common Clauses for High-Voltage Switchgear and Control Gear Standards, Clause 6. "Type Tests," Note 3.

[22] B. Southerlin, "An Environmentally Friendly, Maintenance Free, Universal Protection Device", *Proc. Int'l. Conf. On Trends in Distribution Switchgear*, IEE Conf. Pub. 459, pp. 7-12, Nov. 1998.

[23] M.B.J. Leusenkamp, J.H.L.A. Hilderink, and K. Lenstra, "Field Calculations on Epoxy Resin Insulated Vacuum Interrupters," *Proc. XVII Int'l. Symp. On Discharges and Insulation in Vacuum*, IEEE Catalog No. 96CH35939, pp. 1065-1069, July 1996.

[24] K. J. Cornick, "Current-Chopping Performance of Distribution Circuit Breakers," *Proc. 2nd IEE Conf. On Developments in Distribution Switchgear*, pp. 12-16, May 1986.

[25] R. P. P. Smeets, "Switching Inductive Current With Vacuum Switchgear," IEEE Tutorial on the Vacuum Switchgear, TP-150-0, 1999.

[26] M. B. Schulman and P. G. Slade, "Sequential Modes of Drawn Vacuum Arc Between Butt Contacts for Currents in the Range 1kA to 16kA," *IEEE Trans. Comp., Packag., Manufact. Technol.* A, vol. 18, pp. 417-422, June 1995.

[27] M. B. Schulman, P. G. Slade, L. D. Loud, and W. P. Li, "Influence of Contact Geometry and Current on Effective Erosion of Cu-Cr, Ag-WC and Ag-Cr Vacuum Contact Materials", *IEEE Trans. Components Packaging and Mfg. Tech.* Part A, Vol. 22, No. 3, Sept. 1999.

[28] M. B. Schulman and R. K. Smith, "Better Interpretation of Vacuum Interrupter Tests," *IEEE Industry Applications Magazine*, Vol. 5, No. 2, pp. 18-27, March/April 1999, with an "Erata" in Vol. 5, No. 4, p. 8, July/August 1999.

[29] R. D. Garzon, *High Voltage Circuit Breakers: Design and Applications*, Pub. Marcel Dekker, Inc., pp.29-75, 1997.

[30] R. K. Smith, "Tests Show Ability of Vacuum Circuit Breaker to Interrupt Fast Transient Recovery Voltage Rates of Rise of Transformer Secondary Faults," *IEEE Trans. On Power Delivery*, Vol. 10, No. 1, January 1995.

www.ElectricalPartManuals.com

[31] B. K. Gupta, N. E. Nilsson, and D. K. Sharma, "Protection of Motors Against High Voltage Switching Surges, *IEEE Trans. Energy Conversion*, vol. 7, pp. 139-147, Mar. 1992.

[32] M.N. Jackson, G. M. Richards, D. Kadwa, and K. J. Cornick, "Transients Associated With Distribution Circuit Breakers During Induction Motor Switching," *Proc. IEE Conf. Developments in Distribution Switchgear*, May 1986.

[33] D. Paul and S. I. Venugopalan, "Power Distribution System Equipment Overvoltage Protection," *IEEE Trans. Ind. Applica.*, vol. 30, pp. 1290-1297, Sept./Oct. 1994.

[34] T. Itoh, Y. Murai, T. Ohkura, and T. Takani, "Voltage Escalation in Switching of Motor Control Circuit by Vacuum Contactor," *IEEE Trans. Power Appl. Syst.*, vol. PAS-91, pp. 1897-1903, Sept./Oct., 1972.

[35] M. Murano, T. Fujii, H. Nishikawa, S. Nishiwaki, and M. Okawa, "Three Phase Simultaneous Interruption in Interrupting Inductive Current Using Vacuum Switches," *IEEE Trans. Power App. Syst.*, vol. PAS-93, pp. 264-271, Jan./Feb. 1974.

[36] H. Ohashi, H. Koike, M. Okawa, and Y. Imajyo, "Switching Surge and Application of Vacuum Contactors and Vacuum Circuit Breakers," presented at the IEEE-PES Winter Meeting and Tesla Symp., New York, NY, Jan. 1076, Paper A76 173-5.

[37] Y. Murai, H. Toya, and T. Nitta, "Statistical Property of the Breakdown of Vacuum Circuit Breakers and Its Influence on the Surge Generation in Capacitive and Reactive Current Interruption," *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 232-238, Jan./Feb. 1979.

[38] S. H. Telander, M.R. Wilhelm, and K.B. Stump, "Surge Limiters for Vacuum Circuit Breaker," IEEE Trans. Ind. Applica., vol. 24, pp. 1672-1677, Oct. 1998.

[39] A. Greenwood and M. Glinkowski, "Voltage Escalation in Vacuum Switching Operations," *IEEE Trans. Power Delivery*, vol. PD-3, pp. 1698-1706, Oct. 1988.

[40] Y. Matsui, T. Yokoyama, and E. Nmeya, "Reignition Current Interruption Characteristics of the Vacuum Interrupter," *IEEE Trans. Power Delivery*, vol. 3, pp. 1672-1677, Oct. 1988.

[41] R. Pretorius, Guide for the Application f Switching Surge Suppressors to Medium Voltage Motors, South African Electric Power Coordinating Committee, 1992.

[42] IEEE Red Book, IEEE Recommend Practice for Electrical Power Distribution for Industrial Plants, IEEE Std. 141-1993, Chap. 6 – Surge Suppression.

[43] P. G. Slade, "Vacuum Interrupters: The New Technology for Switching and Protecting Distribution Circuits," *IEEE Transactions on Industry Applications*, vol. 33, No. 6, pp. 1501-1511, Nov./Dec. 1997.

[44] M. Glinkowski, A. Greenwood, J. Hill, R. Mauro, and V. Varneckes, "Capacitance Switching With Vacuum Circuit Breakers – A Comparative Study," *IEEE Trans. Power Delivery*, vol. 6, pp. 1088-1095, July 1991.

[45] B.A.R. McKean and C. Reuber, "Magnets and Vacuum – The Perfect Match," *Proc. 5th Int'l. Conf. On Trends in Distribution Switchgear*, IEE Pub. No. 459, pp. 73-79, Nov. 1998.

[46] A. Sabot, C. Morin, C. Guillaume, A. Pons, J. P. Taisne G. LoPizzo, and H. U. Morf, "A Unique Multipurpose Damping Circuit for Shunt Capacitor Bank Switching," *IEEE Trans. Power Delivery*, vol. 8, pp. 1173-1183, July 1993.

[47] A. Greenwood, *Electrical Transients in Power Systems*, 2nd ed. New York, Wiley 1991.

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