

Insulating and Switching Media in Medium Voltage Distribution and Medium Voltage Motor Control

White Paper IA08324006E

Table of Contents

1. Introduction	2
2. Evaluation of Insulating and Switching Media	2
A. Insulating Media	2
B. Arc Quenching Media	2
3. Conclusions	10
4. References	11
5. Vita	12
6. Appendix A	13

Abstract

An evaluation of insulation and switching media in medium voltage (1 – 52 kV) applications is presented in this paper. Special attention is given to motor switching and to distribution of electricity. The various insulating and/or switching media like oil, epoxy resin, air, SF₆ and vacuum are discussed along with their pros and cons in different applications.

Key words are associated to the prevention of the various overvoltages that might occur in industrial networks and their relation to the switching media. The basic phenomena, such as current chopping and restrikes, are reviewed and the harm that overvoltages can cause either by amplitude or rising time to the equipment. Besides the overvoltage aspects, the operation and maintenance aspects related to different insulating and switching media are surveyed and discussed.

Index Terms — vacuum, SF₆, insulation media, arc quenching media.

1. Introduction

Switchgear designs can be basically distinguished by the use of materials for insulating purposes and for arc quenching media to make and break the currents.

It is important for switchgear to have high availability, with little or no need for maintenance. This is especially valid for industrial applications. Besides the undisputable safety aspects, also life-cycle costs (MLTCO – Minimum Long-Term Cost of Ownership), and environment are generally key factors.

Market driven aspects and changes herein result in the need for considering or reconsidering the criteria for choosing switchgear, both for utility and industrial networks/applications.

2. Evaluation of Insulating and Switching Media

A. Insulating media



Fig.1: open cells in substation

Presently, the main media for insulation are epoxy resin combined in many cases with air and SF₆.

Historically, ambient air has been used as insulating medium in the design of electrical equipment. Ambient air consists for more than 80 percent of nitrogen (N₂), which is also presently used in its pure form. The only reason that some manufacturers apply N₂ as insulating medium is its independency from external conditions; however, clean ambient air also performs equally well in normal circumstances.

Especially in combination with solid insulation materials — like epoxy resin — and design of high voltage components for electrical fields, MV switchgear can be build as compact as with SF₆ (fig. 2).

When designing switchgear, the behavior in service is a determining factor. Several properties of the applied materials like dielectric withstand, aging sensitiveness, environmental impact, flammability, and possible by-products in case of internal faults are important. These aspects should be considered both for occurrences during lifetime of the switchgear, and for the end of life. In fact, an evaluation of costs can be made but mostly it is found that the safety for man and animal is of highest importance.

Over the past century a lot of materials have been used as insulating medium, such as air, wood, glass, oil and plastics as PVC and polyesters, all with their own positive points and



Fig.2: smart dielectric design results in compact non-SF₆ switchgear

Oil is a superb insulating medium, applied since 1890. Oil allows compact installations but it is outdated in MV switchgear as insulating material because of fire risk and its susceptibility to contamination (moisture and by-products after switching). The maintenance requirements with its related costs also play a negative role in the application of oil.

Epoxy resin used since mid 1950s is also a very good insulator that can also be used as a construction material. Epoxy resin consists of 80 percent pure sand and 20 percent epoxy with hardener. Generally, epoxy resin is not aging. However, a good design greatly depends on the knowledge of electrical fields. The epoxy can be shaped in such a way that those fields are minimized, resulting in low electrical stress on the surrounding, which can be normal air at atmospheric pressure. Also for the conductive parts that are embedded in epoxy insulation, it is important to create smooth shapes to avoid too high electrical and mechanical stresses.

SF₆ is a synthetic compound consisting of one sulfur atom and six fluorine atoms. SF₆ is gaseous at room temperature. This gas has the properties for making it very suitable as insulation and switching medium.

SF₆ has been used in HV application since 1965, and recently in MV-switchgear. It is a gas with good insulating properties, having a dielectric strength at atmospheric pressure of about 3 times higher than air. By using SF₆ at relatively low overpressure, it is easy to design compact switchgear. However, this compactness is limited by the need for interfaces, like the cable connections. The minimal practical size is defined by space needed for cable connections. The use of SF₆ is the only practical option for compact HV switchgear (>52 kV), but is not needed for compact MV switchgear, as alternative solutions coexist.

Three fundamental systems can be distinguished to maintain the gas pressure for SF₆ switchgear: [ref 1]

- **Controlled pressure system is automatically replenished from an external or internal source.**
- **Closed pressure system is periodically replenished by manual connection to an external source.**
- **Sealed pressure system for which no further gas processing is required during its expected operating life.**

The SF₆ is highly contributing to the greenhouse effect (22.200 CO₂ equivalents) [ref 2], therefore, the main concern with SF₆, regardless of the type of pressure system used, is how to prevent it from escaping to the atmosphere. It is well known that mechanical seals may leak at some point.

Special attention shall be given when the switchgear has to be cleared at the end of its life. Even more attention is needed when the SF₆ was in contact with electrical arcs (e.g., when used as interrupter) because of the highly poisonous by-products, like S₂F₁₀. For this reason, internal arc tests in SF₆ switchgear may be performed with air instead of SF₆. Although IEC 62271-200 states that the results are different with air [note in cl.A.3.1 of ref 3], this test set-up is accepted due to environmental issues.

The characteristics of the several insulating materials are summarized in Table 1:

Table1: Characteristics of Insulating Materials

INSULATING MEDIUM	AIR, N ₂	OIL	EPOXY	SF ₆
Insulating Properties	+	++++	+++	+++
Aging/Maintenance Need	+	--	+	+
Inflammability	++++	--	+	+
Environmental Aspects	++	-	+	--
Hazardous By-products	+	-	-	--

B. Arc-quenching media

Although there is still a lot of air, compressed air, bulk oil and minimum oil switches and circuit breakers in service, most of the modern switching and interpreting devices are of the vacuum type or SF₆.

Oil can be considered outdated as arc quenching medium, because of the already mentioned reasons as fire risk, susceptibility for contamination and moisture, by-products after switching.

Air can be considered outdated as arc-quenching medium, due to the relatively bulky volumes needed, sound aspects when operating and sensitivity for moisture.

Modern media: The choice is between SF₆ and vacuum, each with certain pros and cons compared to the other. Both have very good arc-quenching properties. The discussion sometimes tends to be biased by the preferences of the manufacturer.

Not only do the vacuum adepts claim to be environmentally friendly, but also SF₆ suppliers stick green logos on their switchgear. Fact is that the traditional manufacturers of SF₆ switchgear have started vacuum developments, while vacuum switchgear manufacturers stick to vacuum.

A lot of activities have been set up to keep SF₆ on the market: ecological studies, sponsored by a SF₆ supplier and SF₆-switchgear manufacturers [ref 4], Frequently Asked Questions concerning the use of SF₆ [ref 5] and self-declared voluntary agreements to reduce the SF₆ release into the atmosphere.

A further obvious token may be the fact that already three dedicated IEC standards exist for SF₆, where none exists for vacuum [ref 6, 7, 8].

In the meantime, the European Parliament and the Council have published a draft regulation about certain fluorinated greenhouse gases inclusive SF₆ with a legal base [ref 9].

SF₆ as arc-quenching medium

Due to the fact that the SF₆ molecule is electronegative, it provides excellent insulation after extinction. SF₆ gives an excellent dissipation of heat which is cooling the arc and which is important around the zero crossing. But in the high current phase, where the temperature is higher than 3000 °K, the SF₆ molecule is completely decomposed.

A less favorable property is that very little energy is needed to revive a discharge that has not yet been sufficiently cooled. Another disadvantage is that due to arcs in SF₆, corrosive and poisonous by-products are created.

Several design principles can be distinguished for SF₆ as arc-quenching medium, see Table 2:

Due to, amongst other things, its construction, the SF₆ circuit-breaker has some attractive features.

The most important are:

- Low force needed for contacts pressure.
- In general low chopping currents, however, this depends on the network (capacitance across the contact gap)

Table 2: Typical Designs with SF₆

SF ₆ DESIGNS	PUFFER	AUTO-EXPANSION	ROTATING ARC	OPEN CONTACTS
Voltage Level	>52 kV	>7.2 kV	<24 kV	<24 kV
Interruption Current	≤100 kA	≤100 kA	≤25 kA	≤1 kA
Type of Interrupter	CB	CB	CB, Contactor	LBS
Energy Mechanism	High	Moderate	Low	Low
Chopping Current	<3 A	<3 A	<3 A	<3 A

Vacuum as arc-quenching medium

Application of vacuum interrupters in MV originates from the 1970s, coming from LV applications.

In its basic form, the vacuum interrupter is comprised of two contacts that are situated in a space in which the gas pressure is extremely low (10⁻⁵-10⁻⁸ mbar). Fig.3 shows the construction of a vacuum interrupter.

Vacuum is only used as switching medium, not as insulating medium, because the corresponding volumes would be too big to guarantee a commercial attractive sealed for life design.

Presently, vacuum is used for current interruption in Circuit Breakers (CB), Load Break Switches (LBS) and contactors.

There are two fundamental designs for CBs; namely, Axial Magnetic Field (AMF, to keep the arc diffused) and Radial Magnetic Field (RMF, to produce a rotating arc along the contacts).

In practice three different designs can be distinguished, if the applied contact material is also considered, see Table 3:

The level of the electrical field at breakdown of vacuum is extremely high, so only 8 to 15 mm contact distance is sufficient for 12 kV to 36 kV applications.

During the arcing phase between the contacts, the arc is substained by metal vapor released from the contact surface until the next current zero occurs.

Table 3: Typical Design with Vacuum

CONTACT DESIGN IN VACUUM	CuCr, AMF	CuCr, RMF	W + Cu (+ additions)
Voltage Level	≤52 kV	>52 kV	≤24 kV
Interruption Current	≤40 kA	≤100 kA	≤10 kA
Type of Interrupter	CB	CB	LBS, Contactor
Energy Mechanism	Low	Low	Low
Chopping Current	<5 A	<5 A	<1 A

(CB =Circuit-Breaker and LBS = Load-break Switch)

Vacuum interrupters have a number of attractive features like being maintenance-free, compact and environmentally friendly. Other important features are:

- **Large operation reliability.** Because of its simple construction, the number of components is small (approximately 50 percent less than a comparable SF₆ or oil circuit breaker).
- **Small amount of operating energy.** Due to the small stroke (≈10 mm) of the contacts and the light weight of the accelerating mass, the required operating force is low. Consequently, the operating mechanism is of a very simple design.
- **Low arcing voltage.** Because of the low arcing voltage (≈30 V) the energy in the arc is limited.
- **Environmentally friendly:** no danger of explosion and/or fire, only little noise when operated.
- **Excellent interrupting characteristics,** arc duration below 10 ms.



fig 3: principle vacuum interrupter

Generally heard objections against SF₆ and vacuum:

SF₆

- **Leakage:** In general, leakage rates of < 1% per year are claimed, although this figure seems to be too low in practice.
- **Safety:** Although pure SF₆ is non-toxic, the by-products after arcing (when used as interrupting medium, or in case of internal arcs) are extremely toxic. So users must have extensive safety procedures on how to act in case of emergencies with dedicated SF₆ aspects. In the event of an internal arc, SF₆ gas and the toxic products of combustion could be released to the atmosphere.
- **Environmental impact:** the impact of SF₆ on the greenhouse effect is 22,200 CO₂ equivalent, and a very long lifetime in the atmosphere (minimum 3,200 years for SF₆ vs. 200 years for CO₂) [ref 2, 10]. So for the next 3,000 years, atmospheric SF₆ will simply accumulate. SF₆ is already listed as 'undesirable' in the Kyoto protocol (1997). Thereupon the Life Cycle Thinking as defined in cl.4: Fundamental Considerations of Environmentally Conscious Design (ECD) is promoted by WG2 of IECTC111 [ref 11].

Vacuum

- **Overvoltages:** Switching surge voltages are often associated with vacuum circuit breakers. This reputation originates from the first generation types in which pure copper contacts were applied. With these pure copper contacts, chopping currents of approximately 20 A could be attained. In the modern versions (from 1980), copper-chromium contacts are applied, which only produce chopping currents of 3 to 5 A. In practice, such chopping currents do not cause high surge voltages any longer. For applications where large interrupting capability is not required (e.g. motor contactor), the level of switching voltages can be even further reduced by adding a small amount of a metal with a high vapor pressure (Cd, Sb, Zn) to the contacts. The mixture obtained lowers the possible chopping currents to extremely low levels. However, in exceptional cases, when switching inductive loads such as stalled motors or transformers during "inrush" at no-load, too high surge voltages still may occur (as a result of voltage escalation). However, this can also occur with SF₆ breakers. Surge suppressors or arrestors may sometimes be beneficial (e.g., for motors smaller than 250 kW, depending on the length of the cable between motor and interrupter). In 3-phase circuits, surge voltages can also occur in very special cases due to so-called virtual current chopping. In Appendix A, the topic overvoltages is treated more extensively. Protection against such switching surges can be easily provided by use of proper surge protection devices (surge arresters, surge capacitors, RC snubber, etc.).
- **X-rays:** A vacuum interrupter (VI) with open contacts, in principal, can act as an X-ray source. However, this phenomenon occurs only at higher voltages (> 24 kV). Extensive measurements on Eaton® Holec® vacuum interrupters demonstrated that a human being at only 10 cm distance from an open VI can endure more than 200 times a year the 1-minute power frequency test of 50 kVrms (for 24 kV switchgear), before

the maximum allowable quantity of X-rays is attained. In practice, this distance will be surely higher than 10 cm and screens in between will be a damping factor. At normal service voltages for switchgear ≤ 24 kV, no radiation could be measured at all (at 10 cm distance) above the natural background value of 0.06 $\mu\text{SV/hr}$. In line with harmonization efforts between the international IEC standards and the North-American ANSI standards, X-ray measurements for vacuum interrupters will be introduced in the IEC 60694 [ref 1], which is currently IEC 62271-1. As a type test, the procedure and acceptable levels will be taken from ANSI C37.85. The maximum allowable values at a distance of 1 m from the vacuum interrupter with open contacts are 5 $\mu\text{SV/hr}$. at maximum operating voltage and 150 $\mu\text{SV/hr}$. at the rated power frequency withstand test voltage. These values are so high that they are of totally no concern for nowadays design vacuum interrupters applied in the MV range.

- **Leakage:** Because of the short contact stroke needed in a vacuum interrupter (about 10 mm), it is possible to apply bellows. Thanks to this, no sealings are needed which makes a real sealed-for-life design possible. Combined with clean room techniques during production, this results in an extremely high reliability in practice. Vacuum integrity can be easily checked by voltage testing across the open contacts.
- **Shelf Life:** Due to the measuring methods manufacturers use, the shelf life is extrapolated to 20 years as a minimum. In practice, this value is considered as very conservative.

Specific features of both SF_6 and vacuum as arc-quenching medium are summarized in Table 4.

Table 4: Comparison Characteristics SF_6 Vacuum

COMPARISON SF_6 VACUUM	SF_6	VACUUM
Arc-Voltage [V]	100	20
Arc Energy	5 ¹	1 ¹
Chopping Currents	Generally Very Low (<1 A), However Depending on the Network	Generally Low (3 A) or Very Low (<1 A) with Contactors
Restrike Possibility	Low	Very Low
Impact Reignition	Killing	Healing
Risk on Overvoltages	Only in Specific Situations	Only in Specific Situations
SC Current [#]	30	>100
Contact Stroke	10 ¹	1 ¹
Closing Energy	10 ¹	1 ¹
Number of Parts	2 ¹	1 ¹
Number of Operations	10,000	30,000
Environmental Impact	Yes	No
End of Life	Complicated	Easy

¹ 1 is 100%; other column is relative to this 100%.

Considerations for the Dow Chemical facility in Terneuzen

The Dow Chemical Terneuzen facility is Dow's largest production facility outside the United States.

For the distribution system, Dow Chemical Terneuzen applies the voltage levels 50 kV, 11 kV, 6 kV, 690 V and 400 V.

Dow Chemical Terneuzen history on insulation and switching media: In 1964, Dow Chemical Terneuzen started with three 50 kV connections to the public grid; the 50 kV switchgear of the public grid has oil as insulating and switching medium.

The three 6 kV Dow switchgear installations used oil as insulating and switching medium, are arc resistant and of the metal-clad type.

Also, one outdoors open-air 50 kV system including minimum oil circuit breakers was installed.

Till the mid 1970s, Dow Chemical Terneuzen installed arc-resistant metal-clad switchgear with air as insulation for the bus bars and minimum oil circuit breakers on the 11 and 6 kV voltage level.

In 1975, Dow decided to go away from oil due to the high fire risk, contamination issues of oil, long switching times of circuit breakers, and high maintenance requirements of systems with oil as insulating and switching medium.

At that time, mainly two systems were evaluated: air insulated metal-clad switchgear with air as insulating medium combined with SF₆ circuit breakers against air insulated metal-clad switchgear with air as insulating medium combined with vacuum circuit breakers or a combination of vacuum contactors with HV fuses. The vacuum contactors have the function as load-break switch and the HV fuses were used as short-circuit protection.

The Dow Chemical Terneuzen philosophy was at that time and still is: where possible, install switchgear with air as insulating medium combined with vacuum circuit breakers instead of systems where SF₆ is used as insulating medium and/or switching medium.

In 1975, the choice was also made to go for the combination vacuum contactors and HV fuses for the load range up to 400 A. For the higher ratings, vacuum circuit breakers were installed.

From 1985 on, Dow Chemical Terneuzen installs air insulated switchgear with air as insulating medium combined with vacuum circuit breakers for all current ratings in the 6 and 11 kV voltage ranges.

With the mentioned grid configuration, SF₆ would only be necessary for the 50 kV level, since alternatives are no longer commercially available.

On the other voltage levels, air insulated systems with vacuum circuit breakers are available and used.

Even on low voltage level, 400 and 690 volt, vacuum contactors are used in new and retrofitted systems, to control large motors.

Vacuum breakers need less maintenance than air or oil breakers; it is also not necessary to overhaul the breakers after switching off a short circuit. The condition of the switchgear can be determined based on measurement of the resistance [$m\Omega$] (Ductor test) and voltage-withstand capability (Hi-pot test).

Maintenance of SF_6 switchgear is comparable with vacuum switchgear in respect of maintenance. Supervision of SF_6 insulated bus bar systems is easy to do (pressure switch). Compared with vacuum, SF_6 as medium needs extra safety requirements.

3. Conclusions

Although a very good insulation and arc-quenching medium, SF_6 applications are not desirable for medium voltage applications because of environmental and safety drawbacks of the SF_6 . The advances in insulation and design techniques using epoxy and other environmentally friendly materials makes it possible to build compact MV switchgear without having to resort to use of SF_6 .

Presently, the main technologies for arc quenching in the medium voltage range are SF_6 or vacuum. The pros and cons for both have been discussed for many years. Worldwide, the application of vacuum is increasing, at the same time, use of SF_6 in medium voltage is declining.

The drawbacks linked to early designs of vacuum interrupters are not valid for today's modern and state-of-the-art vacuum interrupters. The concerns for overvoltages under certain specific switching conditions applies to both, vacuum and SF_6 circuit breakers. Those concerns can be easily addressed by application of proper surge protection devices.

Especially as an arc-quenching medium, use of vacuum has been increasing over SF_6 in MV applications. Even the well-known SF_6 -adapted manufacturers are offering vacuum breakers inside their SF_6 insulated gear. The early vacuum adopting manufacturers however have not switched to SF_6 .

Dow Chemical Terneuzen, as a major industry, has consciously decided not to use SF_6 for switchgear in the medium voltage range.

4. References

- [1] IEC 60694: 2002, Common specifications for high-voltage switchgear and controlgear standards, now IEC 62271-1
- [2] SF₆, the warning signs, T. Dawn, Electrical review 1996, volume 229, no 2, 32-34
- [3] IEC62271-200: 2003, AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV
- [4] SF₆-GIS-Technologie in der Energieverteilung –Mittelspannung. Life Cycle Assessment study commissioned by ABB, AREVAT&D, EnBW Regional, e.on Hanse, RWE, Siemens and Solvay Fluor und Derivate. (2003)
- [5] <http://www.capiel.com>: Frequently asked Questions (FAQ) and Answers on SF₆ 7-12-2005
- [6] IEC 60376: 1971, Specification and acceptance of new sulphur hexafluoride
- [7] IEC 60480: 1974, Guide to the checking of sulphur hexafluoride (SF₆) taken from electrical equipment
- [8] IEC 61634: 1995, High-voltage switchgear and controlgear – Use and handling of sulphur hexafluoride (SF₆) in high-voltage switchgear and controlgear
- [9] Draft regulation European Parliament: 2003/0189A (COD)
- [10] Report 1994 of Intergovernmental Panel on Climate Change (IPCC)
- [11] IEC 62430, Ed.1: Environmentally Conscious Design for Electrical and Electronic Products and Systems Status Committee Draft 11/65/CD
- [12] G.C. Schoonenberg and W.M.M. Menheere, "Switching overvoltages in M.V. Networks," paper 2.17, Cired 1989.
- [13] L. van der Sluis, G.C. Damstra, W.R. Rutgers and G.C. Schoonenberg, "The modeling of circuit-breaker arcs, application and testing of switchgear," paper 13-111, Cigre 1994.

5. Vita



Wim.M.M. Menheere, B.Sc. graduated in electrical engineering from HTS Vlissingen. Working with Eaton Holec since 1973 in several technical and commercial departments in the Medium Voltage range. He was a member of the National committees NEC 32 and several international working groups within IEC SC17C. Already for a long time responsible as product manager of Medium Voltage switchgear but now responsible for Medium Voltage Main Station equipment and New Developments.

Eaton, P.O. Box 23, 7550 AA Hengelo, The Netherlands



Gerard.C. Schoonenberg, M.Sc. received his MS, in Electrical High Power Engineering, in 1984 at Eindhoven University of Technology. After several years within the High Power labs of Eaton Holec, focusing on MV switchgear developments and testing he went in 1989 to the Utility of Amsterdam. A few years later he returned to Eaton Holec, having several positions within the R&D for medium voltage. Presently, he is the manager of the Damstra Laboratory in Hengelo. He is a member of the national committees NEC 17A/C and NEC 99, and is also convener and / or member of several electrotechnical international working groups within IEC SC17A and SC17C.

Eaton, P.O. Box 23, 7550 AA Hengelo, The Netherlands



Jan Verstraten, B.Sc graduated in electrical engineering from HTS Hilversum. Currently a Sr. electrical specialist, he has worked for Dow Benelux BV in Terneuzen since 1990, in various departments: Maintenance central E&I, Maintenance Technology Department and Powerplant. Since 2004 he has held the post of Installation Responsible Person for Dow in the Netherlands, Electrical SME for Dow in Benelux, UK & Scandinavia and Electrical Safety and Reliability auditor. Member of: NEC 623

Dow Benelux, P.O. Box 48, 4530 AA Terneuzen, The Netherlands



Rudy Vervaet, B.Sc graduated in electrical engineering from HTS Vlissingen. He is currently a Technical Consultant Electrical, Energy and Electrical Safety having retired in 2006 from Dow Benelux BV Terneuzen, The Netherlands after 33 years of service. At Dow he worked within several departments: Power Generation and Distribution, Maintenance Technology Department before taking up the role of Electrical Safety and Reliability Audit Leader for Europe in 1996, and in 2000 an additional role in the Energy Systems Technology Centre and Global Technical Resource Leader for Electrical Rotating Equipment.

Dow Benelux, P.O. Box 48, 4530 AA Terneuzen, The Netherlands

Appendix A

Considerations Concerning Overvoltages [Ref 12]

Different Kinds of Switching Overvoltages

Pre-ignitions

When contacts are closing, pre-ignition is unavoidable, no matter what type of switching medium is used. The resulting voltage jump V goes as a surge wave in the direction of the load. On arrival, when relatively high impedance prevails, such as an inductive load, a voltage increasing effect will occur because the wave is reflected. Practical values for this increasing effect are 1.5 to 1.8.

The voltage jump of the first igniting pole is at the most 1 p.u. ($\sqrt{2} \cdot U/\sqrt{3}$). As a result of an oscillation after ignition of the first pole and the voltage on the source-side of -0.5 p.u., a voltage jump of 2.5 p.u. is possible on the two other poles, when ignited. The maximum overvoltage that can be reached on the terminals of an inductive load, therefore amounts to $0.8 \times 1.8 \times 2.5 = 3.6$ p.u. Because of the steep surge, especially the first windings will be stressed.

Normal current chopping

When opening a breaker, the current can be interrupted before it reaches its natural current zero point due to instabilities in the arc. The energy $\frac{1}{2} Li^2$, present at that moment in the inductive load, will oscillate via the ever present (parasitic) capacitance, so that the overvoltage amounts to approximately $i \cdot \sqrt{L/C}$. The frequency range is up to 20 kHz. The overvoltage on both cable ends occurs simultaneously and therefore no surge waves occur. With chopping currents of a maximum of 5 A, the overvoltages are limited in practice to 3 p.u. and can therefore be no specific cause for damage.

Multiple restrikes

In principle, multiple restrikes may occur during both closing and opening operations with breakers having a fast recovering dielectric such as vacuum or SF_6 . Escalation is practically impossible at closing, as the contacts keep moving toward each other so the dielectric strength decreases. However, when opening the breaker, the transient recovery voltage (TRV) may exceed the dielectric strength of the still small contact gap (just opened), so restriking occurs with its high frequency equalizing currents.

Breakers with a fast recovering dielectric can interrupt at these high-frequency current zeros, in a still increasing gap. The restriking itself causes a surge wave as described under pre-ignitions.

Virtual current chopping

When in a 3-phase circuit a restrike occurs in the first opening pole, the instantaneous value of the arc-current in the other poles is forced down to zero, due to the high frequency equalizing currents. This phenomenon is called virtual current chopping because the instantaneous value of the power frequency current ($\sqrt{2}i.\sin60^\circ$) is abruptly interrupted in the phases concerned. As described under normal current chopping, this now high momentary current in the inductive load will be transferred into a high overvoltage (theoretically > 40 p.u.).

Resonance

The resonance frequency of transformers with small ratios such as 10/2 and 10/6 kV can be present in the same area as repeating frequencies of occurring multiple restrikes (25 – 250 kHz). With these transformers, overvoltages may occur on the secondary side of 3 to 5 times the primary overvoltage, as a result of the resonance. With transformers with a larger ratio, e.g., 10/0.4 kV, no harmful overvoltages as a result of resonance can occur in practice.

Probability of Occurrence in Practice When Using Vacuum Circuit Breakers or Switches

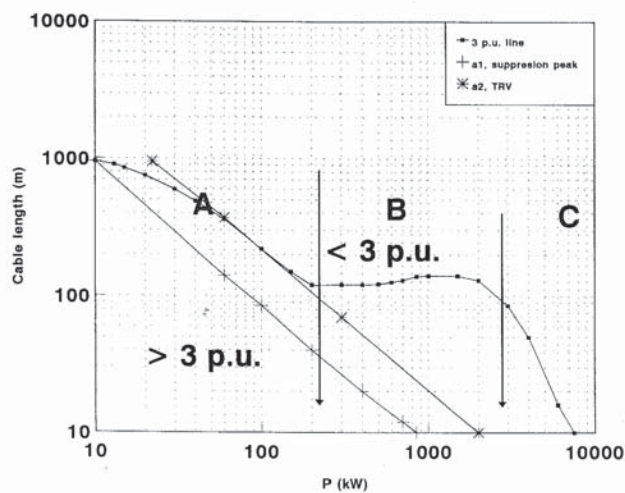


Fig A1: example equi-overvoltage line

The contact material of a vacuum interrupter has a definite influence on the value of the chopping current. CuCr, that is generally applied since 1980 for vacuum circuit breakers, has a chopping level of < 5 A. Additions in contactors result in chopping currents < 1 A. Contact material also influences the repeating frequency and duration of the multiple restrikes and therefore on the chance of virtual current chopping. Extensive tests have been performed over the years, resulting in theoretical models for computer calculations. As an example, Fig A1 presents the 3 p.u. equi-overvoltage line as a function of the motor-load and the cable length between the breaker and the load. (based on a 6 kV network, 5 A chopping current and 6 times the nominal motor current in stalled conditions [ref 13].

Multiple restrikes over the interrupter gap may occur when the contact separation lies close to a current zero. In vacuum circuit breakers with a chopping level of 5 A, this is from approx. 6° before the current zero (old design pure copper contacts result in approx. 15°).

In a 3-phase circuit, a current zero occurs every 60°, whereby the possibility of multiple restrikes and virtual current chopping is set to 25% ($15/60 \times 100\%$) when switching in practice (random opening).

Conclusions:

- Pre-ignitions cause in practice a heavy burden on inductive loads such as motors. They occur during each closing operation and are independent of the type of switching medium.
- Apart from the possible voltage escalation, every restrike gives a steep voltage jump on the inductive load.
- Virtual current chopping causes the most severe overvoltages

Eaton Corporation
Electrical Group
1000 Cherrington Parkway
Moon Township, PA 15108
United States
877-ETN-CARE (877-386-2273)
Eaton.com

Eaton and Holec are trademarks of
Eaton Corporation.



© 2008 Eaton Corporation
All Rights Reserved
Printed in USA
Publication No. IA08324006E
March 2008