

NEW ELECTRICAL DEVICES IN EXISTING NUCLEAR POWER PLANTS

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New Electrical Devices in Existing Nuclear Power Plants

Mapping of challenges with relay protections, circuit breakers and surge arresters

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Foreword

A nuclear power plant has a number of electrical devices in different systems. Due to a long-term operation expectancy of a nuclear power plant, a lot of devices needs to be replaced one or several times during the lifetime of the plant. As a natural progress, development of electrical devices is constantly ongoing on the market. This implies that the new devices that will be installed in the NPPs not only may have a different design, but also a different technology and thus different electrical behavior.

This report summarizes information of what the market offers regarding relay protections, surge arresters and circuit breakers and how the new technology could affect the surrounding systems and devices in the plant. The recommendations that are given in this report represent the view of the author. When an investment is made in a plant, numerous factors need to be considered in the specific investment case, like plant safety, system behavior, system cost, maintenance know-how etc.

The project was carried out by Henrik Hemark, senior consultant at DNV GL within the GINO program. The GINO program is financed by The Swedish Radiation Safety Authority, Vattenfall, Uniper/Sydkraft Nuclear, Fortum, Skellefteå Kraft and Karlstads Energi.

Sammanfattning

Kärnkraftverk är konstruerade och byggda för lång och säker drift. Teknisk utveckling och framsteg har gjort elektrisk utrustning som ursprungligen använts föråldrad och förlegad. Fokus på denna studie är reläskydd, effektbrytare och överspanningsavledare.

Kraven på utrustning för säkerhetssystemen på kärnkraftverk överstiger normala industrikravsstandarder. Väl beprövade och certifierade lösningar måste användas och särskild hänsyn måste tas vid tillämpningen.

Reläskydd har gått från elektromekaniska reläer till statiska halvledarreläer till numeriska (digitala) reläskydd. Det är andra generationens numeriska reläskydd som erbjuds idag. Det finns fortfarande elektromekaniska reläer i drift i kärnkraftverken. Ett numeriskt reläskydd kan ersätta flera elektromekaniska reläskydd och logik som kopplats för hand.

Reläskydd	Elektromekaniska	Statiska halvledarreläer	Numerisk, mikroprocessor
Flexibilitet	En (enda) funktion	Huvudsakligen en (enda) funktion per enhet	Flera funktioner
Underhåll	Rörliga delar kräver underhåll	Mindre underhåll	Självövervakning och självtest (ersätter inte allt underhåll)
Noggrannhet	Låg noggrannhet, kräver kalibrering	Bättre noggrannhet, mindre kalibrering	Hög, mindre kalibrering
Hastighet	Långsam, även om en del var snabba	Högre funktionshastighet Kortare återställningstid	Känslig och snabb
Miljö	Naturligt immun mot elektriska transienter (EMI, RFI, etc.) Kan falla vid seismiska aktiviteter	Motstår seismiska krafter Känslig för elektriska transienter*	Motstår seismiska krafter Känslig för elektriska transienter*
Komplexitet	Rudimentär funktionalitet Logiska funktioner kräver externa reläer och omfattande kabeldragning	Grundläggande justering av karakteristikkurvor. Logiska funktioner kräver externa reläer och omfattande kabeldragning	Omfattande möjligheter innebär många inställningar Inbyggd programmerbar logik
Rapport-funktioner	Ingen registrering av fel	Samma som elektromekaniska tills hybrider som kombinerar analog teknik med mikroprocessorbaserad logik utvecklades	Rapport- och registreringsmöjligheter Kommunikation för skyddsfunktioner

**Not. Standarder och testprotokoll har utvecklats för att säkerställa att reläskydden är konstruerade för att fungera säkert och motstå elektriska transienter.*

Ett specifikt krav i kärnkraftverk (TBE 100) är att utrustning med mikroprocessorer bör undvikas i miljöer som innebär att utrustningen under sin livstid kan exponeras för en total joniserande strålning över 10 Gy.

Numeriska reläskydd är överlägsna tidigare teknologier när det gäller funktionalitet och flexibilitet, inbyggd programmerbar logik, självövervakning, registreringsfunktioner, kommunikationsmöjligheter, etc. De har en potential att förbättra skyddet, men risk för felaktig funktion om inte tillämpningen sker med omsorg. Den mänskliga riskfaktorn och begränsad förmåga att förstå hela systemet ställer krav på omsorgsfull konstruktion, tillämpning, kabeldragning, test och dokumentation. De numeriska reläskydden kräver ny kompetens och utbildning utöver traditionell kunskap om elkraft. IEC 61850 standarden kommer att förenkla integrationen av numeriska reläskydd i lokal och global kommunikation för övervakning och styrning.

Test och underhåll av skyddssystem har i flera fall varit oförändrade sedan reläskydden baserades på elektromekaniska teknologier. Fokus bör flyttas från kalibrering till funktions- och systemtester. Rutiner måste uppdateras och anpassas till den nya tekniken. Mjukvaruuppdatering av de numeriska reläskydden kan inte göras utan att mjukvaran och enhetens funktion certifierats och kvalificerats.

Effektbrytare för mellanspänning domineras idag av vakuumbrytare, detta gäller dock inte för de nordiska kärnkraftverken. I praktiken används idag antingen vakuumbrytare eller SF₆-brytare och dessa har ersatt äldre typer av brytare. Användningen av SF₆ som medium minskar, mycket på grund av miljöskäl. Växthuseffekten är 23 500 gånger högre för SF₆ än för CO₂.

Överspänningar vid brytning kan genereras av effektbrytare, vilket huvudsakligen är ett problem för vakuumbrytare. SF₆-brytare har mjukare brytkarakteristik och det krävs normalt inte ytterligare skyddsutrustning. Vakuumbrytare har förbättrats genom användande av moderna kontaktmaterial som har lägre hackströmmar än tidigare. En del tillämpningar kräver särskild omsorg när vakuumbrytare används. Äldre utrustning kan ha lägre isolationsgrad eller åldrad och försämrad isolation som ökar risken för skador vid överspänning. Överspänningsavledare, överspänningskondensator, och RC-filer är olika lösningar för att begränsa överspänningarna. Sannolikheten för överspänning minskar något med enkelledarkabel än med flerledarkabel. Skyddet ska monteras med korta kablar nära objektet som ska skyddas och jord, effekten av skyddet minskar med avståndet. Kärnkraftverk har lång drifttid och befintlig utrustning är ofta äldre med lägre isolationsgrad och utrymmet kan vara begränsat, därför är det inte alltid möjligt att installera erforderliga överspänningsskydd. Dimensionering av RC-filer erfordrar god kännedom om nätet som omger effektbrytaren. Möjligheten att minska risken genom elektronisk styrning av brytningen diskuteras, men måste för mellanspänningstillämpningar betraktas som relativt ny teknologi.

Vakuumbrytare rekommenderas generellt av tillverkarna, men nödvändiga åtgärder måste vidtagas för att skydda känslig utrustning mot överspänningar, om det inte är möjligt ska SF₆ beaktas särskilt i säkerhetsklassade miljöer.

Överspänningsavledare av metalloxid har gjort att kiselkarbidavledare är föråldrade. Metalloxidavledare har överlägsna energihanteringskapacitet och skyddskapacitet jämfört med äldre teknologier.

Kapsling av silikon för metalloxidavledare har närmast ideala egenskaper; väldigt hög elasticitet, hög rivhållfasthet, hög temperaturstabilitet, mycket låg brännbarhet (självsläckande), högt dielektriskt motstånd, anmärkningsvärd hydrofobi och är vattenavstötande även om det är nedsmutsat (hydrofobin överförs även till smutslagret).

Överspänningsavledaren måste dimensioneras beroende på den utrustning som ska skyddas och driftsförhållandena.

Porslinskapslade kiselkarbidavledare kräver regelbunden kontroll och inspektion efter skador eftersom det finns en risk att kapslingen kan explodera.

Silikonkapslade metalloxidavledare är nästintill underhållsfria men visuell inspektion rekommenderas fortfarande.

Summary

The nuclear power plants are designed and built for long and safe operation. Technical development and evolution has made some of the electrical equipment which was originally used at commissioning obsolete or outdated. The focus of this study is on relay protection, circuit breakers and surge arresters.

The requirements on safety system equipment for nuclear power plants exceed normal industry standards. Well proven and certified solutions must be used, and special care must be taken in the implementation.

Relay protection has gone from electromechanical relays to static solid-state relays to numerical (digital) relay protection. The numerical relays offered today are of the second generation. The electromechanical relays are still in operation at the nuclear power plants. One numerical relay can replace several electromechanical relays and hardwired logic.

Relay Protection	Electromechanical	Static Solid-state	Numerical Microprocessor
Flexibility	Single function	Essentially single function per unit	Multiple functions
Maintenance	Moving parts require maintenance	Less maintenance	Self-monitoring and self-testing (does not replace all maintenance)
Accuracy	Low accuracy, need for calibration	Better accuracy, less calibration	High, less calibration
Speed	Slow, although some were fast	Higher operating speed Shorter reset time	Sensitive and fast
Environment	Inherently immune to electrical transients (EMI, RFI, etc.) May malfunction during seismic activities	Resistant to seismic forces Susceptible to electrical transients*	Resistant to seismic forces Susceptible to electrical transients*
Complexity	Rudimentary functionality Logical functions require use of external relays and extensive wiring	Basic adjustment of characteristic curves Logical functions require use of external relays and extensive wiring	Extensive capability gives numerous settings Programmable logic built in
Reporting features	No fault data recording	Like electromechanical until hybrids with a combination of analog analysis and micro-processor logic evolved	Recording and reporting possibilities. Communication for protective functions

**Note. Standards and test schemes have been developed to secure that the protective relays are designed to operate safely and withstand electrical transients.*

One nuclear specific requirement (TBE 100) is that equipment with microprocessor must be avoided in environments where it may be exposed to an integrated ionizing radiation exceeding 10 Gy during its lifetime.

Numeric protective relays are superior to older technologies regarding the increased functionality and flexibility, built in programmable logic, self-supervision, recording functions, communication features etc. They have the potential to increase the performance of the protection but also if not implemented with care a risk of malfunction. The human risk factor and limitation to understand the whole system require careful design, implementation, wiring, testing and documentation. The numerical relays require new competences and training together with the traditional power system competence. The IEC 61850 standard will simplify the integration of the numerical relays in local and global communication for monitoring and control.

Test and maintenance of protection systems is in many cases unchanged since the relay protection systems were based on electromechanical technology. The focus should move from calibration testing to functional or scheme testing. The routines must be updated and adapted to the new technology. Updating firmware in the numerical devices cannot be done without certification or qualification of the software and behavior of the unit.

Circuit breakers in medium voltage application are today generally dominated by the vacuum technology, this is not the case for the Nordic nuclear power industry. SF₆ and vacuum are practically the two available technologies and have today replaced older types of breakers. The use of SF₆ as a quenching medium is decreasing, much because of environmental reasons. The greenhouse effect is 23.500 times higher for SF₆ than for CO₂.

Switching overvoltages can be generated by circuit breakers, which is mainly an issue with vacuum circuit breakers. SF₆ circuit breakers have soft interruption characteristics and there is normally no need for additional protective devices. Vacuum circuit breakers have improved by using modern contact materials and exhibit lower chopping currents than previously. In some applications special care has to be taken when using vacuum circuit breakers. Older equipment may have lower level of or degraded insulation which increase the risk for damages from overvoltages. Surge arresters, surge capacitor and R-C filters are different solutions to limit the overvoltages. The probability of high overvoltages is lower with single core cable than with multicore cable. The protection should be installed close with short cables to the terminals of the equipment to be protected and ground, the protective effect is reduced with distance. Nuclear power plants are built for long operation and existing equipment is often older and has lower level of insulation and the space for additional protection may also be limited, why it is not always possible to install required overvoltage protection. Dimensioning the R-C filter requires good knowledge of the network surrounding the circuit breaker. Limiting the risk for overvoltages by electronic control of the switching is discussed but must for medium voltage applications be regarded as relatively new technology.

Vacuum circuit breakers are generally recommended by the suppliers, but necessary measures should be taken to protect equipment sensitive to

overvoltages, if this is not possible SF₆ circuit breakers shall be considered especially in safety classified areas.

Surge arresters of metal oxide have made silicon carbide arresters obsolete. Metal oxide arresters have superior energy handling capacity and protective capability over previous technologies.

Silicone housing which is used for metal-oxide surge arresters have almost ideal properties; very high elasticity, high resistance to tearing, high temperature stability, very low combustibility (self-extinguishing), high dielectric withstand, remarkable hydrophobicity and is water repellent even if polluted (the hydrophobicity is transmitted to the pollution layer).

The surge arrester must be dimensioned depending on the equipment to be protected and the operational conditions.

Silicon carbide arresters in porcelain housing need regular control and inspection for damages and there is a risk of the housing exploding. Metal oxide are almost maintenance free but visual inspection is still advised.

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1 Introduction

Different sources have been used to identify, study and compare alternatives and characteristics of the different devices; relay protections, circuit breakers and surge arresters.

- Literature
 - × Textbooks
 - × Guides
- Papers and reports
 - × Conferences
 - × Research
 - × Theses
- Articles
 - × Magazines
 - × Online publications
- Supplier information
 - × Representative selection
 - × Contacts
- User input
 - × Ringhals
 - × Forsmark
 - × OKG
 - × TVO

References are presented as numbered footnotes through the document, cross-reference are used if a reference already has been mentioned earlier in the document.

The study was initially general and broad, these findings are presented as a table for all devices and technologies after which more specific and deep findings on current technologies are presented for each device.

2 Background

A nuclear power plant has several electrical devices in different systems. Due to a long-term operation expectancy of a nuclear power plant a lot of devices needs to be replaced one or several times during the life time of the plant.

This study includes an investigation of the alternatives and characteristics of three important device types; relay protections, surge arresters and circuit breakers. The key characteristics of the devices are linked to identified challenges and risks when replacing existing devices with new devices.

Safety system equipment for nuclear power plants must meet or exceed industry design standards. IEEE refers to the safety classification "Class 1E Nuclear Protection". TBE (Technical Requirements for Electrical Equipment) and KBE (Quality and Inspection Requirements for Electrical Equipment) which are valid for all Swedish nuclear power generators can be found on this link:
<http://tbekbe.se/>

Common mode failure is of great concern and design qualification programs must assure that protection is maintained over time and that no age-related or design failures exist.

3 Relay Protections

3.1 DESCRIPTION

The development of relay protection has gone from electromechanical relays and operated when a measured quantity exceeded a set operation level. There were different relays for different functions like time delays, directional detection and distance protection. State of the art in mechanical relays were the line distance relays introduced in the 1940s¹.

The text below is from ABB²

Thus, national differences in for example communication protocols, special substation automation solutions etc, are an economic obstacle when the international electric companies are seeking even better productivity and economic performance. This is of course also valid for national power companies, with the goal to be competitive in economic terms.

It is therefore necessary to design Substation Automation Systems that are more cost effective to operate and maintain and that ensure quicker returns on investment than in the past. This new perspective with reference to the conceptual design and engineering of modern control systems, has been the driving force for the new standard IEC 61850, with a global approach on communication and information handling. Included in the standard is also that technology changes must be handled effectively, that the implementation must be very flexible to cover different substation automation philosophies, all types of power grids, communication solutions etc.

3.2 KEY CHARACTERISTICS

The evolution of relay protection and the key characteristics of the different technologies is summarized in Table 1.

¹ "100 years of relay protection, the Swedish ABB relay history", Bertil Lundqvist, ABB Automation Products, Västerås

² "A user friendly implementation of IEC 61850 in a new generation of protection and control devices.", Bertil Lundqvist* Berith Björklund Torbjörn Einarsson, ABB Power Technologies AB, 2007

Relay Protection	Electromechanical	Static Solid-state	Numerical Microprocessor³
Market introduction	~1900	1960's	1980's
Expected product life	Claimed product life 40 / average 25 years ⁴ Long product life cycle	Claimed product life 25 / average 15 years Product life cycle limited by product life of components	Claimed product life 28 / average 16 years (1 st gen.) and 30 resp. 19 years (2 nd gen.) Product life cycle limited by product life of components 1 st generation with through-hole mounted components and electrolytic capacitors start to fail. 2 nd generation have more powerful processors, more reliable surface-mount components and improved algorithms
Flexibility	Single function	Essentially single function per unit	Multiple functions
Acceptance	Well proven	Well proven	Well proven performance
Maintenance	Moving parts require maintenance	Less maintenance	Self-monitoring and self-testing (does not replace all maintenance)
Power supply	Relatively high load on instrument transformers	Auxiliary voltage supply required. Low burden on instrument transformers	Auxiliary voltage supply required. Low burden on instrument transformers
Accuracy	Low accuracy, need for calibration	Better accuracy, less calibration	High, less calibration
Speed	Slow, although some were fast	Higher operating speed Shorter reset time	Sensitive and fast
Environment	Inherently immune to electrical transients (EMI, RFI, etc.) May malfunction during seismic activities ⁵	Resistant to seismic forces Susceptible to electrical transients	Resistant to seismic forces Susceptible to electrical transients
Complexity	Rudimentary functionality Logical functions require use of external relays and extensive wiring	Basic adjustment of characteristic curves Logical functions require use of external relays and extensive wiring	Extensive capability gives numerous settings Programmable logic built in
Reporting features	No fault data recording	Like electromechanical until hybrids with a combination of analog analysis and micro-processor logic evolved	Recording and reporting possibilities. Communication for protective functions
Other	Expensive to produce Bulky	Lower manufacturing cost than electromechanical Less space vs. electro-mechanical	Lower manufacturing cost than electromechanical Computer software training necessary

Table 1. Evolution and key features overview of relay protection

It is hard to find general data on expected life, MTBF or other measures for the different technologies. In a report⁶ published by EPRI it is stated *“As customers have added numerical relays, maintenance intervals have been extended due to the nature of the equipment design. Moving parts, contacts, coils, and drift problems have been virtually eliminated. Currently, the focus has moved from calibration testing to functional or scheme testing. The numerical relay has proven to be a reliable and accurate device; therefore, less maintenance is required.”* The self-monitoring and self-test capabilities increases the availability as many faults are detected immediately and can normally be fixed within 48 hours. Electromechanical and static relays which require inspections and tests for detecting faults depend on the inspection intervals. Inspections and tests are still recommended for numerical devices for detecting the faults not detected by self-monitoring and self-test.

End-of-useful life is probably what should be considered⁷. It is claimed that microprocessor based devices have 20 years or less expected life. The reason is technical obsolescence, the processor is not produced any more, the software tools not compatible to the latest systems etc. The primary equipment protected often has a life of at least 40 years. It is important for asset managers to plan for replacement.

The numerical devices also have communication capabilities to and from local and remote locations for more efficient operation. Local communication between substations or numerical devices is fundamental for concurrent protection, like line distance protection. Communication interfaces are also often used for efficient and economic operation of stations and networks. SCADA (supervisory control and data acquisition) include hardware and software systems and allows operators to remotely monitor and control the equipment. Data is collected, processed, recorded and presented in the SCADA system.

Cyber security is obviously of outmost importance for nuclear power plants. The communication and new remote-control capabilities of the numerical devices and a new dimension in the design of the system is added. Decisions on what shall be monitored and controlled from where must be made.

3.3 CHALLENGES AND RISKS

Different human risk factors and limitations must be avoided.

- Increased possibilities with new technologies gives more complex systems with larger risk for design, incorrect settings and programming errors
- Incorrect wiring is a common cause for failures
- Insufficient knowledge of the system and behavior

³ Microprocessor relays are defined as software based numerical analysis

⁴ Upgrading Relay Protection, Daniel L. Ransom, IEEE Industry Application Magazine, 2014

⁵ Seismic functionality of essential relays in operating nuclear plants, W.R. Schmidt, R.P. Kassawara, Nuclear Engineering and Design 107 (1988) 43-50, North Holland, Amsterdam

⁶ Protective Relays: Numerical Protective Relays, EPRI (Electric Power Research Institute – Nuclear Maintenance Applications Center), Palo Alto, CA: 2004. 1009704.

⁷ I22: End-Of-Useful Life Assessment of P&C Devices, Report to Main Committee, Chair; Bob Beresh, IEEE PES, 2015

- Insufficient knowledge of the protective relay functions and behavior

The first generation numerical relay protection had some limitations due to processing power and technical performance which could lead to unexpected behavior. Numerical or digital systems which are discrete (“sampling”) behaves sometimes differently than continuous analog systems, this must be understood and considered.

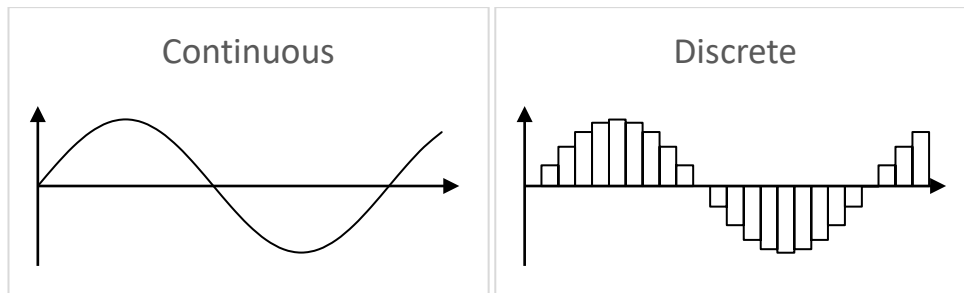


Figure 1. Continuous analog system (left) and discrete or sampled digital system (right), example 50 Hz signal with 1 kHz sample rate ($\Delta t = 1$ ms)

In a numerical or digital system that is discrete the input and output signals are discrete and updated with the sampling rate. Resolution of used analog to digital (A/D) and digital to analog (D/A) converters is also important (measuring for example $11 \text{ kV}_{\text{rms}} \approx 31.1 \text{ kV}_{\text{pk-pk}}$ with for example a 50 kV measuring range and a 10-bit converter gives a resolution of $\sim 48.8 \text{ V}$ and with a 16-bit converter a resolution of $\sim 0.763 \text{ V}$). Dual A/D converters with different amplification of the input signal keeps the measuring range and adds higher resolution for small signals and additionally better possibility to self-monitor the input. Capturing narrow pulses with a low sampling rate can be an issue depending of the design of the digital input of the processor, the pulse is missed if it occurs between the samples. It can also be required that the signal (pulse) is active for more than one sample. An analog RC-filter can solve the problem. Understanding of where to put the filter and whether it should be analog or digital can be important. Higher sampling rates, oversampling and increased resolution in the A/D converters improves the performance and adds new opportunities for advanced digital signal filtering and processing.

One example at a Vattenfall nuclear power plant was a Buchholz relay where the signal was not trapped when a numerical device was installed. The pulse from the Buchholz relay was 8 ms and the numerical protection required minimum 20 ms, with the previous electromechanical equipment the pulse was detected. The solution was to implement an RC-circuit at the input. Current generations of numerical relays are much faster and can capture narrower pulses. The example illustrates the importance of knowing and studying the specifications and behavior of the numerical relay and different components as well as of the relay that is being replaced.

Added functionality and security functions or improved performance in numerical relays that were not present in the previous protective relay can be a problem if not identified or considered. One example that a nuclear power plant experienced was

phase order dependency in a new frequency protection which the old one did not have. Lacking understanding of this led to that the incorrect installation of the phases was not discovered during testing and commissioning. The consequence was a serious incident where the generator protection did not open the circuit breakers

The life expectancy of protective relays decreased with the introduction of new technologies. The early solid-state relays had lower reliability than the electro-mechanical relays they replaced. When integrated circuits were introduced in the solid-state relays the reliability increased and made it easier to combine functions. The use of microprocessor-based protective devices (or numerical relays) had new challenges⁸ when they were introduced.

The electromechanical protective relays are inherently immune to electrical transients. The solid-state and microprocessor devices are susceptible to electrical transients. Standards and test schemes have been developed to secure that the protective relays are designed to operate safely and withstand electrical transients. In TBE 100⁹ one nuclear specific requirement is that equipment with microprocessor must be avoided in environments where it may be exposed to an integrated ionizing radiation exceeding 10 Gy during its lifetime.

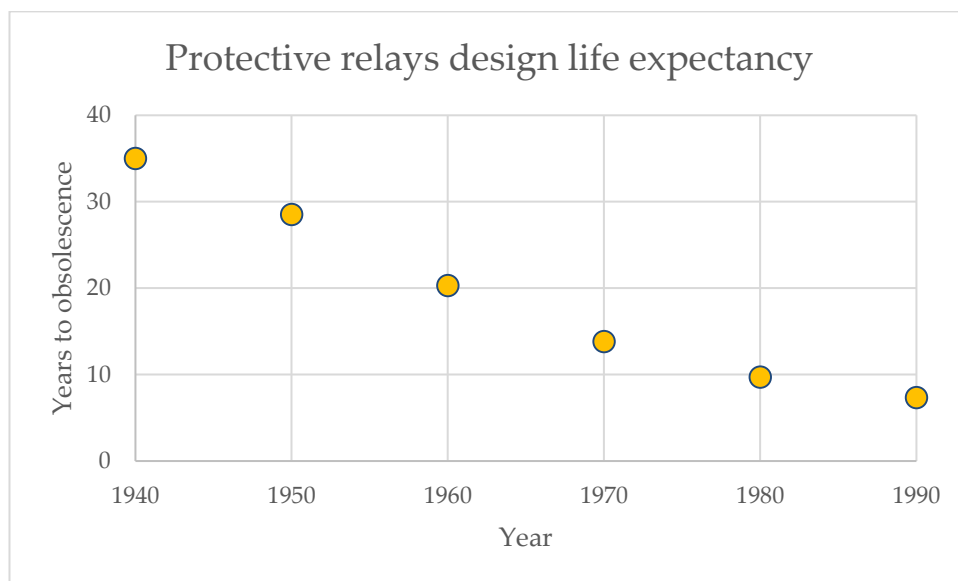


Figure 2. The evolution of years to obsolescence for the product designs

⁸ Reliability of microprocessor-based protective devices – revisited, Vladimir Gurevich, Israel Electric Corporation, Energize, South Africa August 2009

⁹ TECHNICAL REQUIREMENTS FOR ELECTRICAL EQUIPMENT, These Technical Requirements state the general technical requirements necessary for electrical equipment intended for use in Swedish nuclear power stations

In a paper published by GE in 1997 (revised 2002) the reliability of different technologies was discussed¹⁰. A digital relay has less components compared to an equivalent solid-state relay, but requires software. This has led to shorter time to obsolescence of the product designs of 5 years for a digital protective relay compared to 30 years for an electromechanical (*An important note: GE writes design life in the sense the time until the design or product is replaced, the common definition of design life is the time a product is expected to work*). One issue stated is that it is not possible to make long assessments of reliability based on field installations. The second issue was the software reliability. Different standards and procedures have been developed to review software and reduce the number of software errors. Reasonably accurate figures for the failure rates of the hardware can be given. The obvious question is; how reliable is the software? The reliability and performance is highly dependable of the software engineering practices; it is estimated that 80% of the engineering design is in the software. The processors which were available earlier had limited performance, much of the programming had to be done in assembly code to compensate for this. Today with the high performing fast processors it is possible to use function libraries not depending on which processor is used, the amount of code adapted to a certain processor is limited. The software modules used today are well proven and tested and the reliability has improved since the first generation of numerical relays.

Main result	Electromechanical / static		Numerical	
	Single (1 of 1)	Redundant (1 of 2)	Single (1 of 1)	Redundant (1 of 2)
Dependability	98.4%	99.5%	99.4%	99.4%
Security	68.1%	49.5%	95.5%	92.1%
Unavailability of line	0.02%	0.03%	0.01%	0.02%

Table 2. Results of risk analysis¹¹. Dependability – to operate when necessary and Security – to not operate on external disturbances

Microprocessor-based protective devices have advantages over electromechanical protective relays. The mean time to repair (MTTR) is improved¹¹ with self-supervision and increases the availability. With electromechanical equipment, a fault is discovered when a test is performed and depends on the intervals (often 1-6 years) of the tests, self-supervision in digital systems discover and report faults practically instantly and the fault can normally be repaired within 48 hours¹¹. Statistics from electromechanical and numerical relays in Norway were used for a risk analysis of the dependability, security and unavailability of line C, see Table 2. Self-supervision and automatic testing in the numerical devices decrease the risk for unwanted operation and improves the security compared to systems with static

¹⁰ Digital Relay Software Quality, Charles R. Heising (Associated Power Analysts, Inc.), Ronald C. Patterson & Elaine Y. Weintraub (GE - Protection & Control), GER-3660, General Electric, 1997, 2002

¹¹ Self-supervision techniques, 670 series Principles and functions, ABB Document ID: 1MRK 580 172-XEN, October 2009

devices, the possibility to block the protection for internal failure also increases the security. Single numerical protection has the highest security and lowest unavailability in this study, the dependability is almost the same as for redundant electromechanical relays. Modern microprocessor-based protective devices monitor and test the hardware, software, analog signals and communication and can also give historical data adding valuable information for the analysis.

Where redundant solutions are considered for increasing the dependability common mode failures must be considered. At least two diverse systems must be used. Identical software in redundant systems have the potential of simultaneous failure if the failure is caused by a software bug or programming error¹². Software errors are duplicated and identical from one system to another, no manufacturing or difference in tolerances will add randomness. Many common mode failures are not recognized as such because they do not occur simultaneously. The cause or mechanism behind the failure can be common and the fault will appear under the same circumstances. Redundant systems must be different to each other and separated, a failure in one system must not cause a failure in the other, this includes the relay protection. Older systems where each protective relay practically had single functionality often had redundancy from other relays⁷.

An important concern today is the increased complexity due to the number of settings and functions in microprocessor-based protective devices. Different user interfaces between vendors can also be an issue. A thesis¹³ indicates that the power system disturbances with incorrect protection operation were 7%, 45% of the incorrect protection operations in the studied system were caused by human related activities. This indicates that it is important to improve the reliability of the protection systems. The discussion in the thesis is that more standardization of protection systems for similar substations and training of personnel probably would reduce the human impact on and increase the protection system reliability.

Each manufacturer has previously used his own format for storing the settings of the devices and even sometimes a manufacturer has used different formats¹⁴. This has made it difficult to manage and document the system. Different management software solutions exist to manage all the settings and associated documentation to secure the maintenance and surveillance of the system. The IEC 61850 standard has a common format for relay data exchange, once accepted and fully implemented the settings can be stored in native 61850 files.

The numerical protective relays add possibilities and complications¹⁵:

- The supervision detects the major part of the hardware and software errors in the protection and control units, but not 100%.

¹² Defense against common-mode failures in protection system design, R.H. Wyman, G.L. Johnson, Lawrence Livermore National Laboratory, Livermore CA, USA, 1997

¹³ Electricity Supply Reliability, Fredrik Roos, Licentiate Thesis, Dept. of Industrial Electrical Engineering and Automation, Lund University 2005

¹⁴ Protection relay settings management in the modern world, Brad Henderson (DigiSILENT Pacific), Sigre - Seapac 2009

¹⁵ Underhåll och provning av felbortkopplingssystem, Lars Messing (Gothia Power AB), Elforsk rapport 12:21, 2012

- Incorrect settings or configurations are not detected by supervision functions, i.e. settings could be incorrect in the actual application but correct in another application which obviously is impossible for the software to detect. The collected information from both undisturbed and disturbed operation can help identifying incorrectness
- Administrative routines should be well defined and simple. Different types of instructions and documents should be available with definition of responsibilities, equipment requirements, routines of documentation, maintenance etc.
- Numerical protective relays enable additional simple tests that should be done complementing the traditional field tests
- Lack of time and competence to analyze and choose proper settings for each parameter
- The many possibilities to configure the unit with protective functions connected to logical modules and other protective functions will ultimately lead to better protection but it also increases the risk for logical mistakes which can lead to improper protection and control functions
- The software in the units is continuously developed to increase performance and remove programming bugs. Updating firmware cannot be done without certification or qualification of the software and behavior of the unit

3.4 RESEARCH

The Electric Power Research Institute (EPRI) initiated¹⁶ in 2011 a project “Grid Transformation”. One of the research areas is “Setting-less protection method” and was granted to Georgia Institute of Technology. The background is that the overall environment of protective relay settings has become more complex:

- Large number of configuration elements, settings and firmware upgrades require scrutiny
- New power electronics such as inverters exhibits fault currents comparable to load currents
- No substation-level view of protection, all coordination is up to the protection engineer
- Some faults are difficult to detect and leads to gaps in protection
- Modelling errors play a major role in many failures
- Asset management is complicated by the relatively short life of microprocessor relays and frequent firmware upgrades

The setting-less protection approach is a generalization of differential protection, which monitors the satisfaction of Kirchhoff’s Current law. All physical laws that must be obeyed by the protection zone are added and monitored (Kirchhoff’s Voltage law, thermodynamic laws etc.). Dynamic model equations describe the protection zone. A dynamic state estimation monitors how well the measured data fits the dynamic model. The condition and health are monitored and the protective relay acts on the protection zone only, there is no need to know what is happening in the rest of the system. Faults and abnormalities are identified within two or

¹⁶ NYPA Pilots Advanced Power System Protection, Bruc Fardanesh (NY Power Authority), Paul Myrda (EPRI) and A.P. Sakis Meliopoulos (Georgia Institute of Technology), T&D World Magazine, Dec 2014

three samples, faster than traditional phasor based logic requiring one or two cycles. The setting-less protection is being evaluated in a field demonstration on a New York Power Authority system. The expectation expressed by the team is that setting-less protection will provide major advantages over traditional coordinated protection. Until this has been verified and commercialized traditional methods will be used.

3.5 SECOND GENERATION NUMERIC RELAYS

The second generation of numeric relays have some important new advantages⁴

- Faster and better processors
 - × Faster and higher resolution A/D-converters
- Surface-mounted components
 - × Older wire-lead components experienced vibration and heating issues
 - × Surface mounted components have better thermal conduction and are less subject to heating and to vibration
 - × Power supplies use switching design using smaller capacitors. Earlier power supplies required large electrolytic capacitors which could dry out or leak
 - × Manufacturers optimize components better for reliable life
- Ethernet based connection
 - × Standardized protocols like IEC 61850 are available
- Firmware and software advances
 - × Improvements in number and type of protective element, which allows new protection schemes
 - × Increased recording and reporting capabilities and improved diagnosis complying with the latest safety requirements
 - × External setting software with Graphical User Interface including setting analysis and checking
 - × Template import and export to simplify setting and testing process
 - × Some relays have offline logic simulation
 - × Step by step guiding setting

3.6 CONSIDERATIONS

Upgrading relay protection should be done with proper analysis and specifications according to the rigorous design assurance processes that already exist in the Nordic nuclear power plant industry.

The following points are general important considerations.

- Incorrect or inappropriate installation or configuration should be identified preferably already when verifying or at least when commissioning. Lack of time is often a reason for not disclosing faults when commissioning. Configuration and parameter settings must be reviewed and authorized
- Maintenance should include checking the parameter settings and their correctness
- Deviation between actual settings and correct settings must be reported and evaluated

- Changes in system or installation compared to original, do they influence or require changes to the protective functions
- Secure that configuration tools are available and compatible with all devices in use (can include having “older” computers with operating systems from when the system was installed)

Modern microprocessor based protective relays are superior to older technologies regarding the increased functionality and flexibility, built in programmable logic, self-supervision, recording functions, communication features etc. It is important that the system is well designed and documented. The functions not used in the protective relay should be blocked in a secure way and the documentation can include information on why these functions have been blocked.

The manufacturers should supply the following documentation (as much as can be revealed):

- Basic block diagrams of the signal processing and analysis of data
 - × For example, is there analog filters before A/D conversion.
 - × Additional external filtering restrictions or requirements
- Loss of signal quality in the algorithms which can come from filtering, sampling, lack of resolution or other factors
- Description of the different functions with mathematical models
- Interconnection of functions and the influence they have on each other
- Clear definition of which protective functions are active by default, every protective function activated must be obvious to the user.

Some important considerations must be made when selecting protective relays⁷ (in selection):

- Evaluate the manufacturer
 - × History and future of the company
 - × Experience with quality and issues with any products from manufacturer
 - × Service and support
 - × Firmware upgrades, how frequent, how severe
 - × Early adoption or proven technology
- Performance of the device
 - × History of reliability of device and similar devices based on own experience

4 Circuit Breakers

4.1 DESCRIPTION

The circuit breaker technologies SF₆ and vacuum as arc quenching medium were introduced in the mid 60's and have today replaced older types of circuit breakers¹⁷. Vacuum circuit breaker technology is today dominating the medium voltage market.

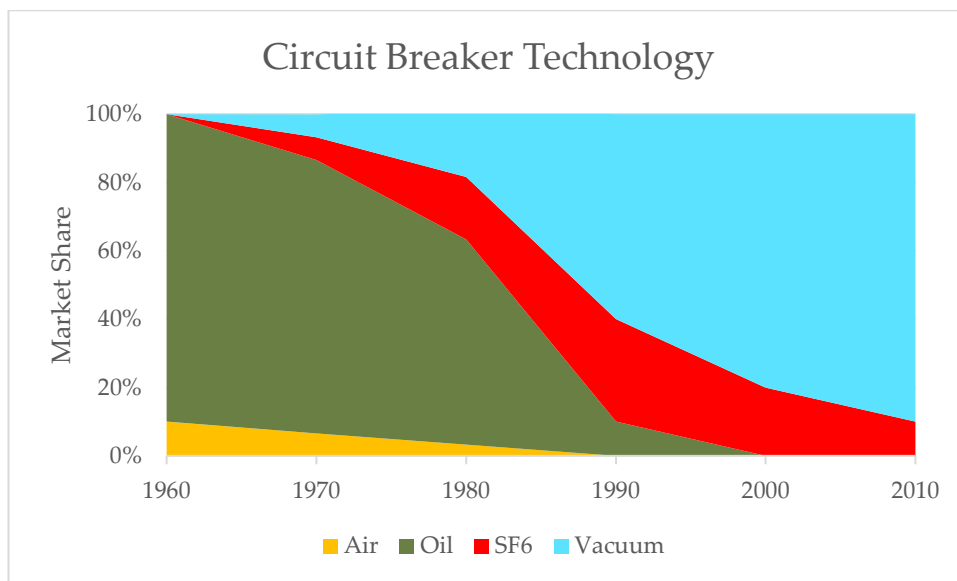


Figure 3. Historical evolution of medium voltage circuit breaker interruption technology¹⁸

Table 3 shows the evolution and typical properties of circuit breaker technologies.

¹⁷ "SF₆ or vacuum?", Guenter Leonhardt, Mauro Marchi, Giandomenico Rivetti, ABB Review 4/2000

¹⁸ "Impact of operating mechanism type on MV vacuum circuit breaker reliability", Juan Tobias, Denis Perrin, Jean Marc Biasse, Marc Bonjean, Philippe Picot, Eduardo Pujadas, 23rd International Conference on Electricity Distribution Lyon, 15-18 June 2015

Circuit Breakers	Oil	Air	SF ₆	Vacuum
Market introduction	1910's Minimum oil: 1930's	1930's	1960's for HV 1980's for MV	1960's
No. of operation ¹⁹ : Short circuit Full load Mechanical			Typical 10-50 5000-10000 5000-20000	Typical 30-100 10000-20000 10000-30000
Dielectric strength	High	Low	~3x higher than air	~2x higher than SF ₆
Application	Outdated in MV	Obsolete technology	MV, HV	LV, MV, low end of HV
Breaking capability	Insufficient at times			
Advantages	Oil absorbs arc energy Good cooling	Air blast: Higher speed and faster arc quenching vs oil CB		
Disadvantages	Flammable Explosive	Large and bulky, air compressor required	Greenhouse effect is 23 500 vs 1 for CO ₂	Overvoltage issues
Maintenance	High cost	High cost, less required vs oil CB	Low cost	Low cost, long intervals
Maintenance procedures ²⁰ (shortened)	Check and adjust contacts Clean tank and parts in contact with oil Test dielectric strength of oil, filter or replace Check breaker and mechanism Adjust breaker Clean and lubricate mechanism Before replacing tank, check breaker operation Check gaskets, nuts and valves	Clean insulating parts and bushings Check and adjust contacts Check bolts, nuts, washers, cotter pins and connections Check arc chutes and replace damaged parts Clean and lubricate mechanism Check breaker operation	Procedures according to manufacturer's instructions Normally consist of removing SF ₆ , filtering and storing until breaker maintenance has been performed when it is transferred back. Some circuit breakers are sealed for life with similar maintenance to vacuum circuit breakers	Measuring change in external shaft position can indicate extent of contact erosion Condition of vacuum can be checked by a high potential test: Vacuum Integrity Test Procedure ²¹ 1. Observe safety precautions 2. Ground each pole not under test 3. Apply test voltage across each pole for one minute (Circuit Breaker open). 4. If the pole sustains the test voltage for that period, its vacuum integrity has been verified.
Speed	Slow	Air blast: Fast vs oil CB		Fast
Complexity	Simple construction			Sealed for life, ~50% less components vs SF ₆

Table 3. Evolution and key features overview of circuit breakers

4.2 KEY CHARACTERISTICS

Medium-voltage SF₆ and vacuum circuit breakers are proven technologies and complement each other from a technical point of view. None of them is generally better than the other. Economic factors, preferences, tradition, experience and switching requirements are the decision-drivers that favor one or the other technology¹⁷. Typical applications that often require attention are switching of dry-type transformers, motors (starting current < 600 A), shunt reactors and capacitors. The use of SF₆ circuit breakers is an environmental issue due to the greenhouse effect.

In applications requiring frequent switching vacuum circuit breakers are preferred. Small inductive currents are effectively interrupted in SF₆ circuit breakers with overvoltage factors lower than 2.5 pu, where vacuum circuit breakers are used it might be necessary to take measures to limit the overvoltages¹⁷ which can reach well over 5 pu. In an existing nuclear power plant with old motors measures are necessary if vacuum circuit breakers are installed. The risk for and consequence of nuclear damage in safety classified parts of the nuclear power plant must always be eliminated and avoided. It must be proven that the safety classified parts in the nuclear power plant can't be affected if vacuum circuit breaker are used.

Switching surge voltages have been reduced in vacuum circuit breakers, especially compared to the first generation in which pure copper contact were used²² with chopping currents of approximately 20 A, today chromium-copper is used with chopping current of only 3-5 A. Two fundamental designs are used to control the arc; axial magnetic field to keep the arc diffused and radial magnetic field to produce a rotating arc along the contacts.

Both oil and air as insulating medium in circuit breakers are regarded as obsolete although both minimum oil and air blast circuit breaker still might be in operation. Oil is susceptible to contamination and is also a fire risk, it also has the highest maintenance costs of the different mediums. Air medium circuit breakers also have high maintenance costs due to their higher mechanical complexity than SF₆ or vacuum circuit breakers. Components for obsolete circuit breakers gets increasingly difficult to secure.

Heat energy generated during multiple re-ignitions is one of the most important factors which causes damages to circuit breaker contacts²³. Motors, generators and

¹⁹ Comparison Between Vacuum and SF₆ Circuit Breaker, Edvard Csanyi, Electrical Engineering Portal, 2010

²⁰ Maintenance of power circuit breakers, United States Department of the Interior Bureau of Reclamation, Denver, Colorado 1999

²¹ Vacuum Circuit Breaker Operator Module Type 3AH, Instructions SGIM-9918D, Siemens 2001

²² Insulating and Switching Media in Medium Voltage Distribution and Medium Voltage Motor Control, White Paper IA08324006E, Wim.M.M. Menheere, Gerard C. Schoonenberg, Jan Verstraten, Rudy Vervae, Eaton Holec, 2008

²³ Comparison of Switching Behaviours Between Vacuum and SF₆ Technologies at 145kV Network, Ruoyu XU, PhD Thesis, Fakultät für Maschinenbau, Elektrotechnik und Wirtschaftsingenieurwesen der Brandenburgischen Technischen Universität Cottbus, 2015

transformers, especially older with aging or inferior insulation, can be damaged by multiple re-ignitions.

4.3 MEASURES

Different actions and measures can be taken when using vacuum circuit breakers. They were simulated and compared in a study²⁴ “Overvoltage Protection Study on Vacuum Breaker Switched MV Motors” for their effectiveness protecting medium voltage motors. Some simulations were validated and compared to real tests. The probability of high overvoltages is greater with multicore cable than with single core cables. The reduction of the overvoltage is also less with multicore than with single core cable with the cable length. Figure 4 shows the tested circuit (circuit A from IEC 62271-110:2005) and the bullet list shows the different measures and results.

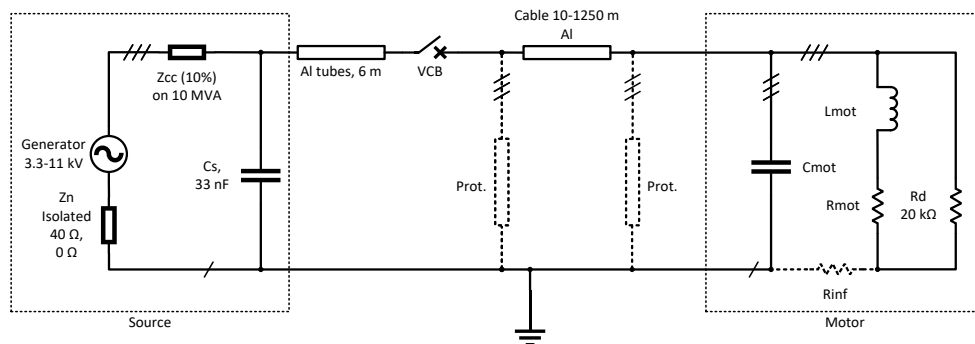


Figure 4. Electrical diagram of the tested circuit²⁴

The following protective measures were compared:

- No protection
 - × Overvoltage levels far above recommended dielectric strength for lightning strike. The cable type is an important factor; multicore cables increase the probability of high overvoltages compared to single core cables. The proximity of the cables and higher capacitive coupling between them is the explanation. Neutral earthing of the power system did not show any clear influence.
- Protection by Surge Arrester (does not limit dV/dt)
 - × At motor terminal
 - 1 m cable between surge arrester hot spot to motor terminal and arrester cold spot to the ground is the most efficient. Overvoltages sometimes below 3 pu and average level never above 5 pu. Best result with single core cable with screens grounded on both sides.
 - 3 m cable between surge arrester hot spot to motor terminal and arrester cold spot to the ground blinded the surge arrester. Is common practice when earthing point is far from the motor.
 - × At the breaker

²⁴ Overvoltage Protection Study on Vacuum Breaker Switched MV Motors, D. Penkov, C. Vollet, B. De Metz-Noblat, R. Nikodem, Schneider Electric, PCIC Europe 2008

- 1 m cable between surge arrester hot spot to circuit breaker terminal and arrester cold spot to the ground is less efficient. It is possible to get an overvoltage level about 4 pu.
- Protection by Surge Capacitor
 - × The surge capacitor on the motor side helps increasing the voltage rise time by reducing the oscillation frequency of the circuit. The tested capacitor value is 500 nF. The capacitor is quite independent of cable type (single or multicore). The overvoltage level is limited far below 3 pu (typically less than 2 pu), motor starting current < 300 A @ 3.3 kV and < 200 A @ 11 kV. With larger motors the situation is similar to the one without any protection.
- Protection by R-C
 - × R=30 Ohm, C=250 nF was tested, but R=30 Ohm, C=500 nF had stronger effect. Multicore cables had some limits, but single core cables grounded on each side limited overvoltages far below 3 pu when connected on motor side for all motors, voltage levels and cable lengths. On the breaker side R-C filter has some limitation in terms of starting current < 600 A @ 3.3 kV and 200 A @ 11 kV for an overvoltage limitation below 3 pu. Connecting them on the breaker side will generally limit the overvoltage under 5 pu with some exception on 11 kV

R-C-filter in combination with single core cables was the most effective when connected to the motor side. This is the most expensive solution.

In another study²⁵ ABB has shown that surge arresters installed on transformers as protective devices against vacuum circuit breaker induced overvoltages limit the amplitude well under the basic insulation level of a transformer. Different configurations are discussed, the recommendation is to install surge arresters both phase-to-ground and phase-to-phase to limit the amplitude of the overvoltage sufficiently.

The possibility to control the switching actively with point of wave controllers has been discussed with different experts²⁶. Controlled switching of high voltage circuit breakers has been used for over 30 years, benefits controlling switching of medium voltage circuit breakers were presented in a paper at a Cired conference²⁷. Many benefits are listed, and the conclusion is that with new independent pole operated circuit breakers and lower cost controlled switching devices (CSD) with higher performance the number of medium voltage applications should increase. It would be a solution to avoid the overvoltages but adds cost and the best results are achieved when the vacuum breakers can be individually controlled. Vizimax recommends bypassing their SynchroTeq MV unit on an opening command when a fault is detected, to eliminate any delay in the execution of an emergency

²⁵ Efficiency of Surge Arresters as Protective Devices Against Circuit-Breaker-Induced Overvoltages, Lars Liljestr nd and Elisabeth Lindell, ABB Corporate Research, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 31, NO. 4, AUGUST 2016

²⁶ From Vizimax and internally at DNV GL

²⁷ Benefits of Controlled Switching of Medium Voltage Circuit Breakers, Andr   Mercier IREQ (Hydro-Qu  bec), Marc Lacroix and Pierre Taillefer, VIZIMAX Inc., Cired 23rd International Conference on Electricity Distribution, 2015

opening²⁸. There is an optimum switching instant that will reduce the inrush current and over-/undervoltage transients, a CSD controls the switching. CSDs have been used on all kind of applications including industrial, power generation, power transportation and distribution, trains among others. It is relatively new technology for medium voltage applications.

Numerous articles and reports verify that the risk for overvoltages when using vacuum circuit breakers exists in certain applications. The investment for the measures to limit the amplitude under the basic insulation level of the equipment and to protect it should be evaluated against the risk for costly breakdowns and repairs. An increased risk or breakdown cannot be accepted in safety classified areas, where necessary measures must be taken, or SF₆-circuit breakers be used.

4.4 RESEARCH

The technical performance of SF₆ matches the technical requirements, the drawback is the high global warming potential. Environmental considerations are the main drivers for the efforts being made to find alternatives to SF₆ in circuit breakers. CO₂ is already in use in high voltage circuit breakers.

The research for an alternative to SF₆ in HV equipment was intensified after the signing of the Kyoto protocol in 1997. The table below shows a summary of different investigated gases and SF₆ as a reference²⁹.

Molecule	Molar mass (g/mol)	Dielectric strength compared to SF ₆	Boiling point at 0.1 MPa (°C)	Greenhouse effect compared to CO ₂	Toxicity
CO ₂	44	~0,45	-78,5	1	+
N ₂	14	~0,4	-196	0	+
Air	29	~0,5	-194	0	+
CF ₄	88	~0,45	-128	6630	+
C ₂ F ₆	138	~0,8	-78	11100	+
C ₃ F ₈	188	~0,95	-37	8900	+
c-C ₄ F ₈	200	~1,25	-6	9540	+
C ₄ F ₁₀	238	~1,25	-2	8900	+
CF ₃ I	196	~1,2	-22,5	5	CMR3 ³⁰
C ₅ -Ketone	266	~1,3	24	1	+
C ₆ -Ketone	315	~1,7	49	1	+
SF ₆	146	~1	-63	23500	+

Table 4. Different gases and important properties compared to SF₆

²⁸ <https://www.vizimax.com/support/faq/synchroteq-faq>

²⁹ Umweltfreundliche Alternativen als Ersatz von SF₆ in metallgekapselten Hochspannungsanlagen, D. Gautschi, R. Lüscher, Y. Kieffel, GE Grid Solutions, Stuttgarter Hochspannungssymposium 2016

³⁰ Substances that are classified as carcinogenic, mutagenic or toxic for reproduction Category 3 (CMR substances of Category 3), EU classification

One conclusion of the information in the table is that the gases either have a low greenhouse effect or good dielectric strength, GE's conclusion is that it is necessary to look for an appropriate gas mixture.

GE Grid Solutions sets the following requirements on a replacement for SF₆:

- Cover the same operating temperature range as SF₆
- Practically the same facility dimensions as SF₆ facilities
- Possible to use the conventional pressure concepts

The application is limited to indoor installations if the first requirement is not reached. GE has cooperated with 3M who could supply fluoronitrile as a good candidate to fulfil the three requirements listed. GE offer circuit breakers (245 kV) with G³ (a fluoronitrile gas mixture) and the equivalent CO₂ emissions give a 49% reduction with G³ compared to SF₆ (30 years operation, including material, electrical losses and gas leakage).

A PhD study³¹ has investigated the CF₃I-CO₂ gas mixtures and their properties. The study showed some promising results, but also pointed out critical areas that need further investigation. The table above highlights the issue of CF₃I's toxicity.

ABB and 3M have cooperated³² to identify an alternative for gas insulated circuit breakers with a low global warming potential. Different substances have been tested. One fluoroketone C5 FK has promising properties and a GWP close to 1. Dry technical air has been used as a carrier gas, a mixture of this and C5 FK has been tested. The C5 FK mixture has not the dielectric capacity of 100% SF₆. Tests have been made according to IEC 62271-200 and have been passed without major modifications.

The current interruption is made with vacuum technology, consequently the gas does not need any switching performance. The gas mixture is used for isolation.

- Thermal performance of MV GIS with C5 FK mixture is slightly reduced compared to SF₆
- Achievable maximum current 7 to 15% lower with C5 FK mixture
- Pressure peak up to 30% higher with C5 FK and peak reached in 10-12 ms compared to 17 for SF₆. This had limited impact in a pressure relief duct and needs consideration.
- Long term behavior must be investigated. Initial accelerated tests have shown that some materials need to be replaced. The required modifications are limited

A pilot project is currently running at a substation in Zürich. The circuit breakers³³ was installed in 2014 and energized in the summer 2015. The gas pressure and concentration of C5 FK in the circuit breakers was measured 2 years after gas

³¹ Investigation into CF₃I-CO₂ gas mixtures for insulation of gas-insulated distribution equipment, Phillip Widger, Cardiff University School of Engineering, PhD thesis 2014

³² Alternative gas insulation in medium-voltage switchgear, Mail Hyrenbach (ABB AG), Tobias Hintzen (ABB AG), Pascal Müller (EWZ), John Owens (3M Company), CIRED 23rd International Conference on Electricity Distribution, Lyon 2015

³³ Betriebserfahrungen der ersten 170-kV- und 24-kV-GIS mit alternativem Isolationsmedium basierend auf Ketonen, Pascal Müller, EWZ, Schweiz 20

filling and 1-year operation. Both pressure and concentration is stable and the gas is in very good condition. The facilities are indoor, and the minimum operating temperature is +5 °C for the 170 kV facility and -5 °C for the 24 kV facility. The results are positive although further product development is necessary, the reliability and accessibility must be increased.

ABB and GE have chosen two different solutions with different characteristics. It seems that ABB have tried to find a replacement for SF₆ both in MV and HV gear. ABB use vacuum technology for the actual switching or interruption and the new gas mixture for the insulation. GE have tried to find a replacement for SF₆ in HV gear.

4.5 REPLACING MEDIUM VOLTAGE AIR-MAGNETIC CIRCUIT BREAKERS

Air-blast circuit breakers are obsolete in medium voltage applications. Electric Power Institute (EPRI) published a revised report in 2003 on considerations when exchanging air-magnetic circuit breakers to SF₆ or vacuum³⁴. The same considerations whether to use SF₆ or vacuum circuit breakers should be made when replacing old circuit breakers.

Motives to replace air-magnetic circuit breakers with SF₆ or vacuum circuit breakers

- End of expected life, risk of failures and uncertain reliability for the old circuit breakers
- Obsolescence of spare parts
- Reduce maintenance cost through reduction of maintenance man-hours
- Elimination of any asbestos

Replacement considerations

- Examine mechanical safety interlocks to avoid interlock failures
- For replacement circuit breaker ensure precise matching with original cell on-site. Existing designs might be out of tolerance. It is advisable to include adjustable interface points
- It is preferable to have a factory representative at site during initial installation, problems can be resolved easier and more swiftly than by a plant engineer and future installation problems can be prevented
- Circuit breaker interchangeability should be clearly defined and understood by vendor and user

4.6 CONSIDERATIONS

The vacuum circuit breaker is the dominant solution for medium voltage. It is reliable, has low maintenance costs and long maintenance intervals. The dielectric strength is high, and it is environmentally friendly. The issue is the risk for overvoltages in some applications where either measures have to be taken or SF₆

³⁴ Considerations for Conversion or Replacement of Medium-Voltage Air-Magnetic Circuit Breakers Using Vacuum or SF₆ Technology, TR-106761, EPRI Project Manager J. Sharkey, Electric Power Research Institute, 2003

circuit breakers should be considered, it can be in existing installations where there is no possibility or too expensive to make the required protective measures. The cost for the measures must be compared to the risk and cost for breakdowns and repairs. Nuclear power plants are built for long operation and existing equipment is often older and has lower level of insulation and the space for additional protection may also be limited, why it is not always possible to install the required overvoltage protection.

In safety classified parts of existing nuclear power plants with old equipment the risk for and consequence of a nuclear damage must be evaluated. Oskarshamn Kraftgrupp have chosen to use SF₆-breakers in safety modernization projects, the risk with using vacuum circuit breakers is considered to be too high.

Vacuum circuit breakers dominate the market and are the preferred technology in many applications. Some applications require special care. When the vacuum circuit breakers need to switch loads (notably small current), capacitive and inductive switching may need special attention, especially when doing so frequently and when the transformer is located “next” to the circuit breakers (no mitigating cable between the two). Switching-off motors during the start (inching cranes, maybe pumps) need proper attention, mostly through RC (“ZORC” – ZnO arrester with an R-C circuit) absorbers. Also, the frequent switching of unloaded transformers is not very attractive (without proper protection).

If the vacuum interrupter (VI) is to be used in a corrosive environment, it is a good idea to perform an annual visual inspection of the VIs to look for corrosion, in addition to a yearly high voltage test³⁵.

The operating mechanism of the circuit breaker has direct impact on its reliability¹⁸. The operational MTBF (mean time between failures) of the vacuum circuit breaker is more appropriate for studying reliability than the rated mechanical endurance which is measured in a laboratory with repetitive close and open operations.

There are today no obvious alternatives to SF₆ and for example ABB and GE are performing tests or have introduced circuit breakers with alternative gas mixtures. They have chosen different gas mixtures with different characteristics.

³⁵ Vacuum interrupter, high reliability component of distribution switches, circuit breakers and contactors, Slade Paul G., Li Wang-pe, Mayo Stephen, Smith R. Kirkland, Taylor Erik D., Journal of Zhejiang University SCIENCE A, 2007

5 Surge Arresters

5.1 DESCRIPTION

Protective devices³⁶ should satisfy four requirements:

1. Provide high or infinite impedance during operating voltages to minimize losses
2. Provide low impedance during surges to limit voltage
3. Dissipate or store energy in the surge without damaging itself
4. Return to open-circuit operation (1) after the surge

Metal oxide surge arresters have become the preferred technology for medium voltage surge arresters and have replaced the silicon carbide surge arresters. When ABB published their latest application guideline³⁷ in 2011 it was stated that “The state of technological development today demands the use of metal oxide surge arresters without spark-gaps and with a housing made of synthetic material. That is why we will no longer discuss the surge arresters with spark-gaps and porcelain housing in the present brochure.”.

Surge Arresters	SiC, Porcelain	MO gapless
Market introduction	1940s	1970s
Expected life span	13 years ³⁸	30+ years, but it is sacrificial to protect other equipment (not failure)
Acceptance	Obsolete	Superior
Maintenance	Regular inspections for damages	No maintenance under normal conditions. In some conditions inspection if cleaning is necessary.
Isolation		Silicon has high dielectric withstand strength ³⁷
Complexity	Gaps require elaborate designs for consistent spark-over level and resealing after a surge	Simpler design

Table 5. Evolution and key features overview of surge arresters

Siemens makes a distinction between surge limiters and surge arresters; surge arresters have higher energy absorption capability and surge limiters have lower protective voltage level. Surge limiters can absorb the energy associated with vacuum circuit breakers and surge arresters can handle lightning and switching

³⁶ Power System Analysis & Design Sixth edition, J. Duncan Glover, Thomas J. Overbye, Mulukutla S. Sarma, Cengage Learning 2016

³⁷ Overvoltage protection Metal oxide surge arresters in medium voltage systems, ABB Switzerland, 5th revised edition: May 2011

³⁸ An assessment of the reliability of in-service gapped silicon-carbide distribution surge arresters, M. Darveniza, D. R. Mercer, R. M. Watson (Queensland University, Brisbane), IEEE Transactions on Power Delivery 1996

surges from all sources. For simplicity surge arrester is used as a term in this report, energy handling capacity and protective voltage level must be dimensioned per the requirements.

5.2 KEY CHARACTERISTICS

Metal oxide arresters have superior energy handling capacity and protective capability over previous technologies³⁹.

The qualities of silicone used for the housing of metal oxide surge arresters include very high elasticity and resistance to tearing, high temperature stability, very low combustibility (silicone is a self-extinguishing material) and high di-electrical withstand strength. Besides all these qualities the most remarkable one is hydrophobicity: water simply rolls off the silicone surface. The silicone insulators are water-repellent even if they are polluted. This means that the hydrophobicity is also transmitted into the pollution layer on the surface. All this provides excellent performance properties for high voltage equipment insulated with silicone.

The first polymer housed surge arrester⁴⁰ was introduced in Ohio, 1987. All distribution arresters that were installed in US 1995 were polymer housed. It is remarkable and illustrates the technical paradigm shift.

The properties⁴¹ of the metal oxide resistors depend on the dimensions of the disc. The current depends on the diameter, the voltage depends on the height and the energy handling capacity depends on the volume and heat transfer capability.

The energy losses⁴² in metal oxide arresters is lower than for silicon carbide arresters.

5.3 CONSIDERATIONS

The ideal location for surge arresters is at the terminals of the device to be protected and directly grounded. The surge voltage will at this location be limited to the discharge voltage of the arrester³⁹.

The suppliers^{41, 43, 44, 45} of surge arresters and for example Nema Arresters⁴⁶ have information and guidelines on what to consider when selecting or replacing arresters.

³⁹ The Application and Selection of Lightning Arresters, Larry Pryor, Sr. Specification Engineer, GE, 2008

⁴⁰ History of Arresters on Power Systems 1965-Present, Jonathan J Woodworth, ArresterWorks 2011

⁴¹ Overvoltage protection Metal oxide surge arresters in medium voltage systems, Application guidelines, 5th revised edition, ABB, May 2011

⁴² Application Considerations for Gapped Silicon-Carbide Arresters Installed on Utility High Voltage Systems Part II: Energy Consumption, Dennis Lenk, Fellow IEEE, 2010

⁴³ High Voltage Surge Arresters Buyer's Guide, ABB 2016

⁴⁴ Metal-Oxide Surge Arresters in High-Voltage Power Systems, Volker Hinrichsen, Siemens, 3rd edition, Siemens 2011

⁴⁵ Medium-voltage surge arresters Product guide, Catalogue HG 31.1, Siemens, 2017

⁴⁶ www.nemaarresters.org

The IEEE and IEC standard differs in some areas which must be regarded if studying data sheets of surge arresters.

The equipment to be protected and operational conditions sets the requirements on the arrester. Different types of arresters are suitable for different applications and must be chosen accordingly. The arresters can be classified in the following classes:

- Station class are designed for switching surges and significant fault current. They have greater energy absorption capabilities. Station class arresters are generally used where uninterrupted service is important.
- Intermediate class arresters are designed for economic and reliable protection.
- Distribution class arresters are often used for smaller liquid filled or dry type transformers (< 1000 kVA) and can also be used for connection at the terminals of rotating machines (< 1000 kVA).

Station class arresters are recommended if energy duties are not known.

Monitoring of medium voltage metal oxide surge arresters (< 72.5 kV) and their condition, according to ABB, is difficult to interpret and hardly give significant information. Surge counters give no information of the condition of the arrester, hence the use of surge counters and mA-meter is limited in these systems. If the current and energy guaranteed levels are not exceeded, no measurable changes will be present. The surge counters can give information about the activities in the system or monitoring substation not the arrester. Use of thermo-vision cameras can be useful for high voltage surge arresters but not for medium voltage. Current measurements with third harmonic analysis are difficult to interpret in practice and measurement of the total current will mainly show the capacitive leakage current, the small Ohmic current can hardly be identified. Experience show that metal oxide arresters are very reliable and failure rates are low. A visual inspection of the surge arresters is mostly sufficient when the substation or installation is controlled. The housing should be checked for any damages, connections and possible disconnectors inspected and mA-meters and surge counter if installed controlled. Clean water and a lint free soft cloth is recommended to clean silicon surfaces if necessary.

The following data given are important to know, read more in the referenced manuals:

U_c – Continuous operating voltage, rms value of power-frequency voltage that can be applied continuously between the terminals. Should be chosen to ensure that the operating voltage never exceeds this value.

U_{TOV} – temporary overvoltage level occur during earth faults and special attention must be taken to it. Curves describe the overvoltage capability depending on time and pre-stress or not, see manuals.

i_c – continuous current through arrester (leakage current) at continuous voltage, is around 1 mA and 90 degrees shifted to voltage. The power losses can be neglected.

U_r – rated voltage, maximum rms value of power-frequency voltage that can be applied under temporary overvoltage conditions as established in operating duty

tests with correct operation. The rated time t is normally 10 s and the quotient U_r/U_c generally 1.25.

U_{ref} – peak value of the power-frequency voltage divided by $\sqrt{2}$ applied to the arrester to get the reference current I_{ref} (resistive component)

U_{res} – peak value of the voltage between the terminals during discharge current passage. The ohmic part of current is normally dominating at this point and the capacitive stray influences can be ignored.

U_{pl} – lightning impulse protective level, maximum peak voltage at terminals at nominal discharge currents. Corresponds to the guaranteed residual voltage U_{res} at I_n .

U_{ps} – maximum peak voltage on terminals on arrester subjected to switching pulses. The higher value in the data table is to be used.

Regarding the energy capability, it is stated in ABB's documentation (Clarification: A metal oxide arrester consists of several metal oxide resistors):

The energies that are listed in our technical documentations represent no limiting or destructive values, but the energies that occur during the different type tests respectively the occurred energies with different current impulses. Therefore, a differentiation is to be made between:

- *The occurring energy of a specified current such as 100 kA 4/10 μ s or a long-duration current impulse of 2 ms. (These data serve only as information.)*
- *The applied energy, which is used as a proof of the thermal stability of the arrester in a test or in the system.*
- *The energy that destroys a MO resistor or an arrester through cracking, puncture or spark-over.*

The energy, which leads to the destruction of a MO resistor or an arrester, is higher than the energy that is applied to an arrester as proof of the thermal stability during an operating duty test. Depending on the type of arrester, the destroying energy is generally much higher than the guaranteed energy for testing the thermal stability.

The cool down period for an arrester after it has been fully loaded is normally between 45 and 60 minutes depending on type and ambient conditions. Thermal stability of the surge arrester must also be considered and dimensioned for, i.e. the power losses in the arrester must be lower than the heat flow from the arrester to the environment to avoid that the surge arrester gets overheated and destroyed.

Generally, the arrester is dimensioned for a lightning level of 4 pu.

6 Conclusions and recommendations

The conclusion from the review of the relay protections, circuit breakers and surge arresters is, that modern technology generally offers better performance and increased reliability. The requirements on safety system equipment for nuclear power plants exceed normal industry standards. Well proven and certified solutions must be used, and special care must be taken in the implementation.

Metal-oxide arresters have replaced and made silicon-carbide arresters obsolete. Metal-oxide arresters have superior energy handling capacity and protective capability over previous technology. The arrester must be dimensioned depending on the equipment to be protected and the operational conditions. The ideal location for surge arresters are at the terminals of the device to be protected. The different suppliers of surge arresters have information and guidelines on what to consider when selecting or replacing arresters.

Silicone housing which is used for metal-oxide surge arresters has almost ideal properties; very high elasticity, high resistance to tearing, high temperature stability, very low combustibility (self-extinguishing), high dielectric withstand, remarkable hydrophobicity and is water repellent even if polluted (the hydrophobicity is transmitted to the pollution layer).

Vacuum circuit breakers dominate the medium voltage market today with a market share of 90% in year 2010. The growth in market share (medium voltage) for SF₆ and vacuum circuit breakers were practically identical from their market introduction in the 1960' until the 1980's when the market share for vacuum circuit breakers started to grow faster. In the 1990's the market share for SF₆ circuit breakers peaked at 30% and began to decrease to become only 10% in year 2010. The greenhouse effect of SF₆ is one important explanation of the lower market share today.

Vacuum circuit breakers have less moving parts, high reliability and are sealed for life. Different technologies to reduce the risk for overvoltages have been developed, but still it is necessary in some applications to take certain measures to protect the equipment against overvoltages. Surge arresters and R-C-filters at the terminals of the equipment to be protected are the most powerful measures. The probability of high overvoltages is greater with multicore cable than with single core cables. Nuclear power plants are built for long operation and existing equipment is often older and has lower level of insulation and the space for additional protection may also be limited, why it is not always possible to install the overvoltage protection needed if vacuum circuit breakers were to be used.

The possibility to control the switching of the medium voltage vacuum circuit breaker actively with point of wave controllers has been discussed with different experts and must be regarded as new technology. Controlled switching of high voltage circuit breakers has been used for over 30 years. Independent pole operated medium voltage circuit breakers together with lower cost medium voltage controlled switching devices with higher performance should increase the

number of applications and installations. Controlled switching devices for medium voltage is relatively new technology.

Numeric or digital relay protection have the potential to increase the performance of the protection but also if not implemented with care a risk of malfunction. The human risk factor and limitation to understand the whole system require careful design, implementation, wiring, testing and documentation.

Extensive studies of the system and need of protective functions are important in the design phase. Keeping it as simple as possible to maintain the necessary protective functions is an important practice.

Matching the different components in the protection system and making sure they are compatible is also crucial.

Incorrect wiring is not to be neglected and is not always detected by the self-test and supervision in the numerical devices. Special care should be made to install correctly and verify and control that it is correct.

New software versions that are released for updating the numerical protective relays are released for improved functionality and removing “bugs”. A new software should never be installed without verification and tests, the updated numerical device should practically be regarded as if a new device was installed.

The practice for test and maintenance of protection systems is in many cases unchanged since the relay protection systems were based on electromechanical technology. The focus should move from calibration testing to functional or scheme testing. It is necessary to analyze how maintenance and testing based on numerical devices should be performed¹⁵. It is concluded that self-supervision detects errors in the supervision to some degree but not 100% of the incorrect equipment. Incorrect configuration and parameter settings are not detected by supervision functions. The numerical protection units can collect information from operation and disturbances, by using and analyzing this information incorrectness can be identified. Well defined administrative routines to assure reliability of the protection system are vital.

Redundant protective systems are sometimes used in vital zone or applications to increase the security or dependability of the protection system. It is advised in such cases to not to connect two identical systems, like using two different suppliers of the numerical protective relays, different sensor technologies, separate independent power supplies and separated cabling.

7 Abbreviations

Abbreviation	Explanation
3M	Minnesota Mining and Manufacturing (Company)
A/D	Analog to digital (converter)
ABB	Asea Brown Boveri (Company)
CB	Circuit breaker
Cired	International conference on electricity distribution
CO ₂	Carbon dioxide
CSV	Controlled switching device
D/A	Digital to analog (converter)
EMI	Electromagnetic interference, disturbance generated by an external source that affects an electrical circuit
EPRI	Electric Power Research Institute
GE	General Electric (Company)
GIS	Gas insulated switchgear
Gy	Gray unit, the ionizing radiation defined as one joule of radiation absorbed per kilogram of matter
HV	High Voltage - 35 kV to 230 kV
IEC	International Electrotechnical Commission
IEC 61850	International standard for communication networks and systems for power utility automation
IEEE	Institute of Electrical and Electronics Engineers
KBE	Quality and Inspection Requirements for Electrical Equipment
LV	Low Voltage - up to 1000 V
MO	Metal oxide
MTBF	Mean time between failures
MTTR	Mean time to repair
MV	Medium Voltage - 1000 V to 35 kV
pu	Per Unit = Present Value/Base Value
RFI	Radio-frequency interference, disturbance generated by an external source that affects an electrical circuit
SCADA	Supervisory control and data acquisition
SF ₆	Sulfur hexafluoride, used as dielectric medium in the electric industry
TBE	Technical Requirements for Electrical Equipment in Swedish nuclear power stations
TBE 100	The general technical requirements necessary for electrical equipment intended for use in Swedish nuclear power stations. It is intended for manufacturers of electrical equipment
VCB	Vacuum circuit breaker
VI	Vacuum interrupter

NEW ELECTRICAL DEVICES IN EXISTING NUCLEAR POWER PLANTS

The nuclear power plants are designed and built for long and safe operation. Technical development and evolution has made some of the electrical equipment which was originally used at commissioning obsolete or outdated.

Numeric protective relays are superior to older technologies regarding the increased functionality and flexibility. They have the potential to increase the performance of the protection but also if not implemented with care a risk of malfunction.

SF6 and vacuum are practically the two available technologies and have today replaced older types of breakers. The use of SF6 as a quenching medium is decreasing, much for environmental reasons. The risk of overvoltages with vacuum circuit breakers and the required protective measures might prohibit the use in safety classified applications at Nuclear Power Plants.

Surge arresters of metal oxide have made silicon carbide arresters obsolete. Metal oxide arresters have superior energy handling capacity and protective capability over previous technologies. Silicone housing which is used for metal-oxide surge arresters have almost ideal properties.

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