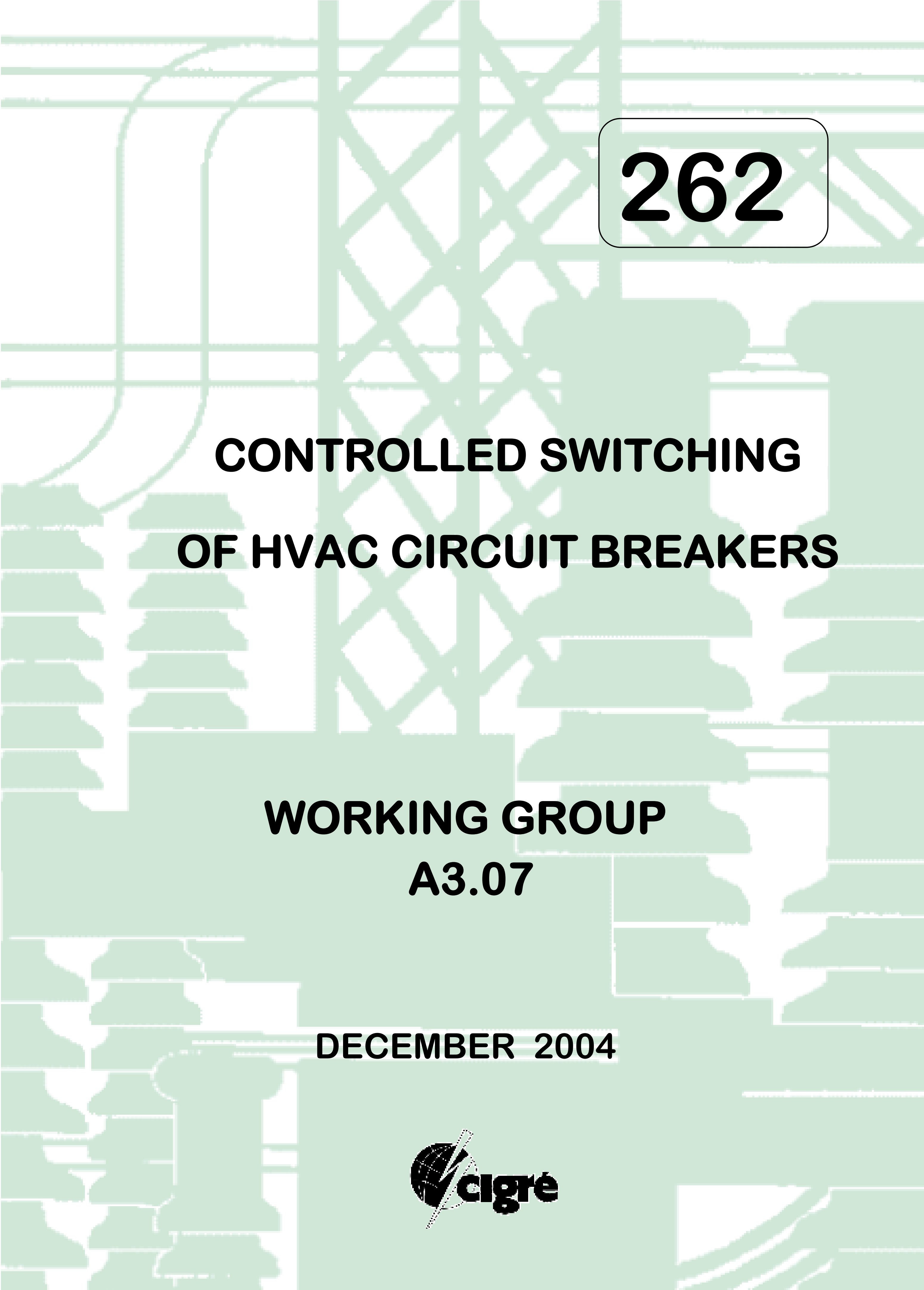

262

CONTROLLED SWITCHING OF HVAC CIRCUIT BREAKERS

WORKING GROUP A3.07

DECEMBER 2004

cigré

CONTROLLED SWITCHING OF HVAC CIRCUIT BREAKERS

BENEFITS & ECONOMIC ASPECTS

CIGRÉ Working Group A3.07

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Table of Contents

Overview of the work of CIGRE WG 13.07 (A3.07)

CIGRE Working Group 13.07 (subsequently A3.07) was convened in 1996 in order to study, and report upon, the emerging technology of Controlled Switching i.e. the operation of switching devices at a pre-determined point-on-cycle of the power system voltage. The working group was disbanded in 2004 having completed its intended tasks and having produced four major publications.

The first publication of the working group, entitled *"Controlled Switching of HVAC Circuit-breakers – Guide for application"* was published in full, in two parts, in ELECTRA No's 183 and 185. The subsequent three publications have been published as CIGRE Technical Brochures, of which this is one. These are entitled:

- *Controlled Switching of HVAC Circuit-breakers- Planning, Specification & Testing of Controlled switching systems.*
- *Controlled Switching of HVAC Circuit-breakers- Guidance for further applications including unloaded transformer switching, load and fault interruption and circuit-breaker uprating.*
- *Controlled Switching of HVAC Circuit-breakers- Benefits & Economic Aspects.*

The following sections make up the final WG document entitled "*Benefits & Economic Aspects*".

1 Introduction

Controlled Switching (CS) of high-voltage AC circuit breakers has become a commonly accepted means of reducing switching transients in power systems. CIGRE working group A3.07 (formerly 13.07) has produced a series of documents covering various aspects of controlled switching [1][2][3]. These documents are primarily technical in nature and this document is intended to be complementary to them. It does not repeat technical information but describes the "softer" issue of the economic benefits that can be achieved by the application of controlled switching. The document presents qualitative and/or quantitative indicators of the economic benefits which can be used to support comparative studies and cost-benefit analyses.

The document considers generic technological and economic aspects and moves on to consider the major switching cases (capacitor bank, reactor, transformer, transmission line) individually. Potential costs savings for more advanced cases such as fault interruption are not addressed. Benefits are considered in relation to the circuit breaker, the switched load, and the wider power system. Where appropriate technical consequences, additional costs and disadvantages are also discussed.

In many cases within this document it is evident that a fixed monetary value cannot be easily established without making a very large number of case specific assumptions. Taking this into account benefits are broadly categorised as follows:

- Technical benefits: cases where only a statement of improvement or enhancement in characteristics can be established (for example, a reduction in the re-strike probability of a controlled breaker when interrupting capacitive currents),
- Qualitative cost statements: cases where cost savings cannot be accurately quantified but a plausible mechanism for cost saving can be identified (for example, lifetime extension of equipment which is real but un-quantified).
- Quantifiable cost savings: cases where the amount of money saved by controlled switching can be established with some accuracy (for example, an increased equipment maintenance interval when controlled switching is installed).

A combination of all three categories appears for almost every application case.

2 General Aspects

2.1 General Cost Considerations Associated with Controlled Switching

Clearly prices, costs, and financial incentives vary widely with factors such as location, regulatory structure, utility ownership, etc. These factors make accurate cost comparisons, taking into account all conceivable penalties/incentives, virtually impossible other than on a case by case basis. Nevertheless, qualitative guidance has been produced and this is presented in later sections dealing with the individual switching cases.

This section deals with the more direct comparisons relating to relative equipment costs, installation costs, etc. which are common regardless of application. Particularly for new installations, a direct comparison can be made between the cost of equipment with and without controlled switching capability. Items which influence this comparison include material, engineering, labour and testing costs at the factory, commissioning and training costs, and additional maintenance, monitoring and inspections during the useful life of the equipment. In the first instance these factors permit a comparison to be made between the use of controlled switching and other means of transient reduction.

Installation costs for a CS system can vary between 16 kUS$ and 140 kUS$ depending on the situation. These costs are made up as follows:

Item	Cost (kUS$)
Investment	5…40
Installation	1…20
Training of personnel	5…10
Replacement of controller after 15 years	0…20

Additional costs which may be incurred when implementing CS into an existing installation are:

Item	Cost (kUS$)
Integration into existing system	20…30
Commissioning, testing	10…20

The incremental cost of equipping a circuit breaker for controlled switching depends heavily upon the design of the equipment (vacuum, SF_6, live tank, dead tank, GIS) and on the configuration of the drive (ganged or independent pole operation, spring/solenoid/hydraulic etc). Most high-voltage SF_6 circuit breakers rated below 245 kV are ganged operated while circuit breakers rated above this voltage typically have one mechanism per pole.

Circuit breakers with a single operating mechanism for multiple phases can perform controlled switching for particular applications by mechanically staggering the poles by means of the linkage. In such cases the incremental cost for controlled switching includes the cost of the electronic controller, changes to the control circuit and the cost of the staggered linkage. Alternatively, independent pole operation can be adopted however the costs of additional mechanisms are often prohibitive. The implementation of controlled switching for circuit breakers with independent pole operation involves the addition of the controller and elements in the control circuit.

The incremental cost of implementing controlled switching, as a percent of the total price of the circuit breaker, depends on the rated voltage. For rated voltages between 72.5 kV and 170 kV, the cost ratio between a circuit breaker fully equipped for controlled switching and a standard circuit breaker is approximately 150…160%. In this voltage range, the cost of the controller is clearly significant in relation to the cost of the circuit breaker alone. This ratio decreases to 120…130% for 245 kV circuit breakers and reaches a minimum value of 105…110% at 362 kV and above. These ratios are further reduced for gas-insulated substations due to the higher initial cost of the switchgear itself.

Clearly, the above costs relate to installation of controlled switching where sufficient infrastructure, in terms of input signals etc, exists. Should this not be the case the addition of instrument transformers will impose an additional cost on the installation such that the cost ratio may be in the range 170…180%.

An additional cost that may need to be considered for niche applications is that associated with dedicated type tests e.g. to ascertain RDDS, mechanical scatter. For common applications such as capacitor banks switching these costs would not be expected to be significant on a per-installation basis.

2.2 Circuit breaker technological issues

The main benefits of controlled switching for the circuit breaker itself are:

- Extension of circuit breaker interrupter life and an associated increase in time intervals between interrupter maintenance or retrofit.
- Performance enhancement during current interruption in the thermal or in the dielectric region.

2.2.1 Circuit Breaker Interrupter Wear Mechanisms

The main effect of controlled switching pertaining to circuit breaker life extension is the reduction of energisation currents and the associated reduction in interrupter wear. Additionally, there is the possibility of optimising the instant of contact part such that life-limiting re-strike or re-ignition phenomena are avoided or reduced in severity.

For SF_6 gas-insulated single pressure puffer or self-blast circuit breakers, interrupter wear refers primarily to arcing contact erosion and nozzle ablation. For vacuum circuit breakers, material is boiled off the surface of the contacts with each arcing event and is deposited on the contacts and on the floating shields that provide voltage grading across the interrupter gap. In each case the source of arcing contact wear is the presence of a burning electrical arc across the contact gap which causes loss of material by vaporisation, melting and burn-off. This leads to contact shape distortion and increase in surface roughness both of which influence the dielectric withstand characteristics of the gap and the co-ordination between main and arcing contacts.

In reality, contact erosion is a complex phenomenon that depends on the following:

- contact material composition and micro-structure (manufacturing process),
- contact surface hardness and porosity,
- initial contact shape,
- arc current duration, amplitude, frequency and shape,
- mechanical forces between the surfaces of the stationary and moving contact.

In addition to contact wear, equipment using nozzles suffers ablation and an increase in the internal diameter of the nozzle throat. The inside wall surface experiences flaking, burn-off and vaporisation. Nozzle ablation changes the gas flow dynamics during interruption and in turn leads to reduced gas density across the contact gap(s). This degrades circuit breaker performance in the thermal region which is critical for short line fault & ITRV duties capabilities.

2.2.2 Methods for Electrical Wear Calculation

Various formulae have been proposed to make an approximate assessment of circuit breaker electrical wear. Methods described in [4][5][6][7] are used in the examples included in this document. In these documents, a relationship is proposed to translate the electrical wear caused by the interruption of low current to an equivalent number of interruptions at higher current. In [4][5] an exponent of 1.7 is used for currents greater than 35% of rated short circuit current (I_{sc}) and an exponent of 3.0 is used for currents less than or equal to 35% of I_{sc}. Evaluation of contact electrical wear is determined by the following formula, assuming equivalent given pre-arcing times.

For interruption of currents less than or equal to 35% of rated short circuit current:

$$N_I = N_{35} (I_{35}/I)^3$$

For interruption of currents greater than 35% of rated short circuit current:

$$N_I = N_{35} (I_{35}/I)^{1.7}$$

Where N_{35}: number of current interruptions at 35% of I_{sc}
N_I: number of current interruption at current I
I_{35}: 35% of rated short circuit current

In [6] the electric wear is assumed to be proportional to the number of operations and the interrupted current with an exponent ranging from 1.2 to 2.0 for reactor switching and with an exponent of 1.6 for capacitor bank switching. Reference [7] uses an exponent of 1.6 to determine the wear associated with small inductive and capacitive current switching.

2.3 Possibility of Controller Malfunction

The benefits which can accrue from the installation of controlled switching are significant. Set against this it is important that any proposal to use controlled switching also considers the possible effects of controller malfunction which may, depending on the switching case, outweigh the potential benefits. The following table details possible failure modes and their causes.

Table 1: Failure modes of point-on-wave controller.

Failure mode	**Description**
Failure to operate on command	A switching command given to the controller is not transmitted to the circuit breaker. ***Possible reasons:*** power loss, loss of reference signal, hardware defect, inappropriate software status, wrong settings.
Operation without command	The controller operates the circuit breaker without receiving a switching command. ***Possible reasons:*** hardware defect, inappropriate software status.
Command not point-on-wave controlled	The switching command is delayed with a time that is not related to the reference signal, or not delayed at all. ***Possible reasons:*** Power loss, loss of reference signal, wrong settings, inappropriate software status.
Wrong switching target	The intentional delay of the switching command is not as desired for the specific situation. ***Possible reasons:*** Wrong settings, inappropriate software status, hardware defect, wiring mistake, inadequate compensation for variables affecting breaker timing (temperature, dwell time, control voltage).

3 Benefits of Controlled Switching of Shunt Capacitor Banks

Energisation and de-energisation of Shunt Capacitor Banks (SCB) are well understood phenomena which can lead to significant power system transients caused by inrush currents and re-strikes. Controlled closing of shunt capacitor banks reduces transient overvoltages and inrush currents, and provides an alternative to the use of fixed inductors, pre-insertion resistors or pre-insertion inductors. Controlled opening of shunt capacitor banks allows for a reduction in the probability of re-strikes by timing the opening of each pole to increase arcing time and allow enough separation between the fixed and moving contacts at the instant when the arc is interrupted.

Possible justifications for the use of controlled switching of capacitor banks can be summarised as:

- Reduced circuit breaker wear
- Improved power quality and/or continuity
- Optimised capacitor bank design

The following sections consider these aspects in greater detail.

3.1 Technical Aspects

It is also well known that energising of capacitor banks will produce transient overvoltages and consequently, reduce the power quality. In most cases, this is not a critical issue for high-voltage equipment because the overvoltages produced are generally lower than their withstand capabilities. Nevertheless, utilities and industrial customers have reported the effect of voltage magnification at lower voltage due to SCB energisation at higher voltage. Theses effects may affect the protection systems and the low voltage equipment of some industrial customers. Reference [8] gives an example showing how the transient voltage produced by the switching of SCB in a 120 kV system causes some mis-operations of the low voltage protection system of a certain customer. Reference [12] gives more detailed explanations on the voltage magnification effects.

3.2 Benefits for the Circuit Breaker

3.2.1 Reduction of Electrical Wear

Electrical wear of circuit breaker interrupters is a function of the magnitude and the frequency of the inrush current. Controlled closing of capacitor banks allows a reduction of the inrush current magnitude and hence a decrease of the electrical wear of the circuit breaker interrupters. The actual magnitude of the inrush current is a function of the system configuration however installations are often configured such that their characteristics do not exceed the values defined in appropriate standards. For example, IEC 62271-100 recommends test values of 20 kA peak at 4250 Hz for back-to-back capacitor inrush conditions. Since it is the back-to-back configuration that presents the most onerous inrush conditions this is also where the maximum circuit breaker benefits associated with controlled closing are likely to be seen. The following example outlines a typical electrical wear evaluation associated with shunt capacitor energisation.

3.2.2 Electrical Wear Evaluation Example

The following example uses the equivalent electrical wear relationships introduced in section 2.2.2. It is assumed that the quoted relationships are appropriate for the evaluation of electrical wear caused by inrush currents. The high frequency of the inrush current is not accounted for in the calculation. The assumptions for the uncontrolled switching case are:

- 25 years of service
- operation twice a day (700 times/year)

- average inrush current = 5 kA
- average pre-arcing time = 4 ms
- rated short circuit current of CB = 40 kA
- average arcing time at T60 = 12 ms

The number of capacitive current interruptions is converted to a number of current interruptions at 60% of the rated short circuit current of the CB (T60). This allows a direct comparison to be made between extended electrical endurance requirements (which are expressed in terms of T60) and the electrical wear resulting from capacitor energisation.

Equivalent electrical wear (in terms of T60 interruption) is given by:

$$N_{60} = N *((I/I_{35})^{3}*(I_{35}/I_{60})^{1.7)})*(\text{average pre-arcing time/average T60 arcing time})$$

Using this equation the equivalent electrical wear for the considered example is:

$$N_{60} = (25*700)*((5/14)^{3} * (14/24)^{1.7)} * (4/12) = \underline{107\ \text{T60}}$$

The electrical wear can also be evaluated for energisation with controlled switching using the assumptions that the average inrush current is reduced to 2kA and the average pre-arcing time is reduced to 2 ms:

$$N_{60} = (25*700)*((2/14)^{3} * (14/24)^{1.7)} * (2/12) = \underline{3.4\ \text{T60}}$$

Table 2: Example of electrical wear evaluation for controlled and uncontrolled switching of shunt capacitor bank.

	Uncontrolled switching	Controlled switching	Extended Electrical endurance requirements (IEC 17A/629/DTR)
Equivalent Electrical wear (25 years of service)	107 T60	3.4 T60	21 T60

Clearly, in this example, the introduction of controlled switching results in a dramatic reduction in the theoretical electrical wear of the interrupters. The electrical wear with controlled switching is negligible however without controlled switching the value is well in excess of the proposed testing in IEC Draft Technical Report IEC 17A/629/DTR as shown in Table 2. Even allowing for assumptions and inaccuracies in the adoption of the proposed wear relationship it seems certain that significant wear reduction can be achieved by using controlled energisation. Using this result a maintenance cost saving can be quantified from the electrical wear tables which are typically given by the circuit breaker manufacturers (see Figure 1).

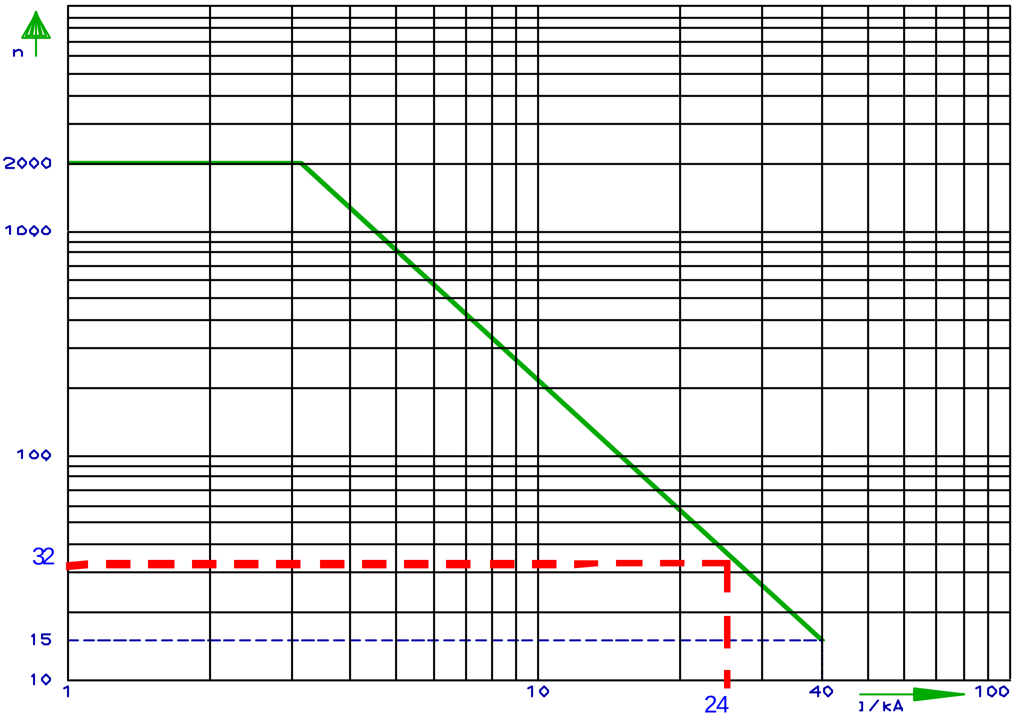


Figure 1: Maximum allowable number of interruptions with respect to the interrupted current (example of electrical wear chart).

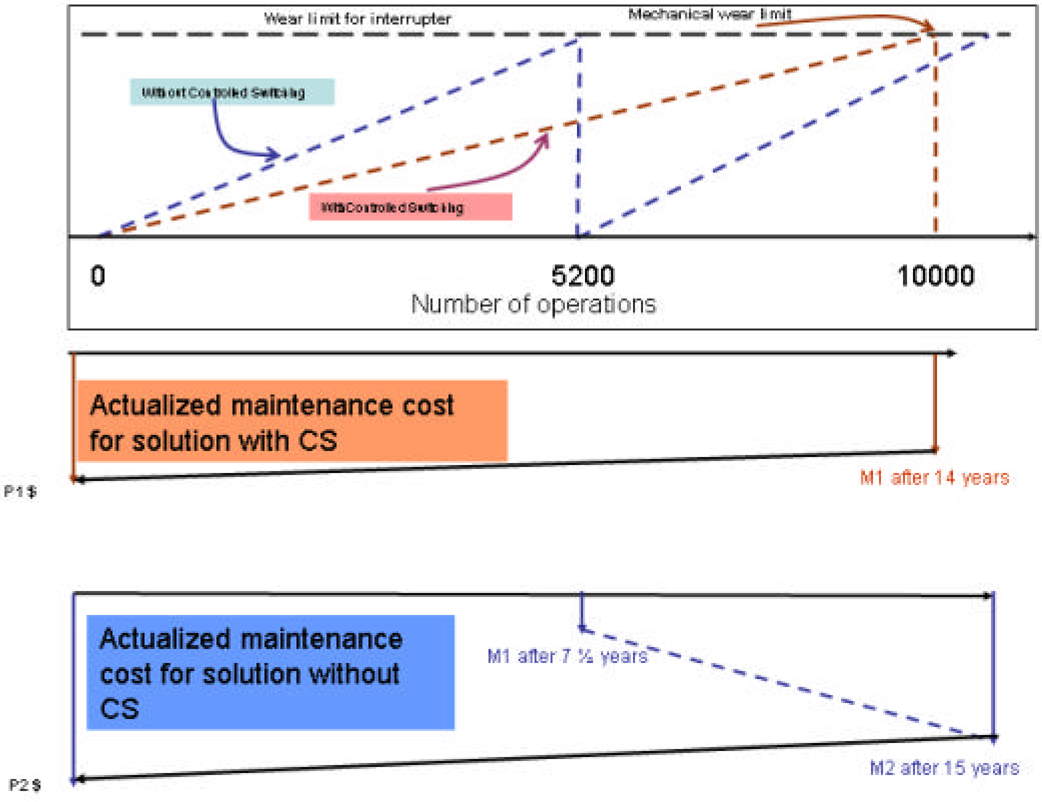


Figure 2: Comparison between circuit breaker maintenance costs with and without controlled switching applied for shunt capacitor banks.

The data in Figure 1 shows that the circuit breaker reaches the end of its electrical life after about 32 T60 interruptions. For this example, without controlled switching, this represents about 5200 capacitor bank switching operations or about 7½ years of service. The addition of controlled switching reduces the electrical wear to such a degree that 10,000 mechanical operations, the defined value for a class M2 circuit breaker, would be reached first after approximately 14 years. This is shown graphically in Figure 2.

3.2.3 Re-strike Avoidance

Interruption of small capacitive currents is often a dimensioning criteria for the design of modern SF_6 circuit breaker and can result in a re-strike of the circuit breaker [9]. International Standard IEC 62271-100 defines different degrees of re-strike probability and associated testing regimes. This standard categorises capacitive switching performance in terms of class C1 (low probability of re-strike) and class C2 (very low probability of re-strike). These are based on 48 and 168 test operations respectively. Whilst these test operations are concentrated in the critical area of short arcing times, thereby increasing their statistical significance, the standard does not recognise the concept of re-strike free circuit breakers and it is accepted that, over very large numbers of operations, occasional re-strikes may occur. The work of CIGRE Working Group 13.04 [9] supports the assumption that capacitor banks are typically operated between 300 and 700 times per year and hence re-strikes during the lifetime of the circuit breaker are to be expected.

Re-strikes may, in rare cases, result in physical damage to interrupter components (e.g. nozzle puncture) and even lead to catastrophic circuit breaker failure. Thus, the use of controlled de-energisation to avoid the critical short arcing times can act to minimise the occasional, but significant, costs associated with unplanned maintenance or catastrophic failure.

Reference [8] details a real case where re-strikes were observed and during de-energisation of SCB on a 120 kV system.

3.2.4 Cost Reduction

Pre-insertion resistors (PIR) have been widely to reduce the switching overvoltages and the inrush currents produced by energisation of shunt capacitor banks. However, it is widely recognised that the cost implications (investment and ongoing maintenance) of PIR are significant. Controlled switching offers an interesting alternative and can be used for both opening and closing. At transmission voltages PIR with auxiliary chambers the purchasing costs of the CB by 20 to 25% [11]. This cost is much higher than the cost for implementing CS system at these voltage levels.

3.3 Benefits for the Capacitor Bank

Potential benefits for capacitor banks of adopting controlled switching are:

- Minimisation of the bank design (increased design stresses) whilst maintaining acceptable performance levels.
- Improving reliability of existing bank designs.

This assumes that switching transient effects are a dimensioning criterion for the design of capacitor banks.

3.3.1 Minimised Bank Design

In cases where transient withstand is a fundamental dimensioning criterion for the capacitor bank controlled switching can, theoretically, allow the use of a design with reduced margins (higher steady state stresses).

Unfortunately the relevant standards (IEEE 1036 and IEC 60871) do not indicate that these transients form a major consideration in capacitor bank design. Since, from a capacitor bank design viewpoint, circuit breakers are considered to be re-strike free (IEC 60871-1, sub-clause 33.2) a reduction in re-strike probability is unlikely to affect bank design costs.

Relevant design criteria are as follows:

From IEEE 1036:
"A capacitor unit may reasonably be expected to withstand transient currents inherent in the operation of power systems. These include infrequent high lightning currents and discharge currents to nearby faults.

For frequent back-to-back capacitor bank switching, peak capacitor unit current should be held to a lower value as indicated in Figure 5. (The capacitor bank current is the capacitor unit current times the number of capacitor units or strings in parallel.) Other equipment such as fuses, circuit breakers, protection and control circuits may require limitation to a lower peak current."

Additionally, IEC 60871-1 states that energisation of capacitor banks will cause transient overvoltages not exceeding 2 p.u. for a maximum duration of ½ cycle and that it is assumed that the capacitor units should withstand these transient overvoltages 1000 times per year. Nevertheless, it has been reported by one utility that the use of capacitor cells operating with a higher electrical field gradient has led to a cost reduction for the capacitor units of 45%. This solution has been adopted on the basis of transient reduction achieved by controlled switching.

3.3.2 Increased Bank Reliability

Benefits from increased bank reliability fall into two main areas: decreased rectification costs and increased availability. The former is relatively easy to assess on a case by case basis whilst the latter is very dependant on local regulatory charging and/or penalty regimes.

Even though normal switching transients are not considered to be a fundamental design criterion for capacitor units it seems likely that the reduction of one element of the stress on the capacitors will contribute to improvements in longevity and decreased failures. Unfortunately there is little published information available on this topic and a clear evaluation of the potential benefits has not been possible to date.

An important element for capacitor bank design is the fusing arrangement. Capacitors are fused to ensure that a dielectric breakdown within a capacitor unit does not compromise the functionality of the entire bank. Reference [11] gives some detailed information on the most common fuse arrangements used today. Regardless of the fusing arrangement used a properly designed capacitor bank should be robust against typical rates of fuse operation. Nevertheless, operation of external fuses, which disconnect an entire capacitor unit, have a much larger effect on capacitance and voltage distribution than operation of internal fuses which disconnect at an elementary level. On this basis it can be speculated that the likelihood of avalanche failure for an externally fused bank is greater than for an internally fused one and that the stress reduction possible from controlled will contribute to minimise this risk.

One utility has reported that most capacitor bank failures occur during energisation which would support the use of controlled closing as an effective palliative.

An area where controlled switching can definitely improve bank reliability is re-strike minimisation. Typical capacitor banks are not designed to cater for re-strike and, should they occur, are very likely to suffer significant damage. Whilst this is a rare event the costs may be significant such that, overall, controlled opening can be supported.

3.4 Benefits for the Power System

The major benefits for the power system from applying CS to capacitor banks are:

- improvement of power quality,
- reduction of phase-to-phase overvoltages at remote substations,
- reduction of nuisance relay tripping,
- reduction of ground potential rise (safety of workers).

The quantification of these benefits is almost totally reliant on the regulatory operating environment of the utility and “softer” issues such as customer relations. It is rare for there to be specific costs associated, for example, with power quality. However, taking the example of power quality, this can be defined in terms of factors such as the magnitude, shape, symmetry and frequency of the voltage wave. SCB switching mostly affect the magnitude and the waveform of the voltage and hence controlled switching provides a means for complying with pre-determined quality requirements. Reference [14] summarises the activities of CIGRE WG 36-07 related with power quality indices and objectives.

Reference [15] details a specific example of the economic benefits of applying controlled switching to shunt capacitor banks. It reports a case where shunt capacitor bank energisation on a 138 kV system resulted in a surge arrester operation at the substation which, in turn, caused two bus differential protection relays to trip out a large refinery in the middle of the winter. This single event involved commercial losses in the range of several million US$.

Reference [9] compares the overvoltages obtained when energising a 225 MVAr capacitor bank in a 400 kV substation with different mitigation means including CS and current limiting reactors.

Reference [1] gives an example where energisation of a 96 MVAr capacitor bank in a 120 kV power system was causing serious relay nuisance for an important customer. Different solutions were studied and the use of CS was found the most cost effective solution.

The most significant benefit for the power system during de-energisation is the improvement of the power quality by eliminating the re-strikes of the CB. Reference [1]shows a case where power quality during de-energisation of SCB was improved by the means of CS.

3.5 Benefits for other Equipment

Other equipment such as power transformers, potential transformers, current transformers and surge arresters are exposed to overvoltages caused by capacitor bank switching. Overvoltages propagate to remote substations and consequently, create additional dielectric stresses to the insulation of the equipment in the remote substations [1] [12]. Various publications have described the effects of phase-to-phase transient overvoltages due to capacitor bank switching at remote substations [12][13][14].

3.6 Disadvantages

There are few specific drawbacks relating to controlled switching of shunt capacitor banks although, in the event that controlled opening is applied, there may be an increase in average arcing time and a consequent electrical wear increase. Due to the low load currents (hundreds of amperes) this is not significant.

3.7 Summary

Table 3: Benefits of Controlled Switching of Shunt Capacitor Banks.

Positive Effect on	Economical Consequences	Remarks	Applies to	Document Reference
Circuit breaker	Capital investment	• Purchasing cost lower compared to conventional solutions with PIR.	C	Section 2.3 [1]
	Increase of life expectancy	• Major asset to reduce the contact and nozzle erosion during energisation of SCB. During de-energisation, electrical wearing of the contacts is slightly increased due to longer arcing times.	C, O	Section 2.3 [1]
	Reduction of failure risk	• Failure risks generally reduced compared to conventional solutions with PIR (depending on the design of the PIR mechanism). • Damaging re-strikes greatly reduced with controlled switching solution	C, O	Section 2.3
	Maintenance cost reduction	• Maintenance costs greatly reduced due to a lower electrical wearing of the arcing contacts and nozzle.	C, O	Section 2.3 [1]
Capacitor units	Capital investment	• By reducing the switching transients levels, capacitor manufacturers could propose new designs of capacitor units using higher electrical gradient (applicable to designs for which the switching transients are a dimensioning criteria)	C, O	Section 2.4 Ref. [10][11]
	Increase of life expectation	• The failure rate of the capacitor units should be reduced by limiting the switching transients. No available field data to confirm. Depending on the fusing philosophy, it may be more critical for some design (for instance design with external fuses),	C	Section 2.4 Ref. [10][11]
	Maintenance cost reduction	• Unplanned maintenance costs should be lower if the failure rate is reduced.	C, O	Section 2.4
Other equipment	Capital investment	• The reduction of inrush current or overvoltages due to point on wave closing does not have a significant impact on the PT or CT design or specifications. • Because of lightning surges, the arresters cannot be eliminated or their specifications reduced.		Section 2.6
	Reduction of failure risk (increase availability)	• Reduction of phase-to-phase overvoltages at remote substations (important for power transformers at remote substations)	C, O	Section 2.6 Ref. [13]
	Increase of PT and CT life expectancy	• Qualitative advantages	C, O	
Power System	Increase of power quality and reliability	• Transient switching overvoltages reduced during energisation • Re-strike probabilities greatly reduced: improved power quality	C, O	Section 2.5 Ref. [15]
	Reduction of risk of failure (increase availability)	• less electrical and mechanical stresses applied to the capacitor units should reduce the failure risks • less electrical stresses applied to the CB should reduce the failure risk (especially by avoiding damaging re-strikes)	C, O	Section 2.5

Table 4: Disadvantages of using controlled switching for shunt capacitor banks.

Item	Economical Consequences	Remarks
Need for independent-pole operated breaker and special tests to prove CB suitability	Capital investment	• Most of CB at 170 kV and lower are gang operated CB. Controlled Switching may require Independent Pole Operated circuit breakers. • Special type tests are needed to prove the RDDS characteristics of the CB, to demonstrate the operating time variation with respect to certain parameters (ambient temperature, coil voltage, idle time, etc.)
Need of Controller	Capital investment	• Cost for controller
	Total increased installation costs	• Includes engineering costs, field tests, training etc. in case of new installation
	Controller maintenance costs	
Consequences of malfunction	Power quality	• Risk of having deteriorated power quality in case of malfunction of the CS system

4 Benefits of Controlled Switching of Shunt Reactors

4.1 Technical Aspects

Potential problems which may exist when switching reactors are: damage to the reactor itself (due to voltage transients or inrush current stresses on closing), damage to the circuit breaker (typically caused by re-ignitions), system reliability issues (e.g. spurious protection operations) and power quality problems (e.g. prolonged harmonic effects due to sympathetic interactions with local power transformers).

In order to mitigate these effects there are three basic strategies for controlled switching of reactors as follows:

- Closure at voltage peak to minimise inrush current
- Closure at voltage zero to minimise the steep voltage wave which is launched towards the reactor terminals
- Opening in the re-ignition free window or, where such does not exist, at a point to minimise the impact of re-ignitions.

Clearly the first two are mutually exclusive however either of these can be combined with the final strategy.

4.2 Benefits for the Circuit breaker

4.2.1 Re-ignition Damage

In recent years, reports of circuit breaker damage associated with shunt reactor switching pertain almost entirely to re-ignition induced damage such as nozzle puncture. Whilst interrupters which are well dielectrically co-ordinated should be robust against this problem, numerous problems are known to have occurred. Even well designed interrupters may suffer re-ignition damage over many thousand of operations which may occur during their lifetime.

In many cases the application of controlled switching can virtually eliminate the occurrence of re-ignitions and thereby remove the major mechanism by which reactor circuit breakers suffer damage. Since the target re-ignition free window is often relatively large (several milliseconds) such applications are often straightforward and the economic benefit assessment is a direct comparison between the cost of the controlled switching equipment and the costs of enhanced maintenance and/or recovery from disruptive failure. On this basis controlled switching is normally a cost effective solution for new applications and for pre-existing applications with proven “weak” circuit breakers. Retro-fitting of controlled switching to pre-existing, well designed circuit breakers is less easy to justify due to the small risk of eventual failure.

It is notable that re-ignition avoidance by ensuring long arcing times will tend to increase chopping overvoltages. For modern equipment these overvoltages are generally a second order concern and it will normally be preferable to adopt a strategy of re-ignition avoidance. Nevertheless, should chopping overvoltages be a primary concern controlled switching can be used to ensure short arcing times and thereby minimise this effect.

4.2.2 Economic Assessment of Avoiding Re-ignition Damage

The following example details an actual assessment carried out by a major power utility in order to justify the application of controlled switching. It is based on two different designs of SF_6 circuit breaker controlling 400 kV shunt reactors. Using a basis of the initial capital cost of the circuit breaker lifetime, savings of 59% for one design and 5% for the other design are justified. An operating life of 10,000 operations has been considered and only the direct cost of replacement parts is included in the assessment. The proposed savings would be increased if outage costing was also introduced into the assessment. The changes in maintenance regime resulting from the introduction of controlled de-energisation are summarised in Table 5. In this table the term overhaul refers to disassembly of the chambers, cleaning of nozzles and the substitution of small parts such as rings, washers, etc.

Table 5: Circuit breaker maintenance schedule with and without controlled switching.

Operations	**1,000**	**2,000**	**2,500**	**3,000**	**4,000**	**5,000**	**6,000**	**7,000**	**7,500**	**8,000**	**9,000**	**10,000**
Breaker type 1 (without CS)	Change nozzles	Change nozzles		Change nozzles	Change nozzles	Change nozzles	Change nozzles	Change nozzles	-	Change nozzles	Change nozzles	-
Breaker type 1 (with CS)	-	-	Overhaul	-	-	Overhaul	-	-	Overhaul	-	-	-
Breaker type 2 (without CS)	-	Change nozzles	-	-	Change nozzles	-	Change nozzles	-	-	Change nozzles	-	-
Breaker type 2 (with CS)	-	-	Overhaul	-	-	Overhaul	-	-	Overhaul		-	-

The cost assessment has been carried out using the following reference costs.

- Cost of overhaul = 3%
- Cost of nozzle exchange = cost of overhaul + cost of nozzles = 9%

Considered over a 10,000 operation lifetime this results in the figures presented in Table 6.

Table 6: Maintenance cost comparison.

Maintenance cost	Breaker type 1 (without controller)	80%
	Breaker type 2 (without controller)	26%
	Breaker type 1 (with controller)	8%
	Breaker type 2 (with controller)	8%
Implementation of point-on-wave controller	Cost of controller	7.5%
	Installation & commissioning	5.5%
	TOTAL	13%
Cost savings	Breaker type 1	59%
	Breaker type 2	5%

In this example the savings obtained are in the range 1…8 times the cost of the application of controlled switching depending on the circuit breaker type.

4.2.3 Contact Erosion

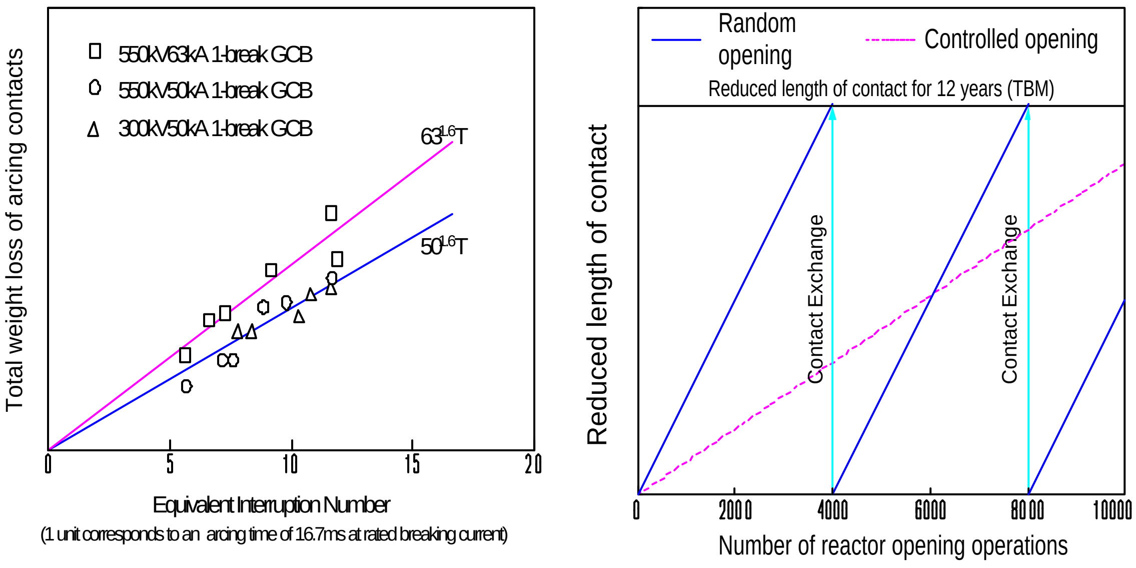
Regarding contact erosion, experimentally obtained values for arcing contact mass loss can be expressed in relation to the rated breaking circuit with an exponent of around 1.6 and the arcing time as shown in Figure 3. The equivalent erosion rate definition is not readily available for small capacitive or small inductive current interruptions and it has, at this time, been assumed that the correlation derived for high currents can be extrapolated to cover small inductive currents.

Considering an example of reactor de-energisation using a typical 245 kV circuit breaker the re-ignition free window ranges from 0.25 cycle to 0.55 cycle at 60 Hz. The circuit breaker re-ignites thermally if the arcing time is less than 0.05 cycle and dielectric re-ignitions are observed at arcing times in the range 0.05 to 0.25 cycle. Thus the probability of dielectric re-ignition due to random opening is calculated as 40% (0.2 cycle/0.5 cycle). Such re-ignitions result in an average re-ignition current of 6 kA for up to 1/50 cycle followed by approximately 0.3 kA at power frequency until interruption at the next current zero after re-ignition. Controlled switching can maintain the arcing time of around 0.5 cycle and hence avoid these re-ignition currents.

Time-based maintenance (TBM) of this circuit breaker, including contact exchange, normally takes place after 12 years (4000 operations). Assuming that this represents a limit of acceptable contact erosion the lifetime enhancement achievable from controlled de-energisation can be derived from the following equation where N is the enhanced number of operations representing end of life [6][7].

$$N^*(0.3kA^{1.6} \text{ x } 1/2\text{cycle}) = [(6kA^{1.6} \text{ x } 1/50\text{cycle x } 0.4)+(0.3kA^{1.6} \text{ x } 1/2\text{cycle})]^*4000$$

In this example N=11,700 operations suggesting that no contact exchange would be required during a 10,000 operation lifetime.



a) b)

Figure 3: Reactor switching example of (a) amount of material loss versus number of interruptions and (b) maintenance interval.

Whilst this example relies on a number of assumptions, making the detailed results open to question, the principle demonstrated here remains valid.

4.3 Benefits for the Shunt Reactor

Whilst switching transients to which shunt reactors are exposed can clearly be reduced by controlled switching there is little substantive evidence of reactor life being measurably extended by the use of this technique. Reduced voltage stress in the vicinity of the input terminals and reduced electromagnetic stresses on the windings are both potentially beneficial effects but their benefits are unsubstantiated by other than speculative means.

A reduction in the magnitude of switching overvoltages may permit the installation of surge arresters providing an increased protective margin however this will also depend on the wider system considerations.

4.4 Benefits for the Power System

Controlled switching of shunt reactors can be used to avoid system effects such as undesired activation of zero sequence protective relays due to saturation effects in earthed neutral shunt reactors and elimination of resonant interactions between the reactor and nearby equipment such as power transformers or generators. The latter case was the subject of a report from a manufacturer of vibrations occurring in generators at the time of shunt reactor energisation.

Applications of this type must be considered on a case by case basis.

4.5 Conclusions

Controlled switching of shunt reactors offers a number of advantages, some of which are readily quantified and some of which are less so. The benefits that can accrue from controlled opening are, at present, much better defined than those from controlled closing. In all cases a relatively modest investment in controlled switching can be shown to have a major transient reduction effect and an associated perceived advantage for equipment longevity. Since end of life, and the factors which contribute to it, are poorly defined for shunt reactors detailed economic assessments on this basis are not presently possible.

What is certainly true is that controlled switching of shunt reactors is a widely used application suggesting that many users are convinced of the benefits. In many cases these applications are justified on the basis of re-ignition avoidance but, having installed the equipment, a controlled closing strategy is also adopted in an attempt to maximise the benefits.

It is notable that there are no major disadvantages which are specific to the use of controlled switching for shunt reactors.

4.6 Summary

The following tables summarise the benefits and disadvantages of controlled switching of shunt reactors.

Table 7: Shunt Reactor controlled energisation benefits.

Positive Effect on	**Economical Consequences**	**Remarks**	**Document Reference**
Shunt reactor	Increase of life expectancy	• Reduction of electrical currents and associated stresses in the bank (energisation at peak voltage) • Avoid saturation of the reactor iron core (energisation at peak voltage)	Section 4.3
Other Equipment	Increase of life expectancy	• Reduction of sympathetic transformer inrush current	
Power System	Increase of power quality and reliability	• Avoid or reduce the probability of relay nuisance tripping	Section 4.4
	Reduction of risk of failure (increase availability)	• Protection scheme mis-operation	Section 4.4

Table 8: Shunt Reactor controlled de-energisation benefits.

Positive effect on	**Economical consequences on**	**Remarks**	**Document Reference**
Circuit Breaker	Capital investment	• Deferral of maintenance and overhaul costs	Section 4.2
	Increase of life expectancy	• Re-ignition is avoided • Nozzle punctures are prevented • Reduction of arcing contact wear	Section 4.2
	Reduction of failure risk	• Reduced risk of catastrophic failure, explosion	Section 4.2
Shunt reactor	Increase of life expectancy	• Reduction rate of rise and amplitude of transients experienced by the reactor	Section 4.3
Other Equipment	Capital investment	• Overvoltage reduction may allow de-rating of surge arresters	
	Increase of life expectancy	• Lifetime is increased	
Power System	Increase of power quality and reliability	• Power quality improvement through the reduction of transient overvoltages and overcurrents	Section 4.4
	Reduction of risk of failure (increase availability)		Section 4.4

Table 9: Shunt reactor controlled energisation disadvantages.

Negative effect on	**Economical consequences on**	**Remarks**
Shunt reactor	Lifetime is decreased	- Steep voltage front is generated (energisation at peak voltage)
Power system	Relay false operation	- Increase the probability of inrush current (wrong point-on-wave target during closing)

Table 10: Shunt Reactor controlled de-energisation disadvantages.

Negative effect on	**Economical consequences on**	**Remarks**
Circuit Breaker	Likelihood of catastrophic failure is increased	- Increase the probability of re-ignition (malfunction of controller)

5 Benefits of Controlled Switching of Transformers

5.1 Technical Aspects

The technical aspects of transformer switching are covered in detail in [16].

Random switching of transformers produces inrush current which level and shape depend upon transformer characteristics, closing moment, and transformer residual flux. This inrush current (which reduces the transformer remaining life) contains direct and harmonics components, the more important being the second, third and fourth rank. It may generate TOV (temporary overvoltage) on the network depending on the prevailing resonance conditions at the closing moment. If the system presents some resonance at the second, third and fourth harmonics, there is a risk of TOV generation. It may also lead to protective relay operation and reduction of the power quality delivery.

5.2 Benefits for the Circuit breaker

The potential benefits for the circuit breaker and the associated costs are heavily dependent upon existing practice for transformer switching: specifically if pre-insertion resistors are used. The capital and maintenance costs of these devices are significant with capital costs being of the order of 10…30% of the cost of a standard circuit breaker at voltage levels above about 300 kV. These costs are increased to prohibitive levels for GIS. In comparison, controlled switching can be installed for about 5% of the initial costs. Furthermore, since only a limited range of circuit breakers are designed for use with PIR, the adoption of a controlled switching solution may create the possibility of purchasing a more cost effective standard circuit breaker. Finally, the maintenance costs of circuit breakers using PIR are about twice as expensive as those for standard circuit breakers and maintenance is required more often. This more than offsets the probable need to change the controller once in the life of the circuit breaker.

The optimum transformer switching strategy generally requires an independent pole-operated circuit breaker. Whilst this is normal practice above about 245 kV, additional mechanisms—and hence costs—may be incurred at lower voltage levels where gang operation is common. The need for measuring some important parameters influencing the timing of the breaker (temperature, gas pressure, oil pressure, coil voltage, etc.) may also have a slight impact on initial costs.

5.3 Benefits for the Transformer

Controlled switching cannot be used to reduce transformer insulation specifications since these are largely dictated by lightning surge stresses.

All transformers start a lifelong deterioration when they are first energised for testing. During their operational life they are exposed to electrical, mechanical, chemical and thermal stresses until they fail (or are replaced before a failure). Specifically in relation to controlled switching, transformer energisation creates mechanical stress on the transformer winding due to the inrush current [16][18][19] (one in six random energisations considerably high inrush current values [20]) and electrical stress on the transformer winding (due to the steep voltage front) [38][39].

The transformer end of life failure rate is reported to be about 2% per year internationally [21][22]. Whilst a significant increase in this failure rate has not yet been seen, the combined effects of loading increases and ageing make a rise in this rate likely. Since switching transients cause cumulative deterioration of the transformer insulation their limitation, by means such as controlled switching, can be used as part of the lifetime management strategy for power transformers.

The quality of the insulation can be defined by its impulse dielectric strength, which is a statistical variable with a probability distribution [24] that can be expressed as follows:

$$P_n \approx 1 - \left[1 - P_1\left(V_T\right)\right]^n$$

where V_T is the applied voltage, P_1 the breakdown probability when applying a single impulse surge V_T, n the number of impulses and P_n the probability of one breakdown after n impulse surges of height V_T. It is assumed that the breakdown probability for each impulse surge is the same.

Figure 4 shows schematically that reducing the number and amplitude of the impulse surges reduces the breakdown probability and increases the remaining life of the transformer providing lightning impulses do not occur late in the transformers life. As the transformer ages its withstand strength gradually decreases until it falls below the normal operating stress [30]. At this point the transformer fails. Prior to this “steady-state” failure point, all transient stresses in excess of normal loading conditions cause step decreases in the withstand capability of the transformer. The control of these transient stresses by means such as controlled switching is an important tool in improving life management of power transformers.

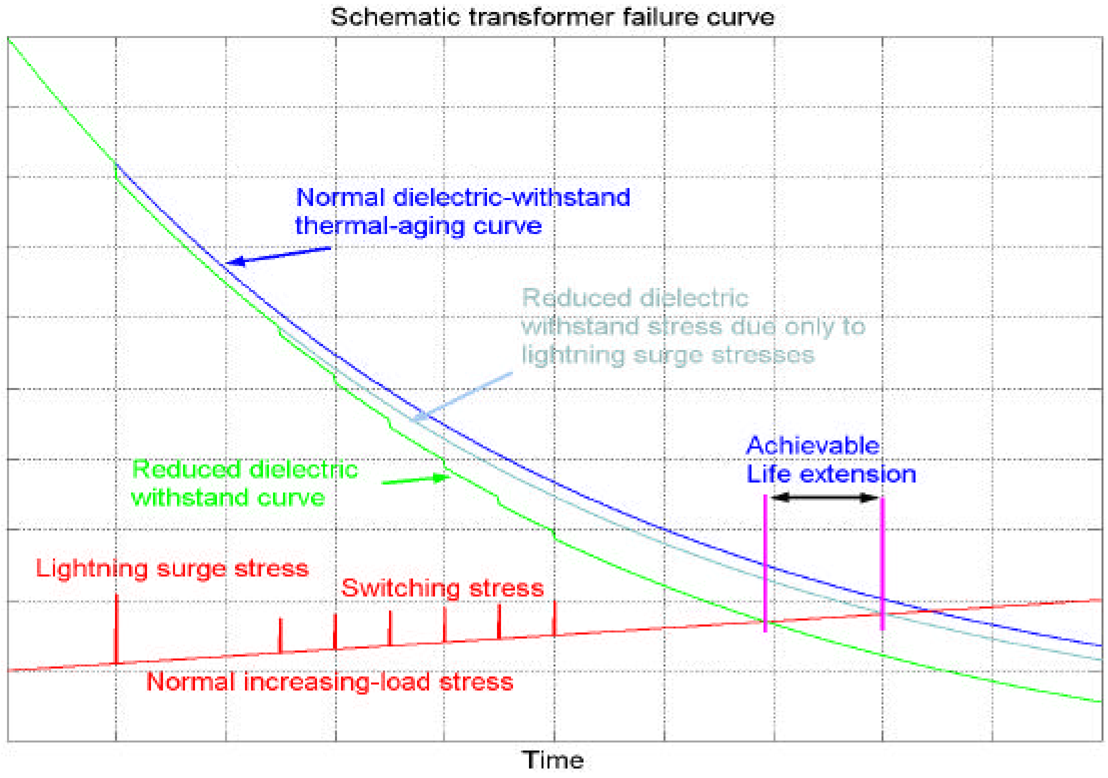


Figure 4: Schematic transformer-failure model (without lightning surge stress).

Transformer loading guides (IEC Publication 354, ANSI C57.95 and IEEE STD 756) state that the principal factor influencing transformer ageing and life expectancy is thermal stress [36]. Whilst there is no doubt that long term ageing in combination with transient stresses make a major contribution to the likelihood of transformer failure [25] the cumulative effect of repeated voltage surges is less well quantified than thermal ageing.

Furthermore, random switching which forces the transformer into saturation may result in rapid eddy current heating of steel components and a consequent deterioration of adjacent insulation material [26][27].

There is still much debate regarding the optimum approach to transformer energisation however any reduction in the transients stresses applied to the transformer will have a positive impact on life extension, will ease the prediction of the remaining life of the transformer and will, at least, defer the cost of unplanned maintenance or failure. It must be noted that achieving even a one year deferral of transformer replacement by means of controlled switching will more than pay for itself on the basis of investment deferral. Unfortunately this benefit will not be achieved in all cases due to the influence of other factors such as short-circuit and lightning stresses which cannot be mitigated by the controller.

Controlled de-energisation of transformers has no real benefit other than the possibility to establish a residual flux with a known value for subsequent controlled energisation.

5.4 Benefits for the Power System

Availability, reliability and quality of electrical supplies have economic consequences which are largely dependent upon the regulatory environment of the utility and the sophistication of its customers. “Digital” and process industries are particularly sensitive to power supply fluctuations and the costs associated with loss of production can be very large. The exposure of the power utility to these costs varies widely making generic economic assessment impractical. As an example, in US, the outages are costing around $100 billion a year and another $20 billion each year to power quality phenomena [14]. A part of this loss is absorbed by the utility itself: each hour of failure represents a lost of revenue, some cost to regain client satisfaction, and a noticeable increase in the transformer failure a few months after the powering-up of the network.

If there is some risk of damaging the equipments or to minimise these side effects, then mitigation means should be used:

- Pre-insertion resistors (conventional method)
- Control switching
- Gradual Voltage ramping (if possible)
- Energising with a resistive load

Controlled-switching has been an economical solution since many years when switching a capacitor bank, a shunt reactor, and a line; recently a transformer controlled-switching taking into account the transformer core remaining flux has been realized.

Controlled energisation of power transformers can make a major contribution to improved power quality. Figure 5 shows an example, albeit extreme, of network behaviour upon transformer energisation with and without controlled switching.

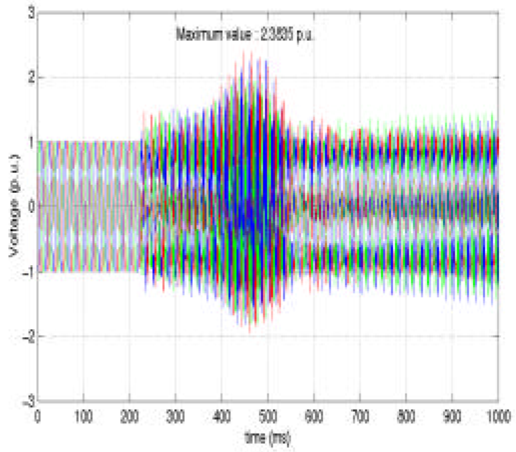
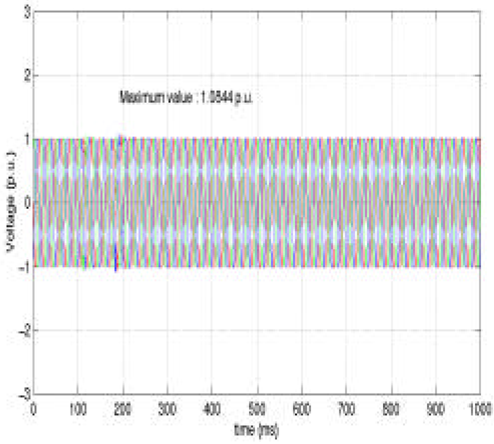
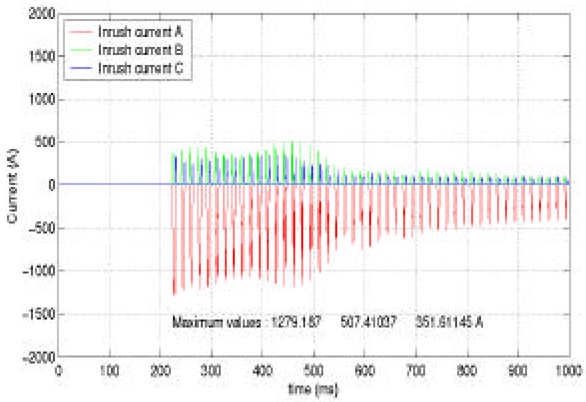
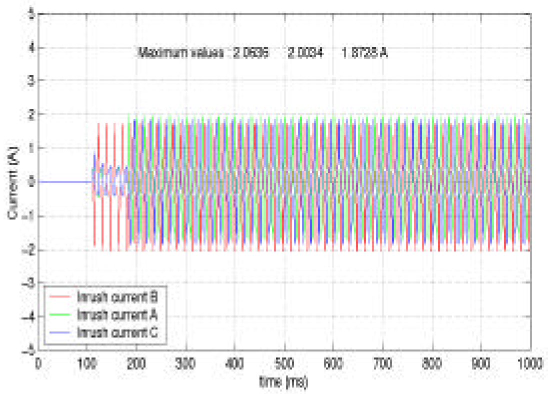
<table>
<tr><th></th><th>Without any applied solution</th><th>With controlled switching system</th></tr>
<tr><td>Network voltage</td><td>
</td><td>
</td></tr>
<tr><td>Inrush current</td><td>
</td><td>
</td></tr>
</table>

Figure 5: Energisation examples of a three-phase transformer.

Transients of this type can be seriously detrimental to connected loads and may result in protective relay mis-operation and, possibly, power interruptions. Controlled switching can virtually eliminate these effects reducing the impact on connected loads and permitting optimised protective relay settings.

5.5 Conclusions

The most well defined benefit of controlled transformer energisation relates to lifetime enhancement of power transformers. The application of controlled switching can be a valuable tool to maximise transformer life thereby maximising the useful life of a very expensive asset.

Whilst power quality benefits are less well defined, in many regulatory environments these will also be very large, particularly if the utility is exposed to costs associated with losses of production in technologically complex industries.

5.6 Summary

Table 11: Transformer controlled closing benefits.

Positive Effect on	**Economical Consequences**	**Remarks**	**Applies to**	**Document Reference**
Transformer	Increase of life expectancy	• The probability of failure is reduced due to reduced stresses on transformer windings	C	Section 6.4
	Reduction of maintenance costs	• By-products generation is lowered due to reduced stresses on transformer windings	C	
Circuit Breaker	Capital investment	• Increase the selection of available breakers • Can replace closing resistors (space savings)		Section 6.2
	Increase of life expectancy	• Reduce the contact erosion and nozzle erosion because only small currents pass through the contacts during energisation	C	
	Reduction of failure risk	• The more conventional design due to the elimination of closing resistor and auxiliary contacts has a direct impact on the failure risk		
	Reduction of maintenance costs	• Due to the elimination of closing resistor and auxiliary contacts		Section 6.3
Power System	Increase of power quality and reliability	• Reduction of inrush due to point on wave closing • Reduction of relay mis-operation	C	Section 6.5
	Reduction of failure risk	• The monitoring function generally present with TCS, gives the status and behaviour of the equipment, thus increases the security of supply.		
	Power-up	• Reduce TOV when energising transformers …	C	
	Increase protection	• By lowering the triggering level of protective relays		
Other Equipment	Capital investment	• The reduction of inrush current or overvoltages due to point on wave closing does not have a significant impact on the PT or CT design or specifications. • Because of lightning surges, the arresters cannot be eliminated or their specifications reduced.		
	Reduction of PT and CT maintenance	*(Same as for the power transformer)*		
	Increase of PT and CT life expectancy	*(Same as for the power transformer)*		

Note: There are no benefits associated with controlled opening for this application, except that it can be used to set the residual flux so that the subsequent controlled closing operation is performed at a low voltage and without generating a high inrush current.

Table 12: Transformer controlled-switching disadvantages.

Item	**Economical consequences**	**Remarks**
Need independent pole operated breaker	Capital investment	• The controlled switching solution necessitates in most cases a three poles independent-operation breaker that may represent marginal cost
Need of controller	Capital investment	• Cost for controller • Cost of monitoring some important parameters influencing the timing of the breaker (temperature, gas pressure, oil pressure, coil voltage, etc.).
	Total increased installation costs	• Includes engineering costs, field tests, training etc. in case of new installation
	Maintenance costs for controller	• Over lifetime period • The controller equips self-diagnostic function.
Malfunction consequences	Increase of failure risk	• Increase of inrush may not cause damage to the system but it may result in relay mis-operation
	Increase of maintenance	• Due to increased stress on power equipment
	Decrease of service life	• Due to increased stress on power equipment

6 Controlled Switching of Transmission Lines

6.1 Technical Aspects

The primary motivation for using controlled switching of transmission lines is to minimise the switching overvoltages both during energisation and during fast re-closing. There is also a possibility of reducing the probability of re-strikes during de-energisation and tripping of healthy phases. Detailed technical information relating to controlled switching of transmission lines can be found in [1][2]. Controlled interruption of fault current on the line is not within the scope of this chapter but is also treated in [16].

Minimising the switching overvoltages during energisation is particularly desirable in EHV systems (300 kV and higher) where the switching surge voltage is the determining factor for insulation co-ordination of the lines [42]. The traditional method for overvoltage reduction has been the use of closing resistors (pre-insertion resistors) however the same results can be achieved by controlled switching.

Uncontrolled de-energisation of an unloaded line may cause re-strikes in the circuit breaker. The probability of such an event depends on the circuit breaker properties as well as on the line characteristics and re-strikes are more likely to occur on an uncompensated line than on a shunt compensated one. International standards allow for re-striking with a certain low probability [43]. Controlled de-energisation further reduces this probability. Nevertheless, for circuit breakers with a naturally very low re-strike probability controlled opening is not as important as controlled closing.

Line circuit breakers are usually operated no more than a few times per year however in a few cases lines are frequently switched for system voltage control. Any proposed application of controlled switching must take into account the expected frequency of switching operations.

Optimal controlled closing requires a circuit breaker meeting certain criteria of accuracy, stability, and RDDS [1]. However, even when applied with a less-than-optimal circuit breaker, controlled switching may improve the power quality during energisation [47] if only by preventing multiple pre-strikes that may occur in a slow circuit breaker.

6.2 Benefits for the Circuit Breaker

6.2.1 Energisation and Fast Re-closing

Controlled closing of the circuit breaker reduces the line inrush current to almost the steady-state charging current value. However, since the maximum inrush is limited by the line surge impedance, this “benefit” is relatively minor.

The main advantage of using controlled closing for overvoltage control is the replacement of pre-insertion resistors (PIRs). While the electrical performance of the two solutions is similar, controlled switching has lower initial costs and increases the reliability of the circuit breaker due to the reduced number of moving parts. The latter has direct consequences on circuit breaker maintenance costs and on the availability of the associated transmission line. For example, one utility reported that inspection of the auxiliary chambers on certain circuit breaker types were required every 500 operations. Another utility recently initiated a major overhaul programme for 500 kV air blast circuit breakers at a cost of 200 kUS$ each. The closing resistors were typically found deteriorated and required replacement representing one third of the overhaul cost.

Introduction of an electronic controller into the control system of a circuit breaker results in a slight reduction in the theoretical reliability of the circuit breaker system. In comparison with other solutions this is considered minor on the basis that:

- modern controllers have self-supervision features which provide alarms for many failure modes
- the consequences of an in-service failure of primary equipment (e.g. PIR) are more severe than for a controller
- controllers with adaptive timing provide some condition monitoring of the circuit breaker at no extra cost.

Provided that relevant data such as RDDS and mechanical scatter are known [3], retro-fit of controlled switching in this application is comparatively easy since no modifications are required to the circuit breaker itself.

6.2.2 De-energisation

By practically eliminating re-strikes, controlled opening further reduces the probability of damage and forced outages of the circuit breaker for electrical reasons. Since, for well designed switching equipment, re-strike damage is rare this is only a major benefit as a retrofit solution to extend the useful life of inherently weak circuit breakers.

6.3 Benefits for the Line

6.3.1 Energisation and Fast Re-closing

When compared to energisation without overvoltage control, controlled switching significantly reduces the overvoltages on the line. This effect is even more pronounced for fast re-closing in the presence of trapped charge on the line, where the worst-case overvoltages may reach 4 p.u. The benefits of controlled switching are a significantly reduced probability of flashovers on the line and a reduced probability of false relay operations.

When the switching surges are the main dimensioning criteria, as is the case in EHV and UHV systems, controlled switching—mostly in combination with surge arresters—permits a reduction of the line insulation level. This allows the use of a more compact line design with smaller towers and insulators which in turn yields savings in capital costs of the line itself. Alternatively existing lines may be operated at enhanced voltage levels.

For example, the design of the 330 km 500 kV line described in [45] was based on an insulation level of 1.7 p.u. achieved by a combination of controlled switching and mid-line and line-end metal-oxide surge arresters. Figure 6 shows a statistical comparison of the different methods for switching overvoltage control in this case. Only by using a combination of controlled switching and surge arresters it was possible to keep 98% of the switching overvoltages below 1.7 p.u.. The use of smaller towers resulted in capital savings of approximately 1 million US$ compared to traditional line designs. Additional investments were required for the mid-line arresters (80 kUS$ for an installed set), a more expensive spring closed breaker on the lead end terminal (additional cost 160 kUS$), and the controller (approx. 90 kUS$ including extensive field testing). Thus, the net savings amounted to about 670 kUS$ or roughly 1% of the total investment.

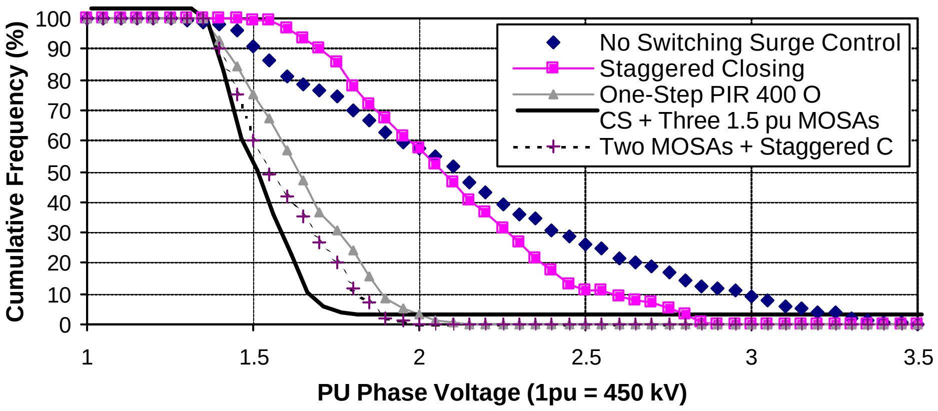


Figure 6: Example of statistical overvoltage for three-phase re-closing with trapped charge. EMTP study, from [45].

A compact line design also increases the surge impedance loading of the line and thus permits transmission of more energy (up to 30% more at 500 kV) [51][52][53]. If this makes construction of a new line unnecessary, huge savings will result. However, in designing a compact line controlled switching is only one of many aspects that need to be taken into account.

6.3.2 De-energisation

Re-strike of a circuit breaker may cause flashover of the line insulation. While an open-air flashover is not expected to cause permanent damage it poses certain safety risks. This, already low probability, effect can be virtually eliminated by controlled opening.

Controlled opening of the healthy phases during fault current interruption can also be beneficial for a subsequent re-closing operation. By pre-selecting the polarity of the trapped DC charge on an uncompensated line there is no need to measuring the line voltage in order to determine the optimal re-closing instant. Thus, there is no need to install additional line CVTs although the complexity of the control system is increased.

6.4 Benefits for the System

6.4.1 Energisation and Fast Re-closing

It is conceivable that high switching overvoltages may erroneously be interpreted as a fault by a protection relay, resulting in tripping of the line. Alternatively, when two lines run in parallel for a long distance, switching transients on one line may be coupled into the other line, which again may lead to unwanted protection operation. Although modern protection devices are designed to cater for such situations there may be an economical benefit from controlled switching due to the increased availability of the respective line(s) and in improved power quality.

A high switching overvoltage may also cause flashover of the line insulation leading to tripping of the line and—under unfavourable system conditions—network instability. In reality, this is only an issue for fast re-closing due to the associated high overvoltage levels. The worst conceivable case would be a complete system outage due to instability caused by unsuccessful re-energisation. A possible sequence of events leading to such a situation is shown in Figure 7. The commercial losses involved could easily extend to hundreds of million dollars. This possibility alone—which is strongly dependent on system sensitivity—would amply justify the comparatively insignificant investments for controlled switching.

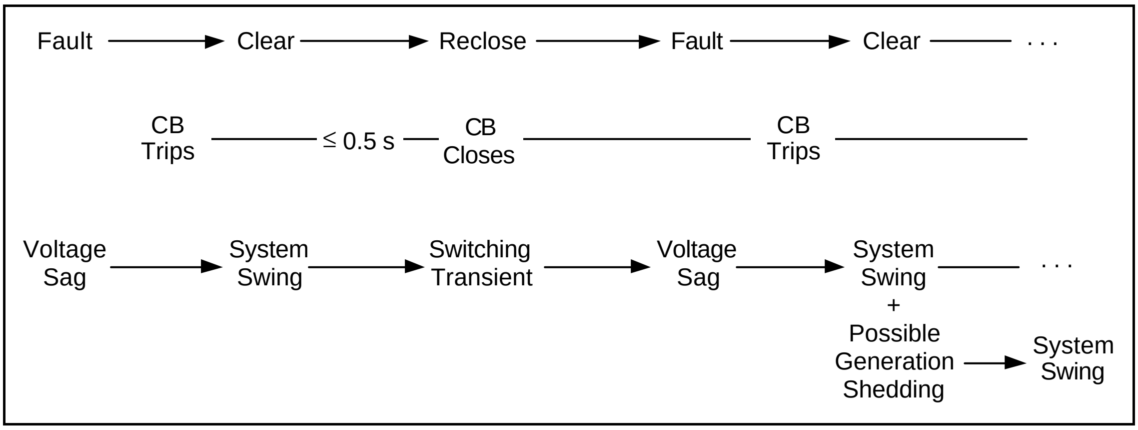


Figure 7: Sequence and power quality consequences of fault clearing and unsuccessful re-close, from [15].

6.4.2 De-energisation

Re-strike of the circuit breaker can cause flashover of the line insulation or of the rod gap. The transients generated by such an event will certainly impair power quality in adjacent parts of the network. Such situations can be prevented by controlled switching.

6.5 Benefits for Other Components

The reduction of switching overvoltages achieved by controlled switching also lowers the transient voltage stress on adjacent PTs, compensation reactors, and transformers. The accumulated surge energy of metal-oxide surge arresters is also decreased. Depending on the frequency of switching operations, this may increase the reliability and service life time of such components.

When switching operations are the determining factor for the specification of surge arresters, controlled switching may allow selection of arresters with a lower energy rating.

Another potential benefit is increased safety during live-line work since every overvoltage poses a potential hazard for the workers engaged in these activities. However, in most countries it is normal practice to disable re-closing and prevent any operator initiated re-energisation during hot line work making controlled switching unnecessary for this aspect.

6.6 Implementation Costs and Drawbacks

6.6.1 Need for Line Side PTs

Controlled closing at voltage zero is straightforward for energising a fully discharged line where the voltage across the circuit breaker is identical to the busbar voltage. This switching case is similar to energisation of a grounded capacitor bank—except for the phase coupling effects—and can be achieved using a rather simple controller.

The task of optimal fast re-closing onto an uncompensated line with a trapped DC charge is more challenging because the controller needs to know the polarity of the line voltage. This may be achieved by:

- Evaluating the signals from a PT or similar device (e.g. a single element on the bottom of a surge arrester stack) on the line side of the circuit breaker. This is the technically optimal state-of-the-art solution because it yields the actual electrical conditions on the line. However, the line-side PT may increase the initial costs of the controlled switching system.
- Making an assumption from the voltage and current signals at the time of current interruption. This is straightforward as long as the controlled circuit breaker is last in the sequence to trip the line. If the circuit breaker on the far end trips last, the polarity of the line voltage may be the opposite of that last seen by the controller. This may result in re-closing at the worst possible phase angle.
- Providing real-time information on the current interruption instants of both circuit breakers. This approach is only feasible for power systems that already have digital data communication between stations, otherwise it would probably be too expensive.

For optimal fast re-closing onto a shunt compensated line, which oscillates at its natural frequency, it is necessary to use line side PTs or similar devices (e.g. reactor bushing taps) that are able to accurately reproduce the non-power frequency signals in the healthy phases.

If sub-optimal re-closing is acceptable—regardless of the line compensation—controlled closing at, or after, busbar voltage zero is a compromise that will produce switching overvoltages not higher than uncontrolled energisation of a fully discharged line. This strategy may be problematic only when closing onto a fault (see below).

6.6.2 Re-closing onto Fault

Most of today's point-on-wave controllers attempt to achieve current making at voltage zero across the circuit breaker, regardless of the conditions on the line. Unfortunately, when re-closing onto a permanent fault, this strategy will consistently produce maximal asymmetry of the resulting fault current. This possibility should be taken into account when designing a transmission line system with controlled switching. As a compromise, it has been proposed to set the closing target to 45° electrical [41]. However, no practical service experience with this strategy has been published so far.

Note that any line connected shunt reactors will also experience maximum inrush asymmetry during normal line energisation at voltage zero.

6.6.3 Compact Line Designs

As explained above, a compact line design will reduce the tower dimensions (and thus the capital costs of the line) and allow more energy to be transmitted. However, there are other issues that need to be considered. In a compact line design:

- It is more likely that a lightning strike to one wire (shield or phase) will result in flashover to another phase,
- Clearances are smaller, which may prohibit hot-line maintenance and inspections that require climbing the structure,
- Maintenance of one circuit of a double circuit line with the other circuit live may be complicated or precluded.
- Closer phase spacing increases the risk of the phases swinging together,
- The audible and radio noise levels are higher.

6.6.4 System Complexity

Point-on-wave controllers should be transparent to the control system. Only when aiming for optimal re-closing on an uncompensated or shunt compensated line will the means for detecting the polarity or oscillating signal on the line add to the complexity of the controlled switching system.

6.6.5 Wrong Switching Instant

Switching at the “wrong” instant (i.e. at a non-optimal point on wave)—regardless of the reason—will always produce higher-than-intended switching overvoltages. It may therefore be necessary to incorporate backup devices into the system. Surge arresters, which are usually applied on transmission lines have proven beneficial in this respect and additionally offer protection against overvoltages from other sources such as lightning.

6.7 Conclusions

Controlled switching provides significant reduction of the switching overvoltages on unloaded transmission lines. While the electrical performance at closing is basically identical to that of pre-insertion resistors, controlled switching offers the added advantages of lower initial costs, the possibility to optimise opening operations, easy retrofit, and higher overall reliability.

Generally, any increase of network availability is expected to save costs. The worst imaginable scenario associated with uncontrolled line switching is a complete system outage due to unsuccessful energisation or auto-re-closing. In this respect, controlled switching can result in a small improvement in network availability (maybe <1%). The associated investment costs are negligible compared to the capital costs of the line and the potential losses incurred by an outage. Therefore, for most applications controlled switching can be recommended on this basis alone.

In EHV and UHV systems, where the insulation level is determined by the switching transients, controlled switching may reduce the switching overvoltages sufficiently to allow a more compact line design, provided the other practical challenges associated with such a design are solved. If feasible, this will not only reduce the capital investment for the towers but also increase the surge impedance loading, allowing transmission of more energy over the same line, providing savings at both construction and operation of the line.

Other benefits are of a mostly technical nature and are often difficult to quantify. Generally, the economical impact of controlled switching on any transmission line needs to be assessed individually on a case-by-case basis.

6.8 Summary

Table 13: Benefits of controlled switching of transmission lines.

Positive Effect on	**Economical Consequences on**	**Remarks**	**Applies to**	**Document Reference**
Line	Capital investment	• In EHV or UHV systems, the reduction of switching transients may allow a more compact line design.	C	6.3.1
	Increased power transmission capability	• Increased surge impedance loading of compact line design.	C	6.3.1
	Human safety	• Flashovers due to switching transients are eliminated.	C, O	6.5
Circuit breaker	Capital investment	• Elimination of closing resistors	C	6.2.1
	Failure risk	• The simpler design due to the elimination of closing resistor and auxiliary chambers directly reduces the failure risk.	C	6.2.1
		• Elimination of re-strikes.	O	6.2.2
		• Monitoring functions inherent in point-on-wave controller give information on the condition of the breaker.	C, O	6.2.1
	Maintenance costs	• Reduced maintenance costs due to the elimination of closing resistors and auxiliary chambers.	C	6.2.1
	Consequences of failure	• In-service failure of closing resistor is far more severe than that of a controller.	C	6.2.1
	Retrofit	• Costs for installation of a controller are lower than for modification of the primary equipment (e.g. adding closing resistors or surge arresters).	C, O	6.2.1
Power System	Increase of power quality and reliability	• Reduction of voltage and current transients during energisation, de-energisation (no re-strikes), and auto-re-closing.	C, O	6.4.1, 6.4.2
		• No unsuccessful re-closing.	C	6.4.1
	System stability	• For sensitive systems, system swing due to unsuccessful re-closing is prevented.	C	6.4.1
Other equipment	Capital investment	• Possibly lower energy rating for surge arresters.	C, O	6.5
	Expected lifetime of PTs and CTs	• Reduced dielectric stress on windings due to controlled switching.	C, O	6.5
	Expected lifetime of compensation reactors	• Reduced dielectric stress on reactor windings due to controlled switching.	C, O	6.5

7 Overall Conclusions

The preceding sections have explored in some detail the potential benefits of controlled switching for all of today's major switching cases. It has been shown that, for all cases, real benefits exist but that their scale is often dependent on a number of case specific factors.

The economic saving identified range from modest, readily identifiable costs (e.g. extended maintenance) through to speculative major cost avoidance in the event of certain rare circumstances (e.g. major supply disruptions). In almost all cases controlled switching involves an investment with the intention of avoiding a future cost where there is some probability that the cost saving will be achieved and an associated probability that it will not. For any user considering the adoption of a controlled switching solution, the accurate estimation of these probabilities on a case-specific basis is a key element in the decision. Having made this estimation, and in light of the relevant regulatory environment, it is intended that the information herein can provide valuable input data to a full, lifetime, economic assessment taking into account the nature of the installation (new or pre-existing), the acceptable level of residual risk, cost & availability of alternative solutions and the "value" of customer perception.

Finally it can be concluded that the largest potential savings are often those associated with rare but extreme events. This makes a case by case assessment essential for all but the most straightforward applications of controlled switching where the solution is already widely accepted.

8 References

Introduction, General Aspects

[1] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers – Guide for Application - Part 1”, *Electra* No. 183, April 1999, pp. 43-73.

[2] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers – Guide for Application - Part 2”, *Electra* No. 185, August 1999, pp. 37-57.

[3] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers – Planning, Specification and Testing of Controlled Switching Systems”, *Electra* No. 197, August 2001.

[4] Pons, A., A. Sabot. and G. Babusci; “Electrical Endurance and Reliability of Circuit Breakers - Common Experience and Practice of Two Utilities”, *IEEE Transactions on Power Delivery*, Vol. 8, No. 1, January 1993.

[5] IEC Document 17A/629/DTR, “Electrical Endurance Testing for Circuit Breakers Rated 72,5 and Above”, IEC draft document, 2000.

[6] CIGRE WG 13.08, “Life Management of Circuit Breakers”, CIGRE document 13-00 (WG08) 01 IWD, January 2000.

[7] CIGRE WG 13.09, “User Guide for the Application of Monitoring and Diagnostic Techniques for Switching Equipment for Rated Voltages of 72,5 and Above”, CIGRE document 13-00 (SC) 02 IWD, March 2000.

Shunt capacitor banks

[8] [1] Filion, Y., Coutu and R. Isbister, “Experience with Controlled Switching System used for Shunt Capacitor Banks: Planning, Studies and Testing According with CIGRE Guidelines (WG 13.07)”, Publication details to be confirmed.

[9] CIGRE WG 13.04, “Shunt Capacitor Bank Switching, Stresses and Test Methods - 2nd Part”, No. 183, pp. 13-41, April 1999.

[10] Reed and Cichanowski, “The Fundamentals of Ageing in HV Polymer-film Capacitors”, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 1 No. 5 October 1994.

[11] Eriksson, Esbjörn, “On the use of Fuses or Fuseless Design Concepts for Protection of Modern Power Capacitors”, Capacitor Subcommittee Panel Session, IEEE Summer Meeting, 1997.

[12] McGranaghan, M.F, R.M. Zavadil, G. Hernsley, T. Singh and M. Samotyj, “Impact of Utility Switched Capacitors on Customer Systems – Magnification at Low voltage Capacitors”, *IEEE Transactions on Power Delivery*, Vol. 7, No. 2, pp. 862-868, April 1992.

[13] Jones and Forston, “Consideration of phase-to-phase Surges in the Application of Capacitor Banks”, *IEEE Transactions on Power Delivery*, Vol. PWRD-1, No. 3, July 1986.

[14] Beaulieu et al., “Power Quality Indices and Objectives”, working documents of CIGRE WG 36-07.

[15] Stanek et al., “Experiences with Improving Power Quality by Controlled Switching”, 13/14/36-01 Session CIGRE 2000.

Transformers

[16] CIGRE WG A3.07, “Controlled Switching of HVAC Circuit Breakers – Guide for New Applications” Publication details to be confirmed.

[17] Steurer, M. and K. Fröhlich, “The Impact of Inrush Currents on the Mechanical Stress of High Voltage Power Transformer Coils”, *IEEE Transactions on Power Delivery*, Vol. 17, No. 1, pp. 155-160, January 2002.

[18] CIGRE WG 12.04, “Calculation of Short-Circuit Forces in Transformers”, *Electra* No. 67, pp. 29-75, December 1979.

[19] Adly, “Computation of Inrush Current Forces on Transformer Windings”, *IEEE Transactions on Magnetics*, Vol. 37, No. 4, “, July 2001.

[20] Elmore, W.A., “Protective Relaying, Theory and Applications”, Marcel Dekker, New York, 1994

[21] CIGRE WG 12.05, “An international survey on failures in large power transformers in service”, *Electra* No. 88, pp. 21-48, May 1983.

[22] Jarman, Lapworth and Wilson, “Life Assessment of 275 and 400 kV Transmission Transformers”, *Proceedings 64th Annual International Conference of Doble Clients*, Section 8-6, 1997.

[23] Maleski, Douville and Lavallée, “Measurement of switching transients 735-kV substations and assessment of their severity for transformer insulation”, *IEEE Transactions on Power Delivery*, Vol. 3, No. 4, October 1988, pp. 1380-1387.

[24] CIGRE WG 12.03, “Considerations about the Impulse Test Procedure for Power Transformers”, *Electra* No. 55, pp. 5-23, December 1977.

[25] CIGRE WG 12.09, “Lifetime Evaluation of Transformers, (Thermal Aspects of transformers)”, *Electra* No. 155, October 1993.

[26] CIGRE WG 34.01, “Transformer Over-Fluxing Protection”, *Electra* No. 31, pp. 65-73, December 1973.

[27] Picher, Bolduc, Dutil and Pham, “Study of the Acceptable DC Current Limit in Core-Form Power Transformers”, *IEEE Transactions on Power Delivery*, Vol. 12, No. 1, January 1997.

[28] EPRI, The cost of power disturbances to industrial & digital economy companies, June 29 2001

[29] Franchek and Woodcock , “Life-cycle considerations of loading transformers above nameplate rating”, *Proceedings 65th Annual International Conference of Doble Clients*, Section 8-10, 1998.

[30] Guuinicand Aubin, “CIGRE’s Work on Power Transformers”, *IX EPRI Substation Equipment Diagnostics Conference*, New Orleans, February 18-21, 2001.

[31] CIGRE TF 38.01.03, “Planning Against Voltage Collapse”, *Electra* No. 111, March 1987.

[32] CIGRE WG 13.02, “Interruption of Small Inductive Currents: Switching of Unloaded Transformers, Part 1: Basic Theory and Single-Phase Transformer Interruption without Re-ignitions”, *Electra* No. 133, pp. 79-107, December 1990.

[33] CIGRE WG 13.02, “Interruption of Small Inductive Currents: Switching of Unloaded Transformers, Part 2: Three-Phase Transformer Interruption, Re-ignition Phenomena, Test Results and Conclusions”, *Electra* No. 134, pp.2-44, February 1991.

[34] CIGRE WG 13.02, “Interruption of small inductive currents, Chapter 6: switching of reactor-loaded transformers”, *Electra* No. 138, October 1991.

[35] CIGRE TF 38.02.10, “Modelling of Voltage Collapse Including Dynamic Phenomena”, *Electra* No 147, April 1993.

[36] IEEE Standard C57.91-1995.

[37] Klwerk, Minhas and Reynders, “Failures in power system transformers and appropriate monitoring techniques”, *International Symposium on High Voltage Engineering*, ISH99, August 1999

[38] CEA (Canadian Electricity Association), “Characteristics of Stress on Transformer Insulation Subjected to Very-Fast Transient Voltages”, Report 253T784, Ontario Hydro Technologies, July 1998.

[39] Wagenaar, L.B., J.M. Schneider and J.A. Fleeman, “EHV Transformer Dielectric Specification Improvements”, *IEEE Transactions on Power Delivery*, Vol. 9, No. 1, pp. 265-284, January 1994.

Transmission lines

[40] CIGRE WG 13.04, “Capacitive current switching—State of the art.” ELECTRA, No. 155, August 1994, pp. 33-63.

[41] K. Fröhlich et al., “Transmission Line Controlled Switching.” Paper presented at Canadian Electrical Association conference, Vancouver, Canada, March 1995.

[42] IEC 61071-1, “Insulation co-ordination—Part 1: Definitions, principles, and rules”, 1996.

[43] IEC 62271-100, “High-voltage switchgear and controlgear—Part 100: High-voltage alternating-current circuit breakers”, 2001.

[44] CIGRE TF 13.00.1, “Controlled Switching—A State-of-the-art Survey.” Part 1, ELECTRA, No. 162, October 1995, pp. 65-97. Part 2, ELECTRA, No. 164, February 1996, pp. 39-61.

[45] Fröhlich et al., “Controlled Closing on Shunt Compensated Transmission Lines. Part I: Closing Control Device Development. Part II: Application of Closing Control Device for High-Speed Autore-closing on BC Hydro 500 kV Transmission Line.” IEEE Transactions on Power Delivery, Vol. 12, No. 2, April 1997, pp. 734-746.

[46] A.C. Legate et al., “Elimination of Closing Resistors on EHV Circuit Breakers.” IEEE Transactions on Power Delivery, Vol. 3, No. 1, January 1988, pp. 223-231.

[47] U. Krüsi, K. Fröhlich, “Model Based Determination of Circuit Breaker Characteristic for Controlled Switching.” Proceedings of IASTED int. Conf. on Modelling, Identification and Control, Innsbruck, Austria, February 2001, Paper No. 324-131, pp. 931-936.

[48] J.K. Bladow, T.L. Weaver, “Switching Surge Control for the 500 kV California-Oregon Transmission Project.” CIGRÉ Session 1990, paper No. 13-304.

[49] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit Breakers. Planning, Specification, and Testing of Controlled Switching Systems.” ELECTRA, No. 197, August 2001.

[50] . Stanek et al., “Experiences with Improving Power Quality by Controlled Switching.” CIGRE Session 2000, paper No. 13/14/36-01.

[51] H.P. St.Clair, “Practical Concepts in Capability and Performance of Transmission Lines.” AIEE Transactions on Power Apparatus and Systems, Paper No. 53-338, pp. 1152-1157, Dec. 1953.

[52] R.D. Dunlop, R, Gutman, P.P. Marchenko, “Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines.” IEEE Transaction on Power Apparatus and Systems, Vol. PAS-98, pp. 606-617, March/April 1979.

[53] E. Friedlander, C.J.O. Garrard, “Long Distance Power Transmission by Alternating Current.” Engineering, January 1942.

[54] B. Khodabakhchian, S. Breault, E. Portales, H. Huynh, Y. Hotte, “TRV and the Non-Zero Crossing Phenomenon in Hydro-Québec’s Projected 735 kV Series Compensated System.” CIGRE Session 1992, paper No. 13-303.