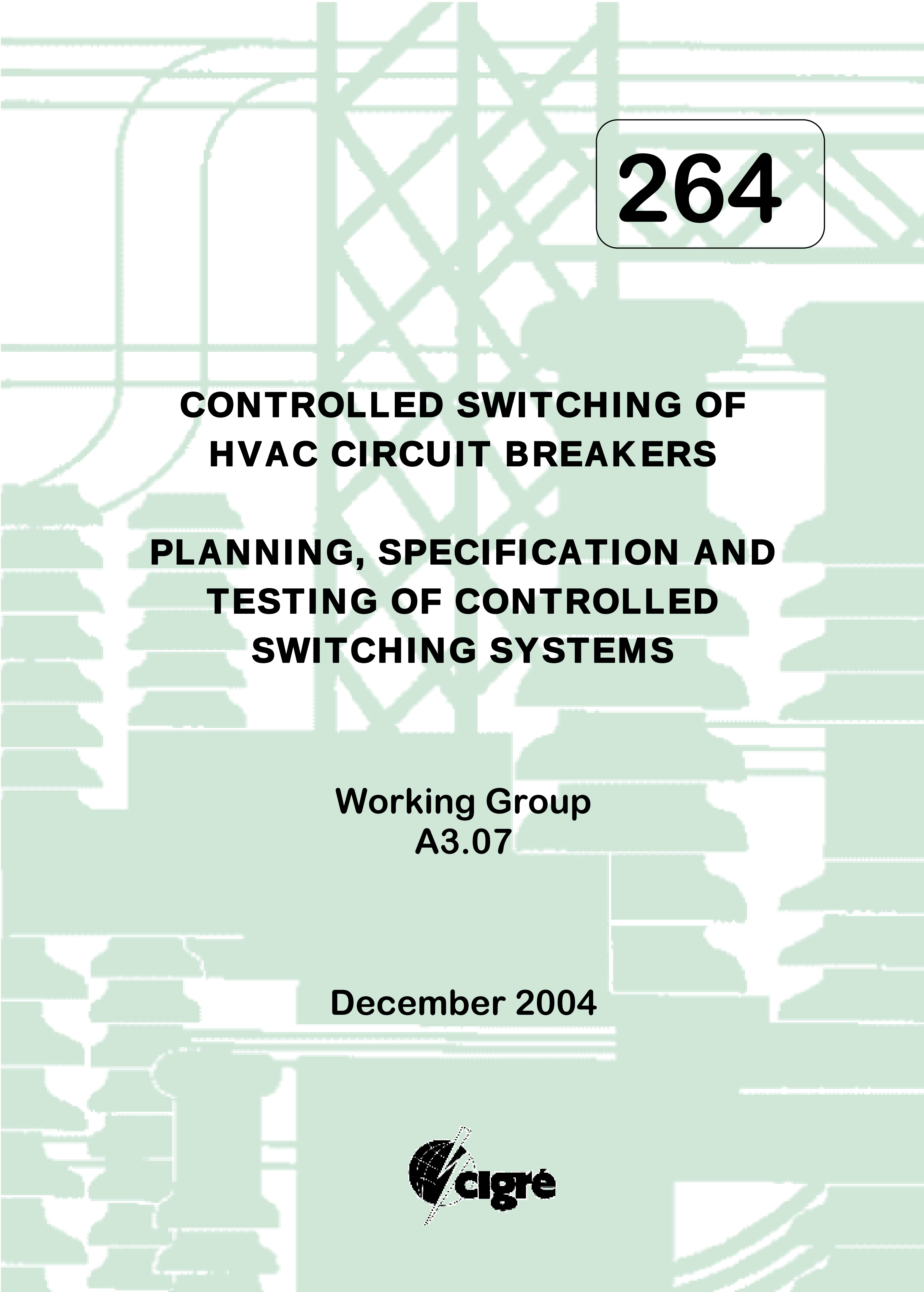

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CONTROLLED SWITCHING OF HVAC CIRCUIT BREAKERS

PLANNING, SPECIFICATION AND TESTING OF CONTROLLED SWITCHING SYSTEMS

Working Group
A3.07

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cigré

CONTROLLED SWITCHING OF HVAC CIRCUIT BREAKERS

Planning, Specification and Testing Of Controlled Switching Systems

CIGRÉ Working Group A3.07

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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 *"Controlled Switching of HVAC Circuit-breakers- Planning, Specification & Testing of Controlled switching systems".*

1 Introduction

Uncontrolled switching of reactive elements may create electrical transients which cause equipment damage and system disturbances. Controlling the point in the electrical cycle at which switching takes place is now a possible method for minimising these negative effects. This document gives guidance to the user on how to approach controlled switching projects and, in particular, how to study, specify and test the circuit-breaker and controller system.

In 1999 CIGRE Working Group 13.07 published an application guide [1] which explains the basics of controlled switching and which should assist users and manufacturers to assess the effectiveness of controlled switching. System applications as well as the necessary characteristics of the circuit-breaker were discussed in this document. The type of the circuit-breaker and the design of the controller were not specifically examined but it was assumed that both circuit-breakers and controllers with adequate capabilities were readily available and would not present any practical limitations.

In this document more practical issues are covered. The second chapter introduces the user to the range of issues requiring consideration prior to the introduction of controlled switching into the power system. Guidance is given on information to be gathered and studies to be performed in order for the user to specify the circuit-breaker - controller system correctly. Initial planning questions such as "Is controlled switching the most efficient way or are alternative methods more cost effective?" are introduced to assist the reader in asking the right questions and making the best choice for any application. More specific questions related to successfully implementing controlled switching are also introduced in this chapter.

In the third chapter recommendations for the specification of a controller-breaker system are presented. The approach followed for this task is to consider the controller-breaker system as a modular structure with separate components which are not necessarily provided by the same supplier. For example, the circuit-breaker (or the controller) might already exist. The hierarchy of responsibility for provision of the various parts of a controlled switching system (CSS) in which there is considerable interrelation between the components is discussed in some detail. Subsidiary issues needing consideration such as the interfaces between the controller and the auxiliary systems of a substation are also introduced.

The fourth chapter is dedicated to suggestions for type testing of CSS components and finally the integrated system. Here again the presentation takes account of the most demanding situation where components are obtained from different sources and where integration issues are the responsibility of the user. Only those requirements not appropriately covered by existing standards applicable to the various components are discussed in detail. The existing standards of importance are referenced where helpful for clarity but these references should not be taken as comprehensive. Detailed guidance on difficult issues such as determining the circuit-breaker characteristics is offered.

The document concludes with complete system performance checks and commissioning tests.

2 Study Requirements

2.1 Understanding the problem

This chapter outlines the issues that need to be studied when considering and implementing a controlled switching installation, however, due to the complexity of the subject this must be considered a general guide only. The general nature of problems experienced due to uncontrolled switching is summarised in the following:

Uncontrolled switching of shunt reactors, transformers or capacitors often causes transient phenomena such as very fast voltage transients or high currents with resulting electrical and mechanical stresses sometimes leading to equipment failure.

The high frequency, high current transients, associated with uncontrolled energisation of capacitors can inductively couple voltage transients into control equipment and protective relays via the switchyard cabling. These transients may cause mis-operation or failure of the control equipment.

Similarly the high current transients associated with uncontrolled energisation of capacitors or transformers can cause voltage sags and harmonics on the primary system which can create problems with power system equipment and customer processes. In deregulated markets improving the power quality at the source with controlled switching can be an economic benefit both for the energy producer and for the consumer.

Energising or, more importantly, re-energising (re-closing) a transmission line with a trapped electrical charge may result in excessive electrical stress when the travelling wave from energisation is reflected at the remote end of the line. This may over-stress the air gaps between the conductor and the transmission tower structure leading to flashover and failure to successfully energise the line.

2.2 Alternatives

Reactive element switching has occurred in power systems for many years and numerous methods have been devised to overcome or eliminate the associated problems. Controlled switching has been known to be a theoretical possibility for a long time [1], [6] but has been made practical only recently by improving circuit-breaker designs and digital control techniques. The addition of an electronic controller should be far less costly than modifying the primary system but, before adopting controlled switching as a method of avoiding or overcoming problems, the system planner should review the conventional methods in order to establish the comparative economics. The general nature of the problems together with possible solutions are summarised in Section 2.7.

2.2.1 Modification of the primary system to reduce the transients

Eliminating the transients requires that the source of switching transients be addressed. Conventional solutions include:

- closing resistors on EHV circuit-breakers to control the voltage transient associated with energising (particularly re-closing) long lines
- circuit-breaker pre-insertion resistors for reactor and capacitor switching
- circuit-breaker opening resistors for shunt reactor switching
- inrush (and outrush) control reactors for capacitor energisation
- circuit-breaker pre-insertion reactors for capacitor switching
- selecting a specific type of circuit-breaker
- surge arresters for limiting the voltage transients.

In principle, all primary side solutions incur significant costs and may reduce the overall primary system reliability.

2.2.2 Strengthen the primary system to withstand the transients

Withstanding the imposed stresses requires that system components susceptible to damage or mis-operation be configured for greater strength.

The conventional approach is to design the system components, such as capacitor banks, transformers, and circuit-breakers, to withstand the voltage and current transients associated with frequent occurrence of worst case switching phenomena. For example,

- transformer winding ability to withstand repeated inrush (mechanical and electrical stresses)
- capacitor bank current transformer secondary voltage withstand
- selecting a circuit-breaker not susceptible to damage from high making current transients
- design transformers at remote stations with adequate insulation or voltage protection measures to resist damage from the phase-to-phase travelling wave voltage transients associated with capacitor switching without other means of transient reduction.

However, strengthening the primary system does not overcome power quality issues that may accompany uncontrolled switching.

2.2.3 Modify control systems

Conventionally, power system control circuits are designed to resist transients originating in the primary system by using shielding and voltage suppression. Arcing during operation of disconnectors is a common source of such transients. Control systems designed to withstand these transients are unlikely to experience problems from uncontrolled switching of reactive elements (These requirements are clearly indicated in international standards like IEC and ANSI, see Appendix A.). However, there are special cases where problems may occur. The long duration offset transient associated with shunt reactor energisation may saturate current transformers or power transformer cores and lead to undesired protective relay mis-operation [1]. Similarly, the very high current inrush current to a capacitor bank and the associated harmonics may cause overvoltages in the secondary measuring circuits or lead to protection mis-operations. These problems have traditionally required solutions such as transient suppression, increased reaction time or reduced sensitivity of the protection equipment.

2.3 Study issues

This section outlines in general terms the issues that need to be addressed when considering the use of controlled switching.

2.3.1 Power system configuration

It is assumed that, as a starting point, the following issues have been addressed:

- Power system configuration is defined
- Location of switched element in the system is determined
- Switching arrangement is determined (busbar configuration)
- Basic network studies are completed.

Numerous busbar configurations can be used: “straight bus-radial circuit-breaker”, “circuit-breaker and a half ”, “ring bus” etc. In those configurations where two circuit-breakers redundantly connect the circuit element to be switched, there will be some complications introduced into the control arrangement. For example,

- If it is to be possible for both circuit-breakers to be used to energise the circuit element, a decision must be made whether to equip both for controlled closing or whether to use a single controller arranged to control the selected circuit-breaker.
- A circuit-breaker in a ring configuration, for example, may be used to switch a different reactive element on either side and the requirements may conflict. The control design will have to be selective enough to accommodate these two operating modes for the single device.
- In some configurations the same circuit-breaker may be used to switch different elements such as a line and a transformer. The controlled switching strategy may be different depending on the element switched.

2.3.2 Defining the need

The application of controlled switching requires a significant increase in the precision of control compared to conventional circuit-breaker operation. This increase requires that many issues and parameters, previously of little consequence, be evaluated or quantified. Key among these are the precision of contact operation and dielectric characteristics of the circuit-breaker. Factors such as the station configuration, and the location and characteristics of instrument transformers are also of importance.

The depth to which studies must progress is a function of the switched load. For instance, energising a capacitor, will require a circuit-breaker that will close at or near a voltage zero with high precision and hence the influence of environmental and control energy variables will need to be investigated carefully. Energising a shunt reactor at a voltage peak requires less precision but this may still exceed the repeatability of an older circuit-breaker design meaning that the same issues must be studied but not necessarily to the same level of precision. Figure 2-1 and Figure 2-2 (from [1]) illustrate the two situations of switching at voltage zero and voltage peak as well as the influence of variations in circuit-breaker operating times.

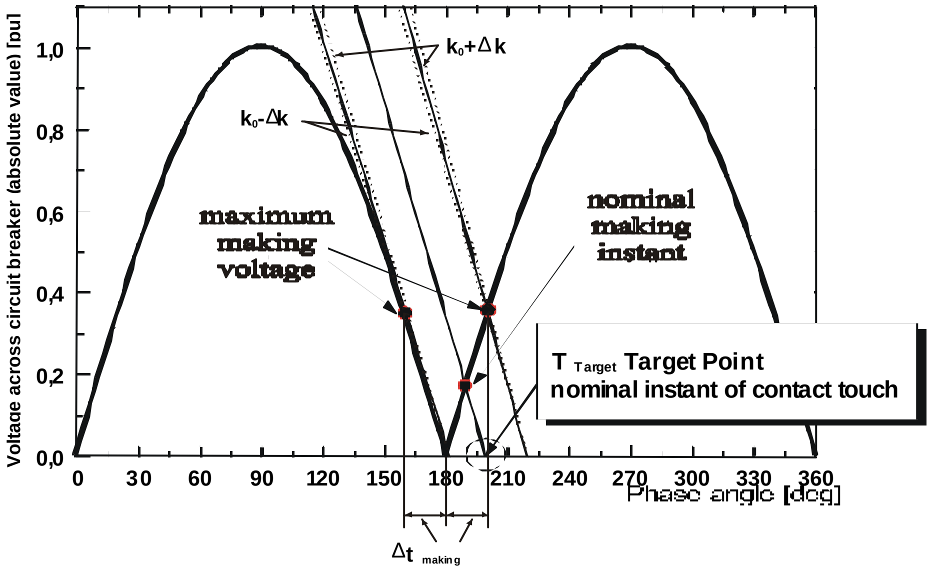


Figure 2-1 Pre-strike characteristic and influence of mechanical and electrical variations for voltage zero target

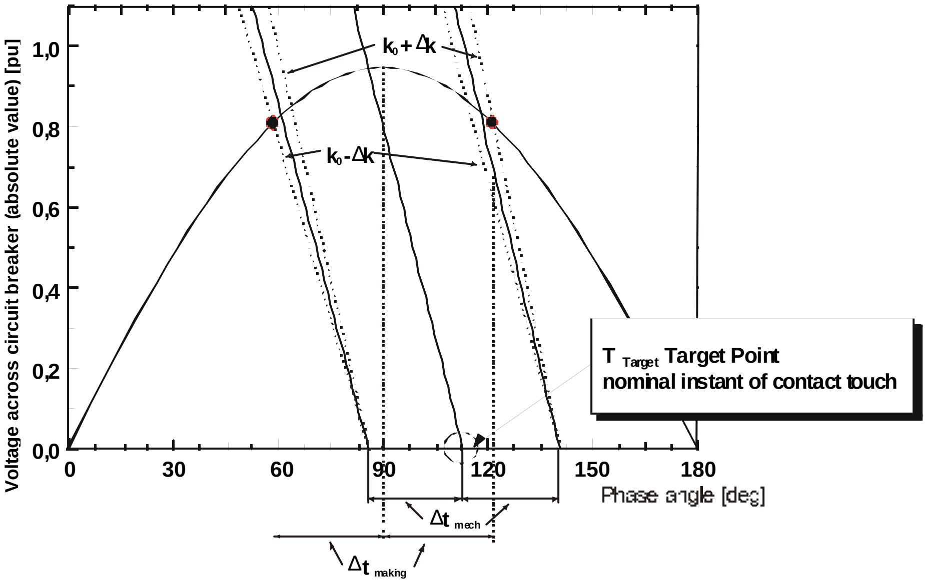


Figure 2-2 Pre-strike characteristic and influence of mechanical and electrical variations for voltage peak target

Key to figure abbreviations:

k_0	*normalised value of the rate of decrease of dielectric strength, RDDS*
Δk	*RDDS variations*
Δt_{making}	*making time window*
Δt_{mech}	*mechanical variation around target point*

Network studies of switching operations (EMTP or equivalent) will be required to define the switching window illustrated in the foregoing diagrams, taking into account the statistical behaviour of the circuit-breaker and variations in network topology.

2.3.3 Circuit-breaker characteristics

First it is necessary to identify the requirements placed on circuit-breaker performance for the specific application. Guidance is given in [1].

The circuit-breaker is the key component for controlled switching and determining whether it is suitable for the proposed task is a critical issue. Figure 2-3 illustrates the circuit-breaker selection process.

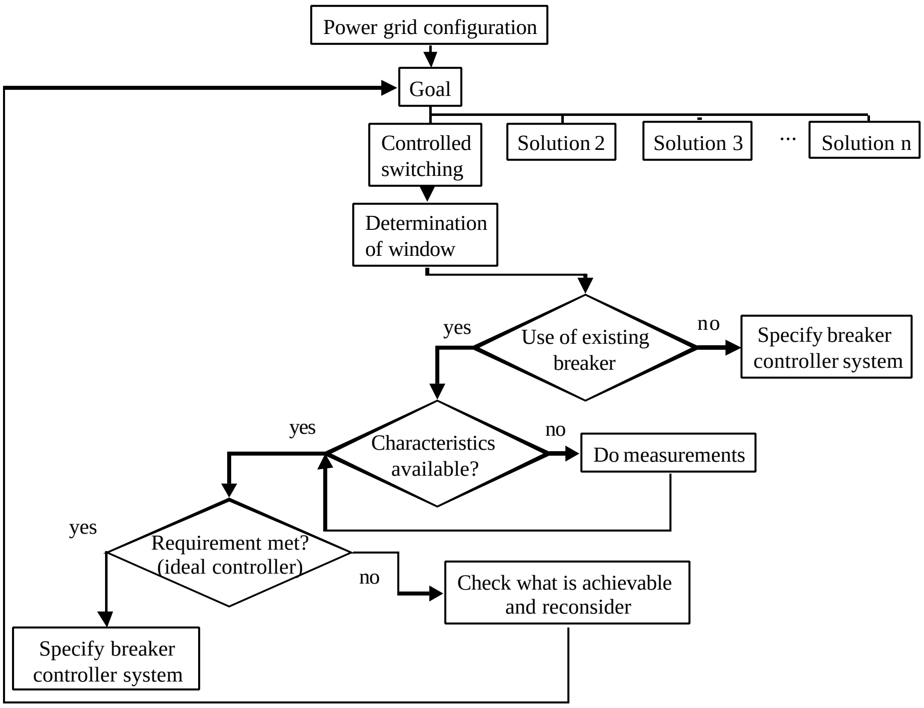


Figure 2-3 Flow chart for selection of the circuit-breaker

Questions about the circuit-breaker characteristics that should be answered include :

- How fast does the rate of decrease of dielectric strength (RDDS) have to be in order to accomplish the objective?
- Does the statistical behaviour of the pre-strike characteristic have a sufficiently small scatter?
- Are the opening characteristics (re-ignition) of the CB suitable for the imposed duty?
- If the RDDS is high enough, is the operating mechanism sufficiently stable throughout the range of operating energy and environmental variables that it will consistently provide adequate service?
- Is the statistical scatter of the operating times sufficiently low over the specified range of operating conditions to ensure the switching objectives?
- Is independent pole control available or, if not, is there the flexibility to adjust the second and third poles mechanically to close or open at the appropriate time?

- What variables that may cause variations in the circuit-breaker operating times have a systematic relationship such that they can be compensated by the controller (e.g. ambient temperature, operating energy, control voltage)?
- Is there an “idle time” issue for operation after a long period of quiescence?
- Is the maintenance plan adequate to maintain the required characteristics?
- Is it possible that the drift of operating times with service time and number of operations will necessitate an adaptive controller? If so, how will the controller determine the required adjustment?

For new installations, most of the foregoing are defined at the specification stage (Section 3.6.1). For existing installations the information can be obtained from the original supplier or, in the absence of this source, must be determined by test.

2.3.4 Voltage and current signals needed for controlled switching

The station configuration will have to provide adequate voltage and current reference signals needed for controlled switching. For optimum re-closing on shunt compensated lines it will probably be necessary to measure the line voltage for comparison with the busbar voltage thereby requiring potential transformers suitably located on both sides of the circuit-breaker. In this case the line side potential transformer will need to be capable of correctly measuring a resonant voltage with a characteristic frequency of a fraction of the power system fundamental.

2.4 Controller and secondary circuit issues

The control equipment must integrate into the substation control system where many practices are often unique to individual users. Issues to consider are:

- location of controlled switching functionality (e.g. stand-alone device, integrated digital control)
- location of stand-alone controller: circuit-breaker control cubicle or station control room
- range of DC power supply variation, particularly if located at the circuit-breaker where the allowable range is greater than in the control room
- integration with the circuit-breaker control scheme
- for which variables does the controller need to compensate the circuit-breaker operating times (cf. 2.3.3)
- does the controller need to be adaptive for operating time drift with age and number of operations? How is this function to be reset with maintenance?
- action on detection of an internal fault or loss of signal
- obtaining transformer residual flux condition
- obtaining voltage across the circuit-breaker for line re-energisation application

2.5 Failure consequence

A key study issue is the consequence of failure to operate within the specified time window. There are two significant possibilities:

1. The circuit-breaker operating times drift away from their normal values. (The consequence of drift may be worse than random operation.)
2. The controller fails to respond due to an internal problem.

The answers to these issues will be installation specific because some installations will not be tolerant of failures whereas others are designed to be tolerant.

2.6 Performance monitoring

Ongoing performance checking of a controlled switching installation may require recording equipment with a frequency response higher than that of normal fault recording equipment in the substation. The provision of this high resolution monitoring system needs to be considered if failure of the controlled switching has significant consequences. The monitoring may be a function of the controller and should be accessible to the user.

2.7 Application specific issues

In this section the specific issues, optional alternatives, risks/consequences, and study issues for the power system elements for which controlled switching is presently viable are summarised.

Each of the following subsections features a diagram of problems, consequences, and possible solutions which should be read as follows:

1. Identify the most important problem to be addressed.
2. Follow the paths emerging from the problem leading to the corresponding consequences.
3. Select the most problematic consequence for the specific application.
4. Proceed to the vertical line associated with that consequence.
5. Check all possible solutions that are connected with that line by an arrow. Cross off all other possible solutions.
6. If desired, repeat steps 2…5 for the next most problematic consequence(s).
7. If desired, repeat steps 1…6 for the next most important problem.
8. The result is a list of the technically optimum solutions for the problems associated with the application. From this list the user can choose the preferred solution.

2.7.1 Shunt capacitor switching

Uncontrolled high amplitude, high frequency inrush currents may stress capacitor bank components, couple into control circuits, propagate to remote stations as potentially damaging voltage transients and cause power quality problems. The issues and options associated with capacitor switching are summarised below.

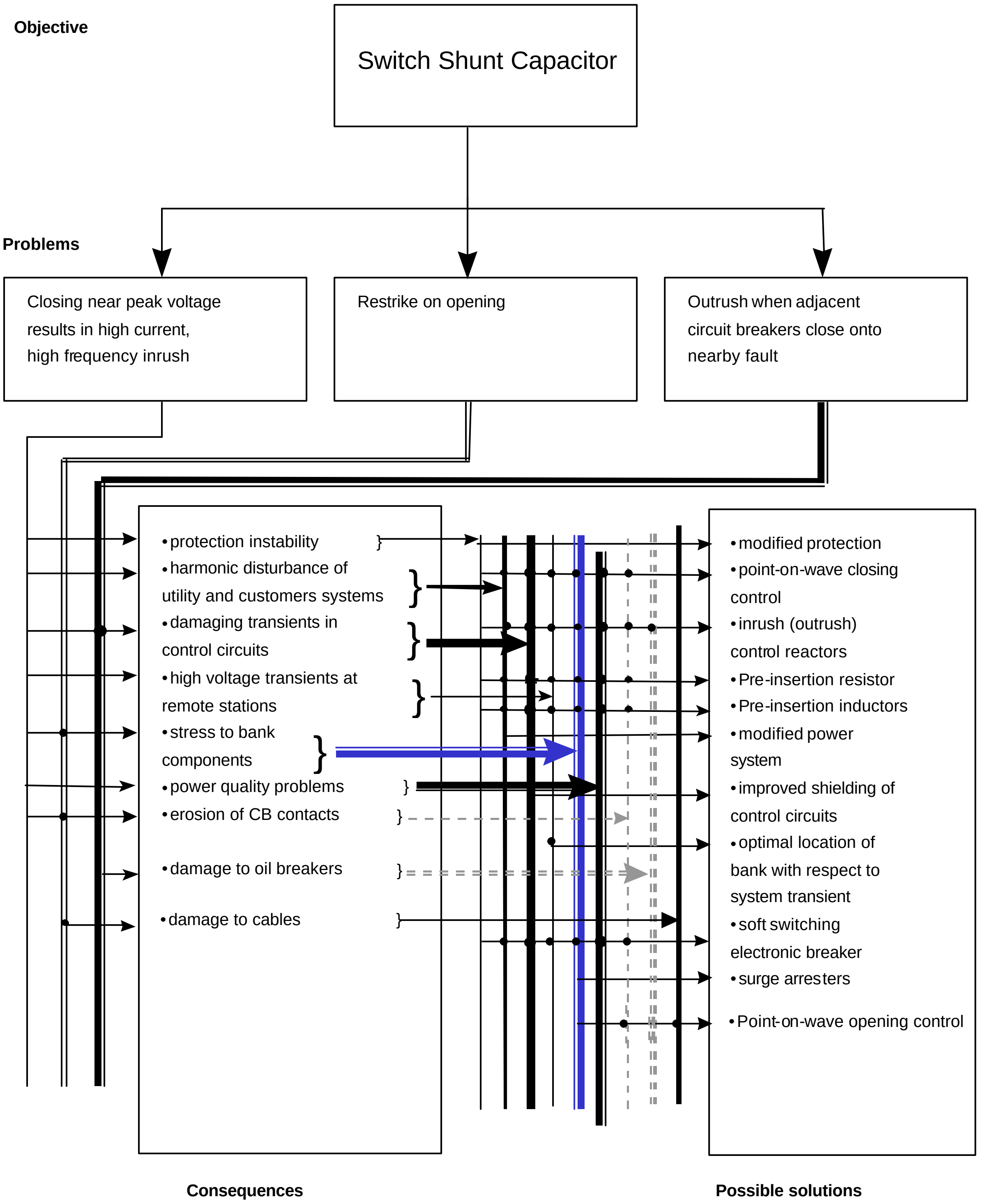


Figure 2-4 Consequences of failure and possible solutions for shunt capacitor switching

Table 2-1 Studies issues for shunt capacitor switching

Solution	**Risk/Consequences**	**Study Issues**
Modified protection	Difficult to identify protection problems in advance and define adequate mitigation measures. Protection selectivity might deteriorate.	a) Desensitizing to avoid mis-operation may reduce needed fault or unbalance detection capability b) Protection changes may prevent undesired mis-operation but they do not solve some of the other system disturbance problems
Modified power system	Changes are costly	Investigate natural frequencies of power system for alternative capacitor bank locations. Avoid fifth harmonic.
Point-on-wave closing control	Moderate cost but risk that control system will not function correctly over a long period of time (Section 2.5)	Refer to sections 2.3.2 and 2.4 for identification of the study issues. Also Study issues of Subsection 2.7.2
Inrush (outrush) control reactors	Provide a high level of transient control but at significant cost. Impact upon rating of capacitor bank.	a) Reactor ratings: • Impedance • voltage impulse rating b) Impact on rating of capacitor bank c) Physical location d) Cost e) Avoidance of creating a circuit tuned to an inopportune harmonic
Pre-insertion resistors	Increases complexity and cost of circuit-breaker	Availability for MV circuit-breakers, resistance value, insertion times, energy capability
Pre-insertion inductors	Increases complexity and cost of circuit-breaker	Availability for MV circuit-breakers, impedance value, insertion times, energy capability
Improved shielding of control circuits	Good practice in any case but better to control significant problems at source	
Optimal location of bank with respect to system transients	Can reduce transients but may be difficult to achieve in an interconnected system	Investigate natural frequencies of power system for alternative capacitor banks locations. Avoid fifth harmonic.
Soft switching electronic circuit-breaker	Possible solution not yet commercial and possibly expensive	Availability of suitable capability
Surge arresters		Arrester location, voltage and energy requirements
Point on wave opening control	Moderate cost but risk that control system will not function correctly over a long period of time	Refer to Section 2.4 for identification of the study issues.

2.7.2 Unloaded line switching

The energisation voltage transient propagates to the remote end of the line, reflects, doubles and may cause the voltage to exceed the air gap withstand capability, causing a flashover. The issues and options associated with unloaded line switching are summarised below.

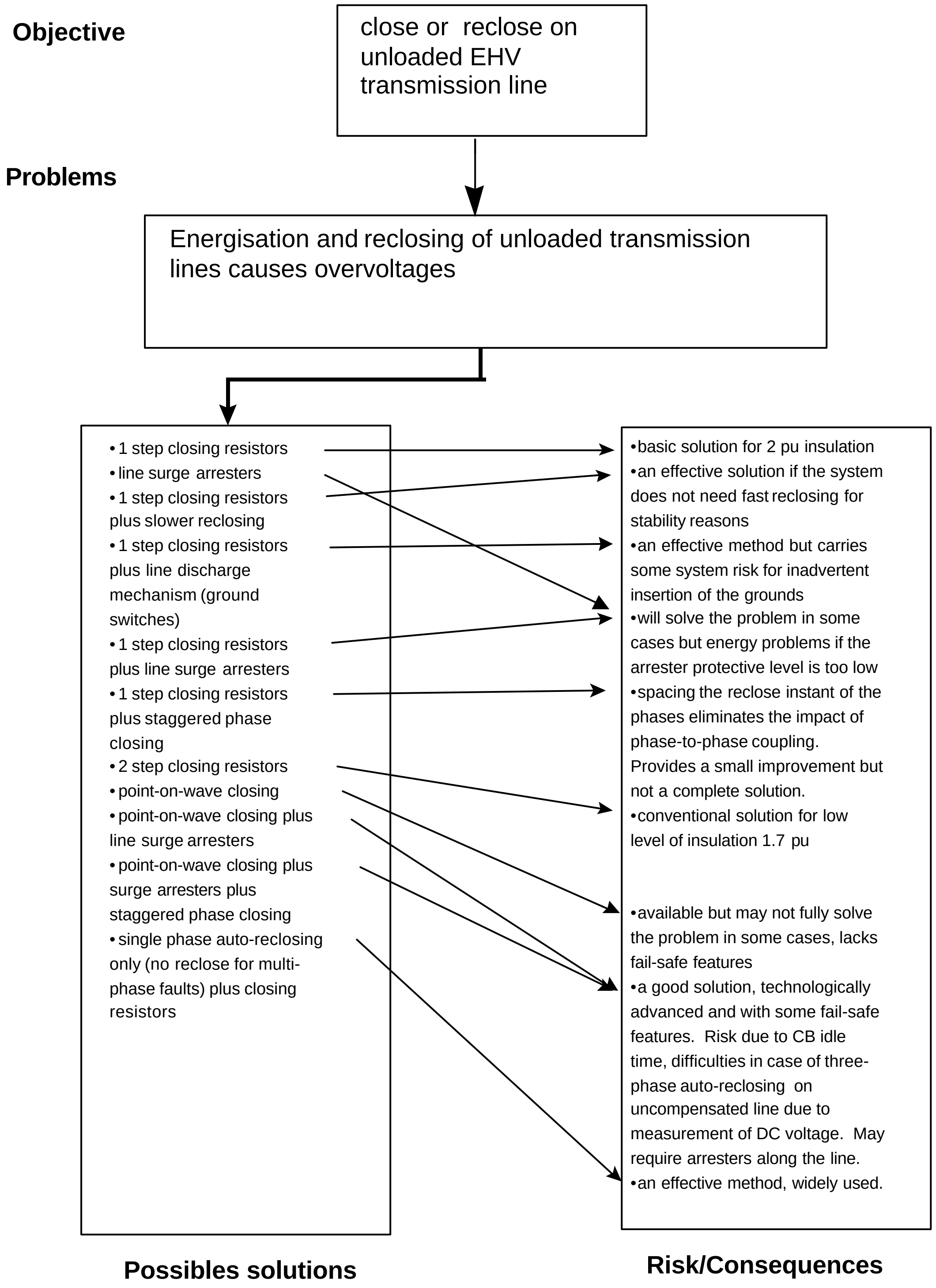


Figure 2-5 Consequences of failure and possible solutions for transmission line switching

Table 2-2 Study Issues for line switching

Point-on-wave control:

a) Suitability of existing CB for point-on-wave control
  - suitable mechanism speed and dielectric capability (RDDS)
  - statistical behaviour of pre-strike
  - stable operating time over range of control energy
  - stable operating time over range of ambient temperature
  - capability to mechanically stagger phases
  - stable operating time over range of operating energy
  - range of random scatter of operating mechanism
  - operating time ‘idle time’ sensitivity characteristics
  - sufficiently high RDDS of the circuit-breaker down to lockout gas pressure
  - statistical EMTP simulations of switching overvoltages in the system

b) Suitability of busbar configuration
  - potential transformers adequately located
  - ring busbar or other multiple circuit-breaker arrangement compatible with control needs

c) Suitability of line side potential transformer (for re-closing only)
  - correct measurement of natural frequency of shunt compensated line during re-close interval

d) Control circuit issues
  - controller ability to synchronize to the complex voltage signal across CB due to oscillation of a shunt compensated line
  - controller fail-safe requirements
  - location of stand-alone controller: CB control cubicle or control room
  - remote control interrogation features and software
  - compatibility for anti-pumping, coil supervision, etc.
  - total minimum and maximum control delay and phase discrepancy
  - how to deal with single-pole and three-pole reclosing
  - impact of inter-phase coupling on control for following phases
  - acceptable range of auxiliary supply variation
  - control signal input requirements
  - ability to work with equipment as complex as the required controller
  - need for adaptive control to track drift in the circuit-breaker operating characteristics

e) Testing and maintenance

- ability to confirm the required performance during a commissioning test
- ability to maintain the equipment, particularly the circuit-breaker, in a sufficient operating state to achieve the desired performance

Line surge arresters

a) Standard or special ratings
  - energy requirement for multiple re-close operations
  - suitable MCOV for open ended line conditions
  - energy requirements for temporary overvoltages

b) Need for mid-line arresters
  - suitable site

CB closing resistors

a) Resistance value

b) Insertion time

c) Energy requirements

2.7.3 Shunt reactor switching

Energisation at a voltage peak may cause a long duration dc offset component within the inrush current which in turn causes current and power transformer core saturation. Uncontrolled de-energisation may result in circuit-breaker re-ignition and the possibility of damage to the circuit-breaker interrupter or the reactor. The issues and options associated with reactor switching are summarised below.

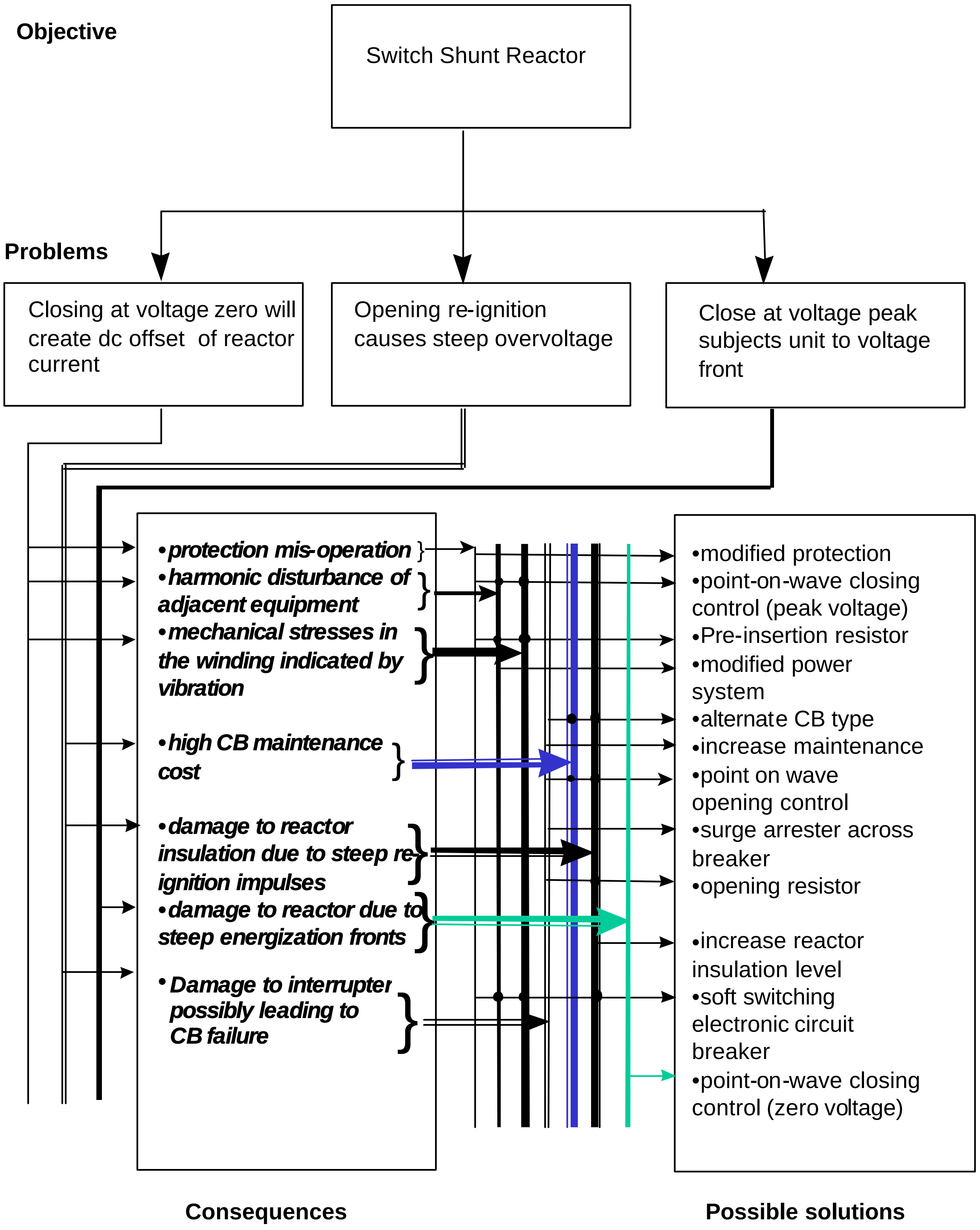


Figure 2-6 Consequences of failure and possible solutions for shunt reactor switching

Table 2-3 Study issues for shunt reactor switching

Options	**Risk/Consequences**	**Study Issues**
Modified protection	Difficult to identify in advance protection problems and define adequate mitigation measures. Protection selectivity might deteriorate.	a) Desensitizing to avoid mis-operation may reduce needed fault or unbalance detection capability b) Protection changes may prevent undesired mis-operation but they do not solve some of the other system disturbance problems
Modified power system	Analysis of power system problems uncertain as this requires representation of non-linear magnetic circuits. Changes are costly	
Point-on-wave closing control	Moderate cost but risk that control system will not function correctly over a long period of time	Refer to Sections 2.3.2 and 2.4 for identification of the study issues. Also Study issues of Subsection 2.7.2.
Point-on-wave opening control	Moderate cost but risk that control system will not function correctly over a long period of time	Refer to Section 2.4 for identification of the study issues. Also Study issues of Subsection 2.7.2.
Pre-insertion resistor	Increases complexity and cost of circuit-breaker	Availability for MV circuit-breakers, resistance value, insertion times and energy capability
Opening resistor	Increases complexity and cost of circuit-breaker	Availability for MV circuit-breakers, resistance value, insertion times and energy capability
Alternate CB type		Cost & availability
Increased CB maintenance	Cost of interrupter maintenance	Probability of failure in spite of extra maintenance
Soft switching electronic circuit-circuit-breaker	A possible solution not yet commercial and possibly expensive	Availability of suitable capability
Surge arrester across circuit-breaker		Rating and mechanical mounting arrangement
Shunt surge arrester		Effectiveness of shunt surge arrester to protect against fast front surges
Increase reactor insulation level	Cost	What level of insulation is required to resist damage from restrike wavefront

2.7.4 Transformer switching

High amplitude inrush current may stress the transformer windings make protective relays mis-operate and causing power quality problems. The issues and options associated with transformer switching are summarised below.

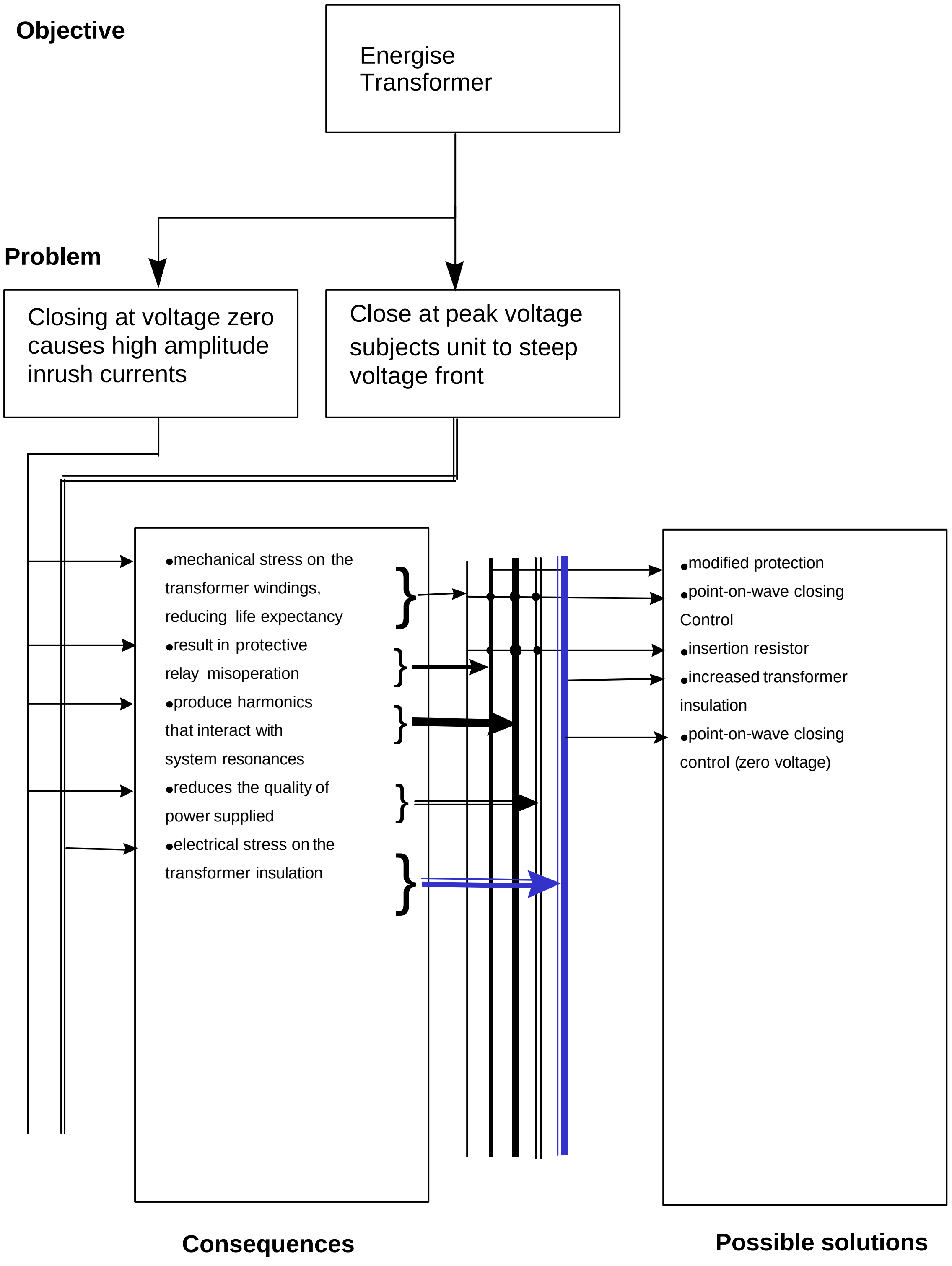


Figure 2-7 Consequences of failure and possible solutions for transformer switching

Table 2-4 Study issues for transformer switching

Options	Risk/Consequences	Study Issues
modified protection	difficult to identify protection problems in advance and to define adequate mitigation measures due to complexity of non-linear magnetic circuits	a) desensitizing to avoid mis-operation may reduce needed fault or unbalance detection capability b) protection changes may prevent undesired mis-operation but do not solve some of the other system disturbance problems
point-on-wave closing control	moderate cost but risk that control system will not function correctly over a long period of time	Refer to Sections 2.3.2 and 2.4 for identification of the study issues. Also Study issues of Subsection 2.7.2. Means of determining core residual flux.
pre-insertion resistors	increases complexity and cost of circuit-breaker	may not be effective to adequately minimize inrush
increased transformer insulation	costly and only an option for new installation, might not be effective if internal resonances are excited	distribution of switching voltage stress within the winding; partial winding resonance

3 Specification of Controlled Switching Equipment and Systems.

3.1 Degree of specification required prior to study

The specification process associated with the installation of controlled switching equipment can be divided, initially, into two distinct parts: the aims and the specifications. The first part of any specification process is to define, from an overall electricity system perspective, what the intended aims are. These will be related to, and driven by, the overall commercial strategy of the user as well as any regulatory requirements and restrictions. However, for the purposes of this section, this level of specification process is considered to be an integral part of the study process by which the application of controlled switching is identified as the best solution and is covered by chapter 2. This chapter concentrates upon the specification process of the controlled switching installation which will be required to meet the objectives on which the preceding study process has been based.

3.2 Specification of a controlled switching installation

Having established that controlled switching is a viable solution to a present or predicted unacceptable condition or conditions it is important that a clear and comprehensive specification is produced. This document identifies the wide range of factors which must be considered and defined when preparing a comprehensive specification for a controlled switching system (CSS). Various aspects of the specification of a CSS which is a combination of a switching device, a controller and a variety of associated ancillary equipment are considered. Since such a system may be assembled from components from a single source or disparate sources it is important to identify which parameters or requirements are of particular relevance to each component of the system and which to the system as a whole. It is vital that any application of controlled switching is undertaken with due regard to the characteristics, interactions and compatibilities of its component parts.

As an example, switching device accuracy, controller accuracy and the performance of individual components of the system are of limited interest in isolation since it is the overall accuracy requirement which should be met.

This does not alter the fact that the performance of the individual components must be well defined and understood such that their interactions when operating together can be predicted.

In preparing this guidance an approach has been adopted whereby the individual components of the CSS are discretely identifiable units. It is important to note that, with the ongoing developments in integration and digitization of substation protection and control facilities, controlled switching is ultimately likely to become a small component in a larger system rather than an assembly of discrete components. The principles of this document will be equally applicable in all cases whether analogue, digital or hybrid.

The following sections consider specification requirements at three levels termed Performance, Switching System and Component. These are discussed in greater detail later but a general principle of requirements being incorporated at the highest possible level and being cascaded down to lower levels has been adopted.

The intention of this document is to highlight the areas which must be considered for specification and the relative responsibilities of the involved parties. This is not a prescriptive document and it is vital, commercially and technically, that specifications for CSSs and their components and interfaces are aligned with existing specifications wherever possible. A relatively specialist area such as controlled switching cannot sustain extensive dedicated specifications.

3.3 Responsibility considerations

The division of the responsibility for ensuring the satisfactory assembly of a CSS may vary widely. There are likely to be numerous parties involved (utility, switching device manufacturer, controller manufacturer, project manager, consultants working on behalf of any of the foregoing, …) and it is paramount to clearly identify which of these has responsibility for the performance of the power system, the entire CSS and the individual component parts of the CSS. Depending upon circumstances, the requirement may be to construct a total system on the basis of a comprehensive specification but may equally require the application of controlled switching into an existing uncontrolled scenario. In this latter case, whilst the overall specification remains valid, certain parameters will be pre-determined (or may not be available in an accurate form) resulting in a need to ensure that any newly installed equipment is sufficiently robust in its abilities to negate such potential difficulties.

Three parties have been identified in line with three levels of specification. The preparation of the Performance level specification is the responsibility of the “owner/operator”, the preparation of the Switching System level specification is the responsibility of the “implementer” and the preparation of the individual Component level specification(s) is the responsibility of the “assembly coordinator”. The responsibilities for meeting the various aspects of these specifications are less easily categorized but must still be clearly defined at the time of contract placement. Reference should be made to the flow diagram, Figure 3-1.

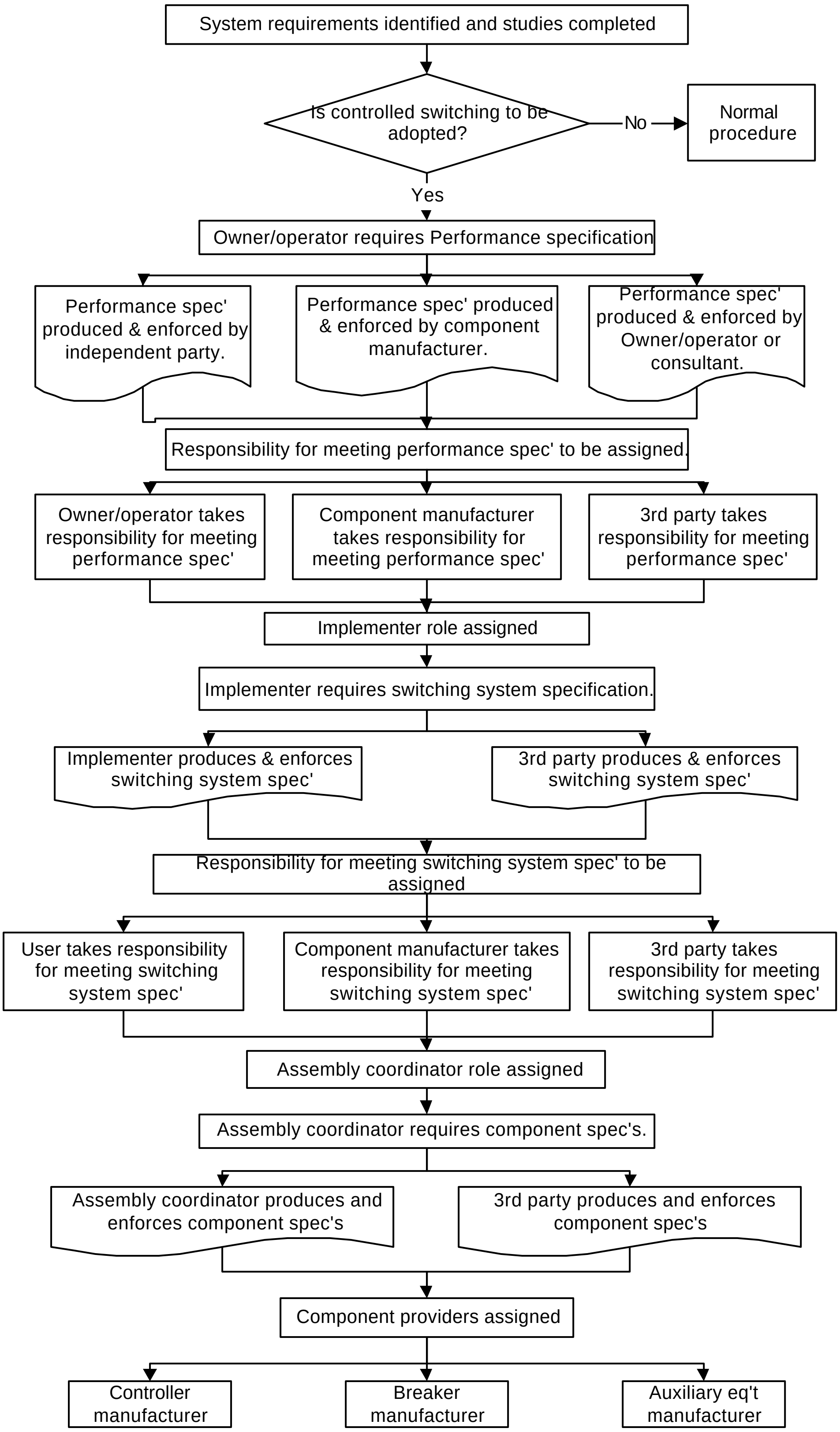


Figure 3-1 Responsibility decision tree

The most important point is that at any stage there must be a single party responsible for specifying a requirement and a single party responsible for meeting it.

3.4 Performance level technical specification of controlled switching systems

The implementation of a controlled switching solution is intended to achieve an improvement in the technical, and normally the resultant financial, performance of a power system. The definition of the method by which this is achieved can be considered to be the most basic specification. It incorporates issues such as the overall objective, the inherent nature of the existing power system, the existing ambient conditions and the normal operational and installation practices of the power system into which the CSS is to be incorporated.

Figure 3-2 indicates this situation graphically showing how the performance level specification defines the basic functional and compatibility requirements to which the chosen CSS will be subjected. No specific requirements are placed upon the CSS and, indeed, the performance specification may be able to be met with methods other than a CSS. It is the study work of Chapter 2 which will have indicated the CSS solution.

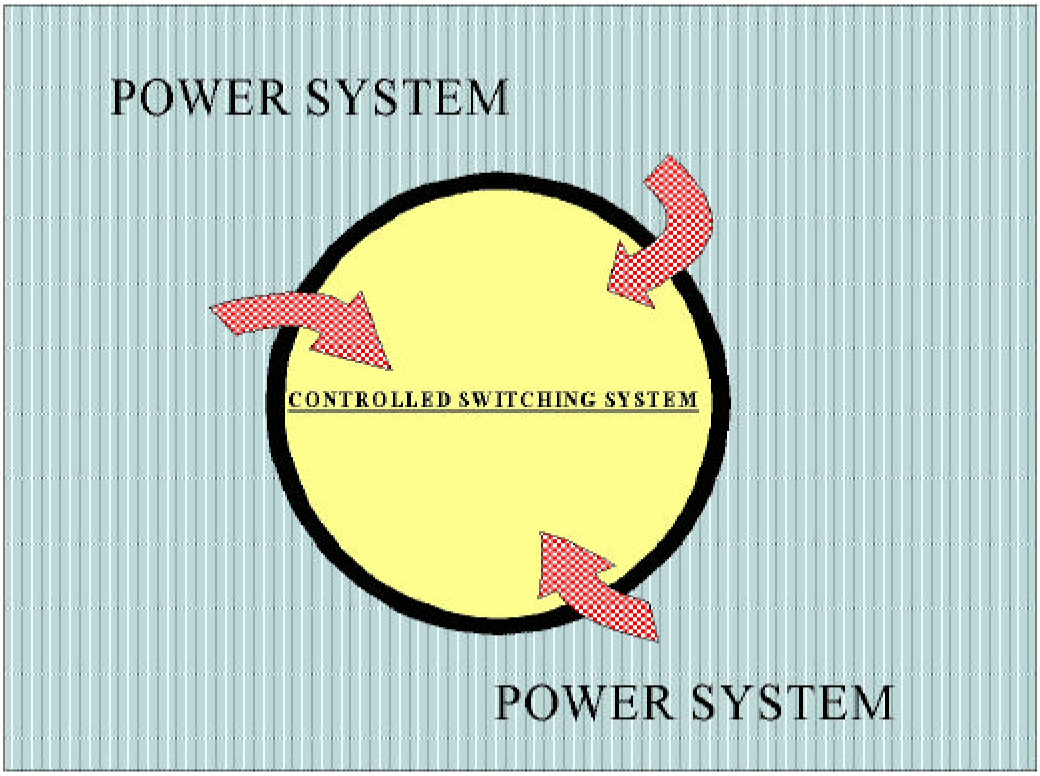


Figure 3-2 Conceptual impact of Power System on the CSS

A performance specification as defined here would typically provide information and requirements in the following key areas:

- Objective (related directly to the preceding study requirements). Typically to limit overvoltages to a predetermined level, reduce inrush currents, eliminate reignitions, reduce cost, etc.
- Nature of the power system. Including earthing practice, existing substation/line layouts, availability of existing reference signals, intended connection arrangement for new plant, normal & abnormal operational arrangements, restrictions on controller location, etc.
- Operational requirements. Expected operating regime, outage planning restrictions, required availability levels, local & remote access facilities, interaction with existing protection & control systems, actions in

the event of malfunction, actions in the event of loss of inputs and subsequent restoration, special MMI facilities, need for redundant equipment.

- Compatibility requirements. Including ambient temperature range, auxiliary supply voltage conditions, existing control, protection & communications systems, parameters & protocols, etc.
- Long term supportability and provision of information. Including requirements to supply operating instructions/training, testing facilities, software support, expected operating lifetime, maintenance regimes, provision of spares, mid-life refurbishment.

3.5 System level technical specification of controlled switching systems

It is at the Switching System Level that specific technical and material requirements for the CSS itself are introduced. With reference to Figure 3-3, the CSS can be considered as a discrete entity forming an integral part of the Power System and interacting with it. Communication, both in terms of physical connections and resultant effects, will exist between the Power System and the CSS and it is the interactions between the entire CSS and the Power System which are addressed at this level. The interactions within the CSS itself are not addressed at this level of specification, however it is important to note that the CSS provider is responsible for the compatibility of the various equipment making up the CSS and its overall compatibility with the existing power system. The CSS will be expected to take input from, and to be compatible with, the network in which it is to operate and must provide appropriate outputs, which are again compatible, to achieve the desired result.

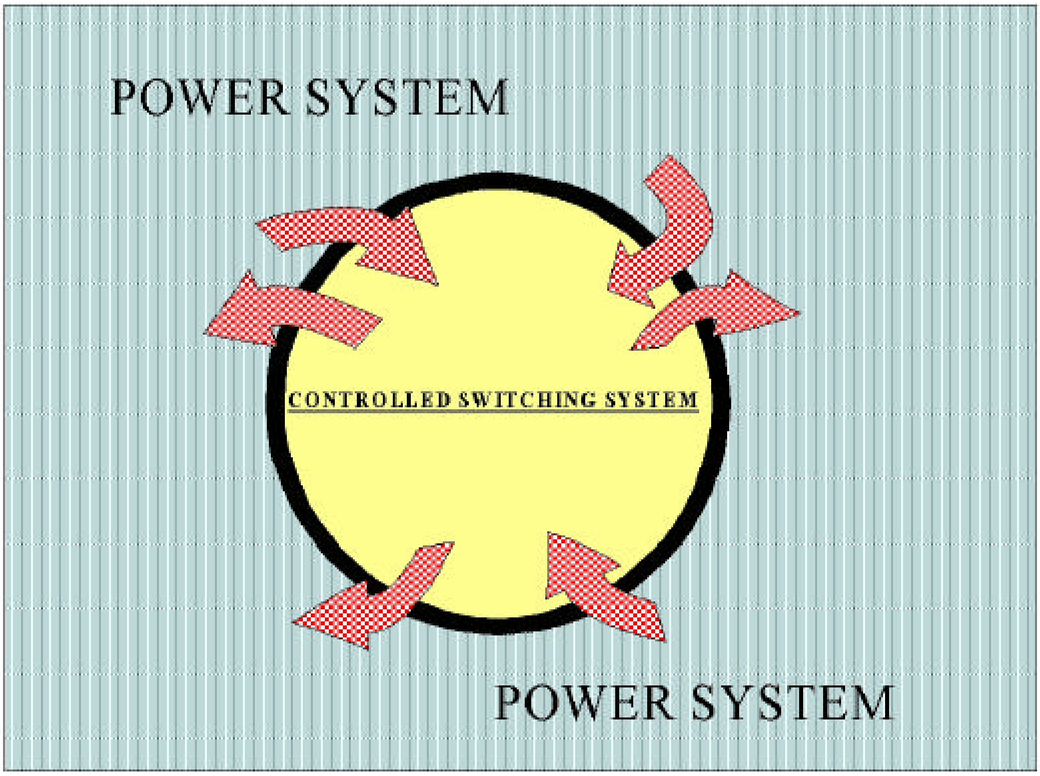


Figure 3-3 Conceptual interaction between Power System and CSS

On this basis the system level specification can and should be used to address the detailed aspects of the requirements of the performance level specification. A simple, but nevertheless valuable, example of the relationship between the performance and switching system levels is that a definition of an expected ambient temperature range is a performance requirement whereas the requirement for the CSS to operate within agreed tolerances within that range is a switching system requirement. The responsibilities for providing data regarding the ambient temperature range and designing a system to meet the requirement lie with the owner/operator and the implementer respectively.

The responsibility for the production of the switching system level specification lies with the implementer of the CSS i.e. the party with the overall responsibility for installing the agreed controlled switching solution into the Power System.

Key topics falling within the scope of the switching system specification are as follows:

- Accuracy and consistency
- Interface and installation philosophy
- Environmental withstand
- Reliability & failure performance
- Non-standard electrical duties

Whilst these divisions are, to some degree, arbitrary they allow the system level specification to be addressed in a manageable format.

Further topics which fall within the switching system level specification are routine testing and commissioning of the CSS and the identification of maintenance requirements to ensure continued satisfactory performance.

3.5.1 Specification of required accuracy of controlled switching systems

As has been previously discussed the performance specification in conjunction with knowledge of the network can be used to identify an electrically optimum target point and a required accuracy (or tolerance) around this point.

It is important to differentiate between mechanical accuracy, which is purely an internal function of the CSS, and the required electrical performance which, by necessity, takes account of the switching device dielectric characteristics in relation to the particular switching duty. Furthermore, it is important that the influence of factors such as environmental conditions, supply conditions, switching device "idle" time, switching device conditions (drive & insulation), etc. are addressed. Thus, an accuracy specification for a CSS must detail:

- The required target point(s) (e.g. making at voltage zero in each phase) and the acceptable tolerance(s) around this point. Such tolerances may be two stage based - on a high percentage within a small band and virtually all within a wider band.
- A detailed electrical assessment of the required switching duty in sufficient detail to determine the precise electrical conditions imposed upon the switching device. System/substation configuration, earthing, line configuration, fault levels etc may be of relevance in deriving this. The need for dedicated load side instrumentation may also be included for some complex switching cases such as overhead lines and transformers.
- The temperature range over which the system is expected to operate including maximum expected changes between subsequent operations. This will apply to the system but, clearly, will also be reflected in the component specifications.
- The range of drive and insulating medium condition over which the system is expected to operate (normally aligning with the rated/lockout values of the switching device).
- The range of auxiliary supply voltages over which the system is expected to function correctly.
- The maximum (& minimum) idle times expected between subsequent operations.

- Details of the required reference signals and inputs and which of these can be derived from existing sources and which require dedicated equipment as part of the CSS.
- Details of dedicated reference signals and the associated sensors which are required.
- The required accuracy of reference signals and inputs in relation to overall CSS accuracy.

A number of these, whilst appearing at the Switching System specification level will also be reflected in the various component level specifications.

3.5.2 Interface and installation philosophy

This aspect of the system specification addresses the issue of achieving seamless interaction between the Power System and the CSS forming a part of it. The principles which apply in this area are, at a basic level, identical to those which apply to all applications of control and protection technology in Power Systems and coordination with existing utility practice is a pre-requisite.

A summary of topics which should be incorporated in a switching system level specification are:

- The characteristics of the supply from which the CSS will be operated in terms of derivation, voltage, operating range, polarity, protection, fusing, and stability.
- Compatibility of the CSS with existing reference signals where these are to be utilized.
- Requirements for the CSS to perform more than one function or to control more than one circuit-breaker and any resultant logical and operating priorities.
- Intended control philosophy in terms of permissive or definite operation.
- Local man-machine interface requirements - full, partial or no facilities.
- Remote access and communication facility requirements.
- Acceptable degree of integration with existing system.
- Transient withstand.
- Maximum levels of complexity of CSS equipment in relation to staff capabilities and simple system operations.
- Special requirements relating to the location of the system components and associated communication requirements.
- Security of communications.
- Analogue input & output ranges in terms of voltage range, polarity, etc.
- Compatibility with existing control and monitoring systems such as anti-pumping, coil supervision etc.
- Ability to accommodate intended protection philosophy e.g. should the CSS form part of the protection system or should it be bypassed during protection operations.
- Details of communication protocols and data transmission rates.
- Extent of required recording, self-diagnostic and self-verification facilities.
- Software availability, compatibility, testing & support.

It is important to note at this point that throughout the Electrical Power Industry initiatives with names such as "Substation Integration of Control and Protection (SICAP)" are being developed. These, with their vision of substations being controlled by a central computer based system, have a major impact upon this aspect of the system level specification since it is conceivable that controlled switching will be implemented as a software routine rather than a hardware modification. There will clearly be intermediate scenarios utilizing digital equipment within conventional substations and, in all scenarios, it is the responsibility of the CSS supplier to demonstrate the compatibility of the CSS with the existing or planned control and protection functions. A CSS should not degrade the overall performance of conventional protection & control functions. The detailed specification & testing of digital computers and software routines, whilst of vital importance, is beyond the scope of this document.

3.5.3 Environmental withstand

Clearly the CSS must operate satisfactorily in, and not be damaged by, its intended environment. In order to verify this it is necessary to specify, in an unambiguous and widely recognized manner, precisely what environmental conditions are applicable. Factors which it is necessary to consider include vibration, production of and susceptibility to electrical interference (EMI), mechanical shocks, extremes of temperature and or humidity, etc. Producing a dedicated specification to address each of these factors for a CSS is a complex procedure and it is not considered valid to pursue such an approach. More appropriate is to rely on existing International, National (and local) standards & specifications to address the capabilities of the individual components of the system. These existing documents, being the result of extensive deliberations, are able to provide an appropriate basis for specification (and testing) in terms which are already widely understood. This is clearly another area where coordination with existing utility practice is a pre-requisite. It is also important to note that, whilst many environmental issues will be addressed at the component level, it is important that the environmental requirements for the CSS as a whole are included at the System level. Put another way the environmental specifications of the system as a whole are carried forward into the environmental specifications of the individual components.

Environmental issues of particular importance for the CSS are:

- Location of CSS components.
- Operating range of temperature, humidity and pressure.
- Resistance to vibration dependent upon installation philosophy.
- EMI

3.5.4 Reliability & failure performance

Where CSSs are incorporated into Power Systems with the intention of eliminating or preventing an unwanted or dangerous occurrence their reliability is of paramount importance. Whilst most utilities have requirements relating to reliability, of particular importance is the relationship between reliability and consequence of failure. The possible nature and consequences of CSS failure should be taken into consideration by the switching system specification. At a system specification level CSS failure can take one of 6 basic forms namely:

1. Failure to operate on command without prior indication.
2. Incorrect operation on command without prior indication (target missed).
3. Operation without command.
4. Indicated total inability to operate.
5. Indicated inability to operate within required parameters (e.g. inadequate accuracy or total operating time due to controller failure).
6. Indicated failure of input signals (e.g. reference voltage, ambient temperature, etc.)

The implications of each of these failure modes will vary according to switching duty, operating regime and nature of surrounding system and clearly some are much easier to accommodate than others. It is important for the switching system level specification to address each of these in terms of a required course of action.

Taking the possible occurrences in turn, system level actions requiring consideration are as follows:

1. Since no pre-event action is possible, a decision is required whether this event should result in automatic or manual actions. Options include repeated attempts, blocking the command, bypassing the control device, selecting alternating switching devices, etc.
2. Same as 1, excepted the repeated attempts option.
3. The most appropriate action is to block the command until further investigation is performed.
4. As 3.
5. The possible consequences of operation of the CSS outside the intended tolerances must be assessed and set against the consequences of not performing the operation. The duty being undertaken, the possible effects on locally connected customers, the likelihood of resultant equipment damage and the financial implications of these will heavily affect this balance. In particular, cases where controller failure occurs in such a way that uncontrolled operation remains possible require very careful consideration since further safeguards will probably not be present in the overall installation.
6. This case is similar to 5 but, dependant upon the nature of the lost input, it may be acceptable to continue operation of the CSS. This will require an assessment at the design stage of critical vs non-critical inputs.

A further consideration for any switching system specification is the sophistication of self diagnosis and failure detection facilities which are required. These might range from a simple "CSS faulty" indication to a complex self-diagnostic system capable of limited decision making processes in terms of ability, or otherwise, to continue in service. For critical installations where failure cannot be tolerated the additional cost of installation of redundant equipment, e.g. duplicate or triplicate controllers, and complex self-checking facilities may be deemed appropriated.

A final consideration is the effect on overall CSS reliability of minor components such as dedicated sensors. Unnecessary complexity should be avoided.

3.5.5 Non-standard electrical duties

It has been assumed for the purposes of this document that the switching device in question has been proven suitable for the basic duty for which it is being used. It is possible that in a small number of cases, as a result of the application of controlled switching, switching devices may be subjected to more onerous conditions than those for which they are typically tested. If this is the case the existence of these should be identified and incorporated at the system specification stage.

Specific examples of such situations are as follows:

1. Probably the most obvious case is the effect of intentional non-simultaneous pole closure on the making duty experienced by switching devices closing onto pre-existing faults in unearthed or impedance earthed systems. The basic IEC requirement of 2.5 times [2] the rated RMS breaking current has been derived on the basis of assumptions, one of which is that pole spread on closure will be small. The introduction of a more significant pole closure spread leads to a temporarily unbalanced situation during the closing operation such that the making peaks are enhanced. Typical, quantified, examples of this effect in an unearthed neutral system are detailed in Table 3-1. These theoretical values refer specifically to the simultaneous closure of two poles followed by closure of the third pole at a later instant defined by the pole spread.

	Pole spread on closing (ms)										
	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
τ = 45ms	2.55	2.62	2.69	2.76	2.82	2.87	2.92	2.95	2.98	3	3.01
τ = 60ms	2.61	2.69	2.77	2.83	2.9	2.95	2.99	3.03	3.06	3.09	3.09
τ = 90ms	2.68	2.76	2.84	2.91	2.98	3.03	3.08	3.11	3.14	3.16	3.17
τ = 120ms	2.72	2.8	2.88	2.95	3.02	3.07	3.12	3.16	3.19	3.2	3.21
τ = infinite	2.83	2.92	3.01	3.08	3.15	3.21	3.26	3.3	3.32	3.34	3.35

Table 3-1 Pole spread on closing table

This phenomenon also impacts upon the maximum arcing times associated with short circuit breaking.

2. A further issue may be the interruption of asymmetric fault current immediately subsequent to closure on fault. Possibly the worst case is the use of a circuit-breaker with fixed mechanical stagger to close onto a capacitor bank in an earthed neutral system. In the event that an attempt to energize the capacitor bank is made with a pre-existing three-phase fault (e.g. failure to remove maintenance devices) the following sequence of events can be envisaged. Firstly if the circuit-breaker achieves optimum point switching for capacitor bank energisation (voltage zero in each phase at 60 degrees intervals) a fully asymmetric fault current will be initiated in each of the three phases. This in itself may have testing implications. Upon energisation of the fault in the first phase the system protection will operate however the fault current will probably not be initiated in the third phase for another 120 degrees. The effect of this delay in achieving closure in the third phase is to decrease the effective protection operation time by about 120 degrees. Furthermore, since the last phase to close will be the first to open, since the fault current in all phases is fully asymmetric, and since the protection time is a factor in the asymmetric switching specification, the asymmetric interruption requirements of the first phase to clear (third to close) may be more onerous than those of the standard specifications.

It is important that any such conditions are foreseen at the system specification stage such that supplementary switching device Type Testing can be incorporated at the component stage or appropriate palliative measures can be applied.

3.5.6 Maintenance, supportability & lifetime issues

Whilst particular levels of maintenance will not be included in a system specification it is important that, as part of the overall specification of the CSS, information regarding maintenance required specifically to maintain the performance of the CSS is identified. It is the responsibility of the assembly coordinator to identify such maintenance (probably by reference to the maintenance philosophies for the components of the system) and include it in the overall data provided to the owner/operator in support of the CSS.

3.6 Component level specification of controlled switching systems

The preceding section has concentrated upon the interaction of the complete CSS with the power network in which it is to operate. However, it is clear that, in order to achieve the required overall CSS performance it is necessary for the individual components internal to the system to be correctly specified. The component level specification(s) and the coordination thereof, can be considered to address the internal interactions of the CSS taking into account the external requirements of the system specification and is the responsibility of the CSS assembly coordinator. Figure 3-4 illustrates this interaction .

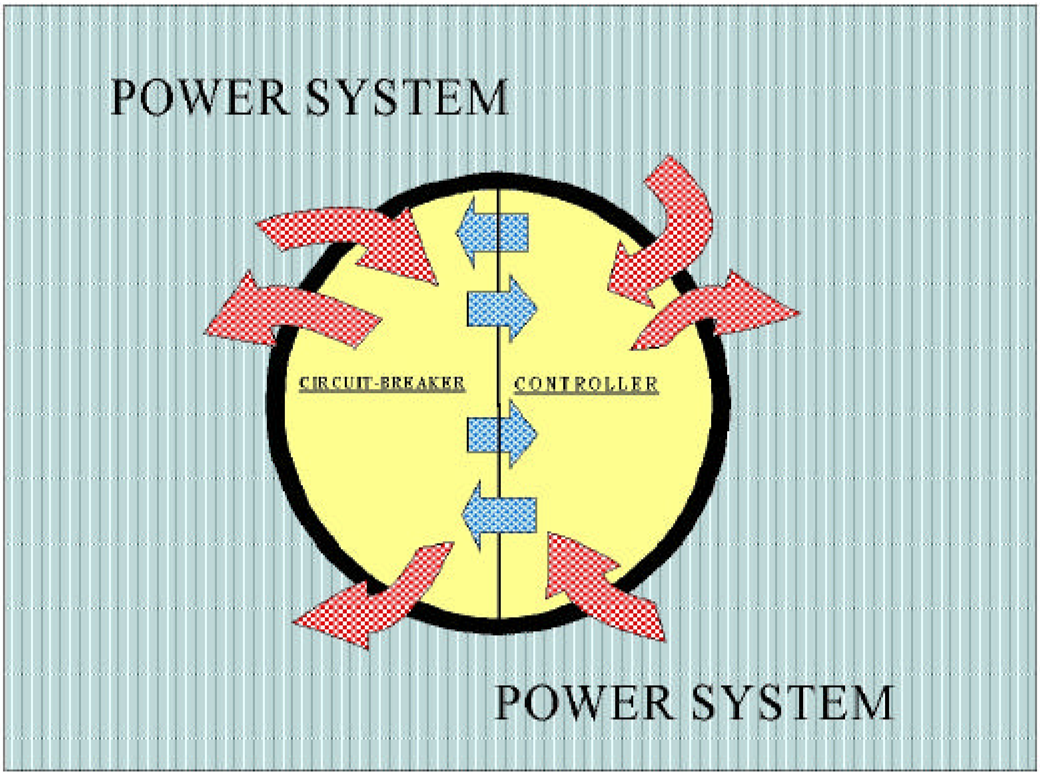


Figure 3-4 Conceptual interaction between Power System, circuit-breaker and controller

A definitive specification at the component level is less easy to identify since there is a large degree of interaction between the requirements of the individual components. Clearly if a particular component (e.g. controller) is to be retro-fitted to an existing installation then the specification for the controller (i.e. an individual component) must be sufficient to ensure adequate performance of the CSS. However, if a number of components are to be installed, the individual component characteristics (and hence specifications) can interact providing the overall result is achieved.

Whilst it is clearly the responsibility of the supplier of each of the components making up a CSS to have proven the capabilities of his equipment it is the specification and coordination of these abilities by the CSS assembly coordinator that is of paramount importance.

The relationship between the component specification(s) and the higher levels can be clarified by returning to the earlier example relating to ambient temperature. Having defined the expected ambient temperature range (performance) and the range over which the CSS is expected to operate (switching system) the resultant component level specifications must reflect these. However, at the component level it is necessary to incorporate details of the actual application. Hence, an ambient temperature range of –25°C to +40°C may be interpreted as –25°C to +40°C for the specification of the outdoor switching device but as 0°C to + 50°C for a controller housed in a controlled environment.

Clearly most, if not all, issues that appear in the system level specification will have a related requirement at the component level. However, there are a number of parameters which are of specific importance for components (circuit-breaker, controller, auxiliary equipment) intended for CSS applications and these are highlighted below.

3.6.1 Circuit-breaker data

When specifying or assessing the suitability of a circuit-breaker for controlled switching there are a number of basic parameters which must be taken into consideration over and above those which might be considered for normal, uncontrolled applications. Typically these include:

- Dielectric characteristics (RDDS/RRDS) at varying interrupter & drive conditions.
- Operating time random scatter at various conditions.
- Operating time temperature sensitivity characteristics.
- Operating time drive condition sensitivity characteristic.
- Operating time control voltage sensitivity characteristics.
- Operating time "idle time" sensitivity characteristics.
- Interaction between the various operating time sensitivity characteristics.
- Re-ignition characteristics [3].
- Duty related changes in performance.
- Age related changes in performance ("drift").
- Availability of independent or staggered pole operating facilities.

3.6.2 Controller data

Whilst the interaction between controller and switching device is a dynamic process the practicality of designing and coordinating CSS systems is that controllers are designed to take account of the typical and/or specific characteristics of circuit-breakers rather than vice versa. Thus, the basic specification of the function of the required controller is normally developed by considering the inherent characteristics of proposed (or typical) switching devices in relation to the system level requirements and developing/applying the controller facilities accordingly. The controller can be viewed as the control link between the power system and the switching device.

Typical factors that can be specified in this way might be:

- Accuracy of controller.
- Relationship between controller input errors to controller output errors.
- Compensation abilities.
- Adaptability abilities.
- Required nature and characteristics of input and output signals.
- Output capabilities
- Reaction of controller to power frequency variations
- Environmental withstands.
- Ability to predict pre-existing conditions and adequately interpret input data.

In addition to these basic functional parameters it is also necessary to address a number of operational areas such as:

- Extent and discrimination of self checking facilities.
- Controllers bypass or inhibit in the event of malfunction.

- Need for specific input parameters.
- Action in the event of out of limits operation.
- Action in the event of sensor failure.
- Action in the event of loss of supply and restoration thereof.
- Compatibility of communication interfaces & protocols.
- Maintainability/testability of soft/firm/hardware.

3.6.3 Auxiliary equipment data

For the purposes of this work "auxiliary equipment" can be considered to be any equipment which is required to be installed for the implementation of a CSS but which falls outside the scope of the circuit-breaker or the controller. Sensor systems, power supplies, communication systems, cabling, connectors, dedicated instrument transformers, user interfaces, dedicated test facilities, etc are auxiliary equipment. With reference to Figure 3-4, the auxiliary equipment can be considered to be denoted by the various arrows permitting and facilitating communication between the power system, the controller and the circuit-breaker.

As previously mentioned, the majority of auxiliary equipment will be specified against existing pertinent requirements within IEC, ANSI etc. in conjunction with existing utility practice. Nevertheless, it is important that sufficient consideration is given in the following areas such that auxiliaries do not limit the overall performance of the CSS.

- Compatibility, suitability and interchangeability of communication channels & protocols.
- Reliability of connectors & connections (optical, galvanic or wireless).
- Immunity to interference.
- Range, accuracy & reliability of sensors.
- Maintainability/testability.
- Reliability.

The software should be considered as a major sub-component and special considerations should be given to this matter: specific documentation and testing results should be provided by the manufacturer to guarantee its reliability.

4 Testing and Verification

Verification of performance is decisive for the practical application of controlled switching. The requirements for the recommended studies, including transient simulation of the complete CSS, are presented in chapter 2.

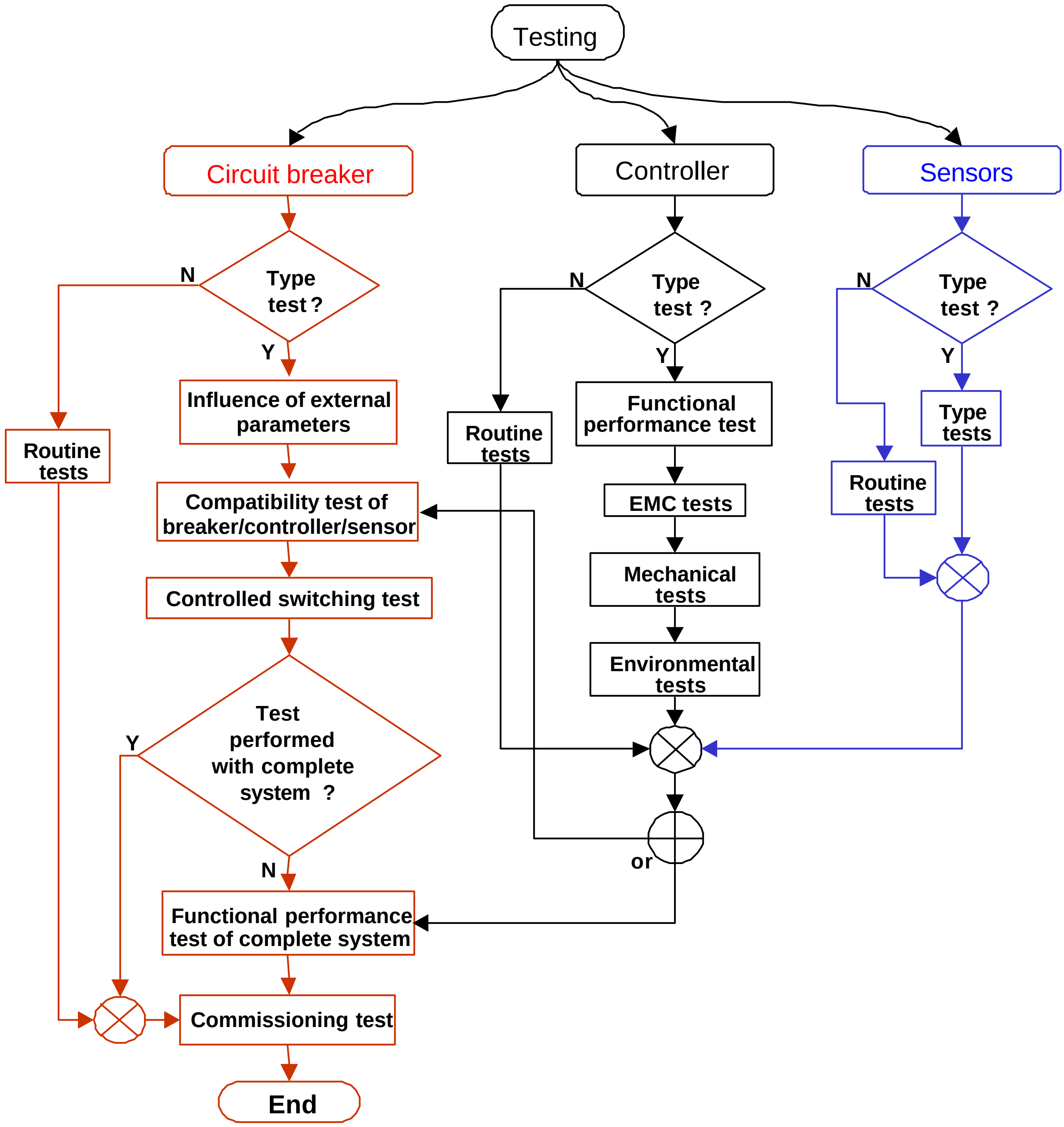


Figure 4-1 Flow chart describing testing sequence

In this chapter the focus is on the performance check of components of the CSS. Considering the modular nature of these systems, an efficient test procedure should aim at:

- performance check of functionality of the components, i.e.
  - controller
  - sensors
  - circuit-breaker
- performance check of the complete CSS.

In the following sections testing requirements and recommendations for testing procedures are presented. These are summarised graphically in Figure 4-1.

4.1 Controller testing

The necessary tests to prove the controller's ability to perform correctly in the network can be classified in two main categories:

1. Functional performance tests → to verify controller performance under realistic service conditions
2. Hardware conformance test → to check the hardware withstand capability under different stress conditions of internal or external origin (e.g. electromagnetic interference)

In practice these categories can be further divided into type tests, routine tests, commissioning tests and periodic maintenance tests. The first two of these are covered in the following subsections. Commissioning tests are treated separately in Subsection 4.4.3, where the circuit-breaker is also taken into account. Periodic maintenance tests are highly dependent on product design and utilities practices, therefore, they are not considered in this document.

4.1.1 Type tests

Controller testing shall take account of all intended connections (inputs, outputs). These can be simulated from external signal sources. The most common required signals are:

- Controller power supply
- Circuit-breaker control voltage
- Control signal for close and/or open operations
- Reference voltage and/or current for synchronisation purposes
- Current/voltage onset, or other indication of operation timing (e.g. auxiliary contact)
- Other signals used for compensation purposes, such as temperature sensor, hydraulic oil pressure sensor, spring position sensor, etc.

Fluctuations of amplitude and frequency, presence of harmonics as well as all common disturbances affecting those signals should be considered when defining the test procedure. A load simulating the circuit-breaker trip and close coils shall be connected to the controller. It is recommended to apply a real circuit-breaker operating coil due to the high switching transients that can be generated by these, mostly inductive, components.

4.1.1.1 Functional performance tests

Functional performance tests are not yet standardised. Their purpose is to verify the following characteristics and functionalities of the controller:

- Controller timing scatter for close operations ($\sigma_{C\text{-cont}}$)
- Controller timing scatter for open operations ($\sigma_{O\text{-cont}}$)
- All compensation features, such as temperature or control voltage compensation
- Self-adaption features
- Alarms and signalling
- Communication protocol
- Self-check

- Behaviour upon loss of power supply

4.1.1.2 Electromagnetic, mechanical, and environmental tests

The tests already specified in existing standards for protection relays and secondary systems applied to high voltage network are also applicable to controllers. IEC 60694 [4] prescribes the following mandatory tests on all auxiliary and control circuits of high voltage switchgear:

- power frequency voltage withstand
- impulse voltage withstand
- electromagnetic emission
- electrical fast transient/burst immunity
- oscillatory wave immunity

Further tests shall be selected from the lists given in Appendix A, taking into account the intended location, and hence operating environment, of the controller. It is strongly recommended that in addition to the tests specified above, a controller is also subjected to all type tests applied to relays (IEC 60255-21-x and -22-x).

4.1.2 Routine tests

The following test should be carried out on all manufactured units:

- dielectric withstand according to IEC 60255-5 [5] and IEC 60694 [4]
- functional performance tests: close at voltage zero and voltage peak as well as open at a specified voltage/current phase angle
- check of parameter setting procedures (including external computer software if required for this purpose)
- self-check
- alarms and signalling
- additional functions such as event recording, communication, etc.

4.2 Sensor testing

External sensors should be considered an integral part of the CSS and should be tested accordingly. This testing should take account of stresses due to the location of the sensors and the recommended installation procedures (routing of cables, grounding points, shielding etc.).

Sensors and their associated analogue and/or digital links to the controller (metallic, optical, or RF, etc.) should be tested as far as possible in accordance with existing standards. However, standards do not yet exist for testing of low voltage sensors for application in power systems. This topic is being addressed by CIGRE Working Group 13.09, dealing with monitoring of high voltage circuit-breakers, which is considering the appropriate requirements for sensor testing. (See Appendix A, [7].)

4.3 Circuit-breaker testing

Circuit-breaker tests are essential for two reasons:

- To determine the suitability of the circuit-breaker for the specified controlled switching application
- To determine the optimum close target as described in Subsection 4.3.2

In order to achieve this information for new circuit-breaker designs, specific development tests are normally undertaken. Type and routine tests are necessary to verify satisfactory performance according to the network and user specific requirements. In order to minimise overall testing effort it is beneficial to determine the circuit-breaker characteristics during the existing type tests specified by international standards (IEC 60056 [2] and ANSI C37). Performance parameters that might be strongly unit dependent should be checked on a routine test basis.

Ideally this procedure also applies to existing circuit-breakers, however, in practice the costs would be prohibitive and a less rigorous procedure may be employed on agreement between the involved parties.

4.3.1 Determination of circuit-breaker characteristics

Three basic parameters of the circuit-breaker determine its controlled switching performance:

- scatter of mechanical operation
- rate of decrease of the dielectric strength of the contact gap (RDDS)
- and rate of rise of the dielectric strength of the contact gap (RRDS).

Refer to Figure 2-1 and 2-2 of Chapter 2.

The measurement of these parameters provides a generally applicable method of determining both suitability and close target for any application. Testing procedures and requirements are described in the following sections. The main advantage of this test is to obtain information that is applicable to any switching condition and to operating voltages lower than that tested.

For specific applications detailed knowledge of these parameters is not necessarily required and a direct method of determination of the circuit-breakers suitability and the closing target as described in Section 4.3.2.1 can be used. However, results of this apply only for the specific application.

4.3.1.1 Scatter of mechanical operation

It should be verified that the random variations of close and open times of the circuit-breaker are within a range of ±2 ms around the mean value. For certain applications such as closing on capacitor banks the variations should be less than ±1 ms. Higher spreads generally do not yield the expected switching transient reduction [1].

This verification should be carried out at normal operating conditions.

4.3.1.2 Determination of the rate of decrease of the dielectric strength (RDDS)

The principle of measuring the RDDS is to close by point-on-wave control and apply a well defined power frequency voltage across the circuit-breaker. Measurement of contact travel is also required. The pre-strike voltages measured can then be used to plot the RDDS.

The simplified diagram of a typical test circuit is presented in Figure 4-2. It is necessary that the no-load closing time of the circuit-breaker has been determined prior to the test and it is recommended to use travel recording to detect contact touch for each test. Tests can only be performed without travel recording if the mechanical spread has been determined and is low.

Closing operations of the circuit-breaker should be carried out taking into account the rated voltage and frequency of the intended applications(s). For example, loads with directly earthed neutral in a solidly earthed network generally require 1.0 pu testing voltage, ungrounded loads 1.5 pu. The RMS value of the testing voltage is given by:

$$U_{test} = k_{ph} \cdot \frac{U_{rated}}{\sqrt{3}} \qquad \text{eq. 4-1}$$

where U_{rated} is the rated voltage of the circuit-breaker and k_{ph} the phase factor. k_{ph} is 1.0 for solid earthing and 1.5 for isolated neutral.

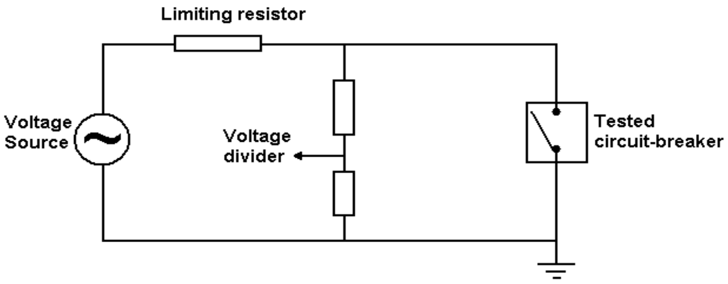


Figure 4-2 Schematic test circuit diagram (with resistor and/or reactance for current limitation) for determination of RDDS and controlled switching tests

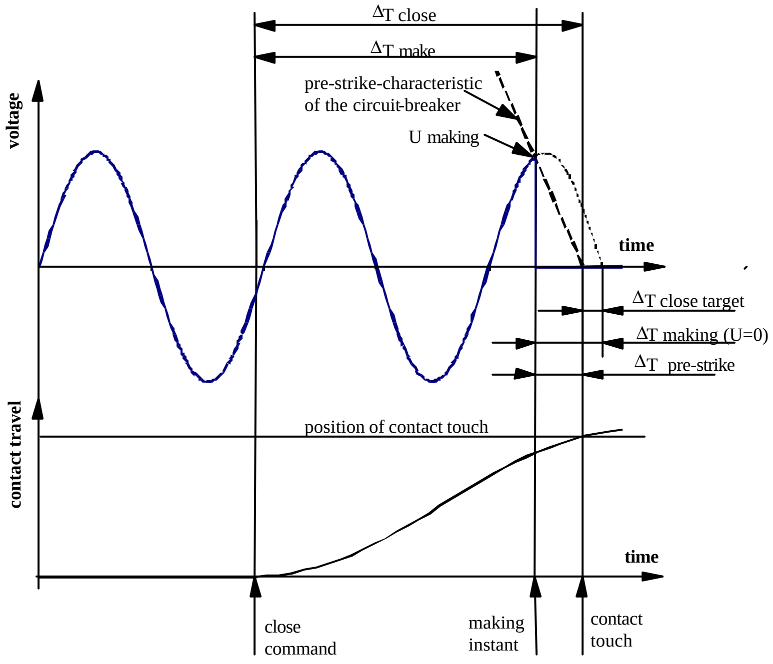


Figure 4-3 Test record showing closing time, pre-striking time and pre-strike voltage

The sequence of tests consists of a series of operations “around-the-clock”, which can be performed according to the procedure represented in Figure 4-4 and described below.

(1) Close the circuit-breaker at the peak of positive voltage polarity and perform 4 making operations.

(2) Delay the close impulse by 15 electrical degrees (making instant displaced towards subsequent voltage zero) and perform the next 4 shots. Successively delay the close impulse by further time steps of 15 electrical degrees and perform 4 shots at each phase angle until voltage zero or the minimum making voltage is reached.

(3) Perform 4 operations at minimum making voltage.

(4) Return the close impulse setting to the value corresponding to making at voltage peak (1) and perform a series of 4 operations advancing successively the close impulse by 15 electrical degrees until voltage zero or the minimum making voltage is reached

(5) Perform 4 operations at minimum making voltage.

With reference to Figure 4-4, tests (6) (7) (8) (9) and (10) shall be performed in the same way as (1) (2) (3) (4) and (5).

At each operation the pre-strike voltage and the corresponding pre-strike time (i.e. the absolute value of the difference between the instants of pre-strike and of contact touch) shall be tabulated. The test results for each voltage polarity shall be treated separately for determination of the respective RDDS curves. Figure 4-5 shows a typical test result where the time axis ends at the contact touch point. The lines representing the RDDS were determined by linear regression. The kind of regression which best fits a given set of points might be dependent on the circuit-breaker design.

The influence of burn-off on the RDDS should be verified.

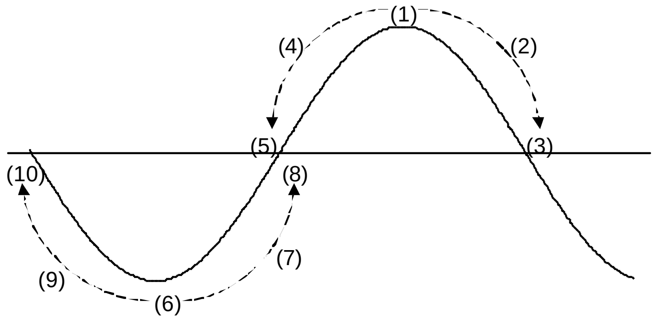


Figure 4-4 Test sequence for determination of RDDS, covering positive and negative polarities for evaluation of making voltage and pre-strike time

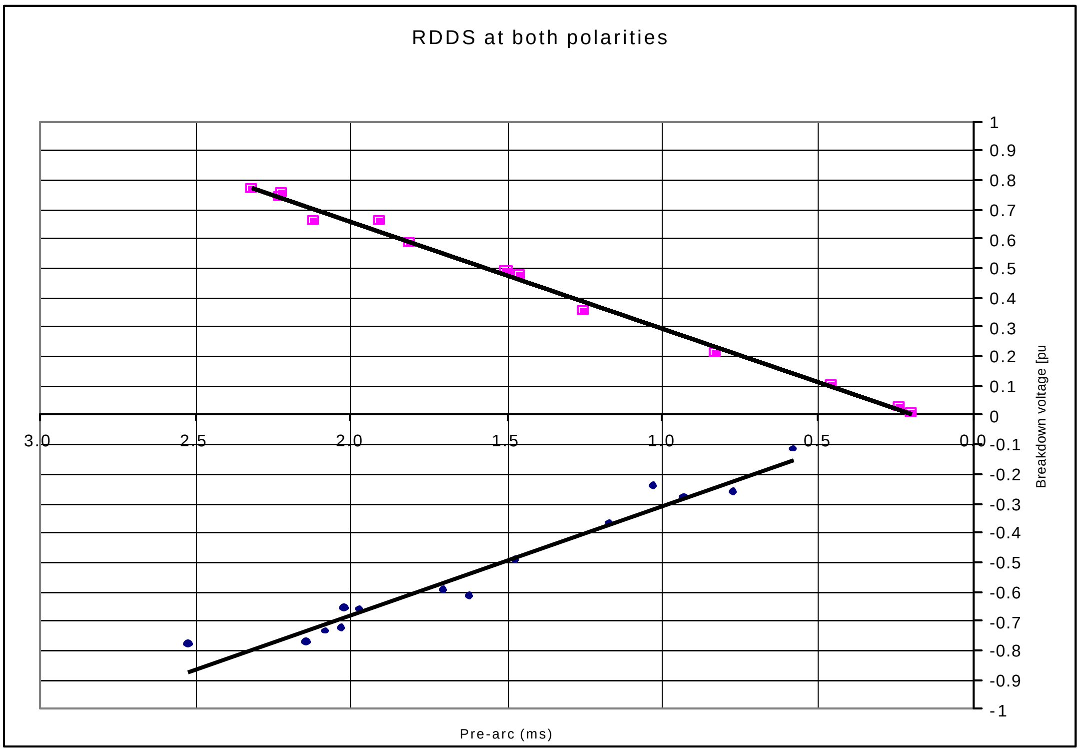


Figure 4-5 . Typical RDDS for positive and negative voltage polarities

4.3.1.3 Effect of contact velocity and gas pressure on RDDS

There is a systematic relationship between the RDDS and the contact velocity. In the case of gas circuit-breakers there is also such a relationship between RDDS and the gas pressure. It is therefore important that the RDDS determination test is done under well defined conditions. Figure 4-6 shows, schematically, the effect on the RDDS of variations in dielectric strength and contact velocity. As the RDDS is proportionally dependent on the product of gas pressure and contact velocity it is possible to correct systematic changes in these values. It is recommended to perform RDDS determination tests at rated conditions in order to keep the deltas small to either side. Detailed theoretical considerations will be published separately in the near future.

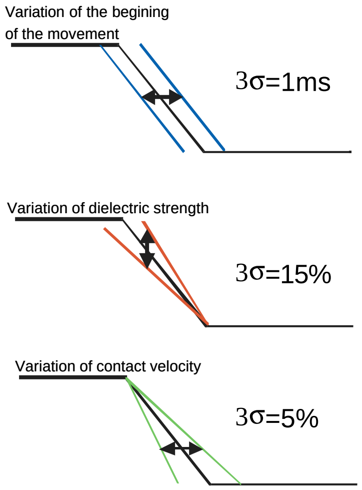


Figure 4-6 Schematic representation of variations in RDDS

4.3.2 Determination of the optimum close target

The practical application of controlled switching requires an optimal close target[1] t_{target}. The theoretical approach to choosing t_{target} was presented in [1]. In practice, a precise assessment of t_{target} can only be obtained by suitable interpretation of development test results.

Re-arrangement of the test data from the test series described in sections 4.3.1.1 and 4.3.1.2 allows the close target to be determined as described in the following subsections.

If full derivation of the RDDS and mechanical scatter is not practical (e.g. for older circuit-breakers) it is also possible to undertake making tests ignoring mechanical scatter in order to derive directly results in the same format as those presented below. Test results derived in this way are limited to the tested application conditions. In other words the derivation of the close target described in the following subsections can be derived either from the RDDS in combination with the mechanical scatter or, alternatively, by a dedicated test series.

4.3.2.1 Close target[1] as a function of the making voltage

Figure 4-7 plots the per unit making voltage against the phase angle of the applied power frequency voltage. From this plot it is possible to extract the following information.

- The boundaries of the required close target interval (? T_{target}) that guarantees the making voltage to be below a predetermined maximum permissible value, $U_{making\text{-}max}$.

---

[1] Close target = time interval between the prospective instant of contact touch and the closest voltage zero. For a graphical definition of the close target see Figures 2-1 and 2-2 of Chapter 2.

- The minimum achievable value of maximum making voltage resulting from the ?T_{target} of the circuit-breaker.

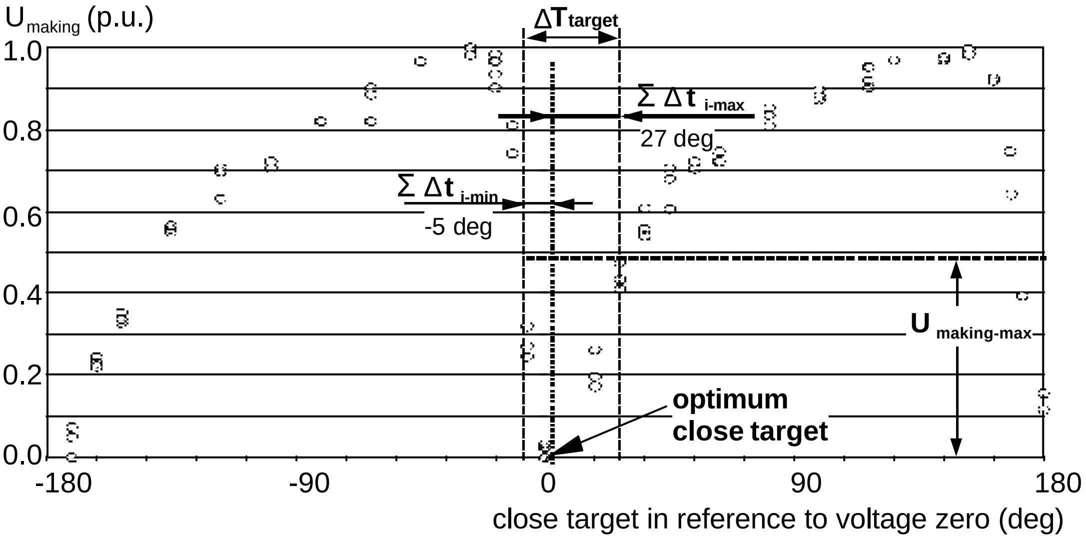


Figure 4-7 Example of making voltage (pre-strike) characteristic as a function of the close target (with reference to voltage zero) T_{target}

The voltage corresponds to the actual service voltage and U_{making} is the pre-strike voltage as given in Figure 4-7 ? T_{target} is defined as the drift of the circuit-breaker close time around its mean value caused by external parameters and is given by:

$$\Delta T_{target} = \sum_{1}^{n} \Delta T_i \qquad \text{eq. 4-2}$$

? T_i is the variation interval of the close time due to external parameters, as listed in 4.3.4.2. If external parameters are compensated by the controller they need not be considered in eq. 4-2. The close target is only valid for the SF_6 pressure and drive conditions used during the test because the RDDS depends on these parameters. A practical example of determining the optimum t_{target} from the plot of Figure 4-7 is given in Table 4-1

Variations of close time due to external influences (ms):							
Control voltage		Ambient temperature		Idle time		Drive energy	
$\Delta T_{1\text{-}min}$	$\Delta T_{1\text{-}max}$	$\Delta T_{2\text{-}min}$	$\Delta T_{2\text{-}max}$	$\Delta T_{3\text{-}min}$	$\Delta T_{3\text{-}max}$	$\Delta T_{4\text{-}min}$	$\Delta T_{4\text{-}max}$
0 (*)	0 (*)	0 (*)	0 (*)	0	0.8	–0.3	0.7

$$\sum \Delta t_{i-\min} = -0.3\ ,\ \sum \Delta t_{i-\max} = 1.5 \Rightarrow \Delta T_{target} \in (-0.3, +1.5)$$

(*) Influences that are most often compensated by the controller.

Table 4-1 Example of determining t_{target} from development test results

It is notable from Table 4-1 that t_{target} is not necessarily in the centre of ? T_{target}

In this case, with reference to Figure 4-7 the optimal set point of t_{target} should be 0.1ms after voltage zero and $U_{making\text{-}max}$ resulting from the spread of –0.3ms to + 1.5ms is approximately 0.5pu.

4.3.2.2 Close target as function of making instant

This section describes the derivation of the close target from measurement of the making instant rather than the making voltage which was described in the preceding section.

Figure 4-8 plots the absolute value of the time difference between making instant and voltage zero against the difference between mechanical contact touch and voltage zero measured in electrical degrees. From this plot it is possible to extract the following information.

- The maximum allowable variation of the instant of mechanical contact touch, ? T_{total} , for a given interval of making instant referred to voltage zero (? $t_{making(U=0)}$
- The interval for the making instant referred to voltage zero (? $T_{making(U=0)}$) for the ? T_{total} of the circuit-breaker.

Figure 4-8 shows that for increased service voltage and equal ? $T_{making(U=0)}$ the ? T_{total} will be decreased.

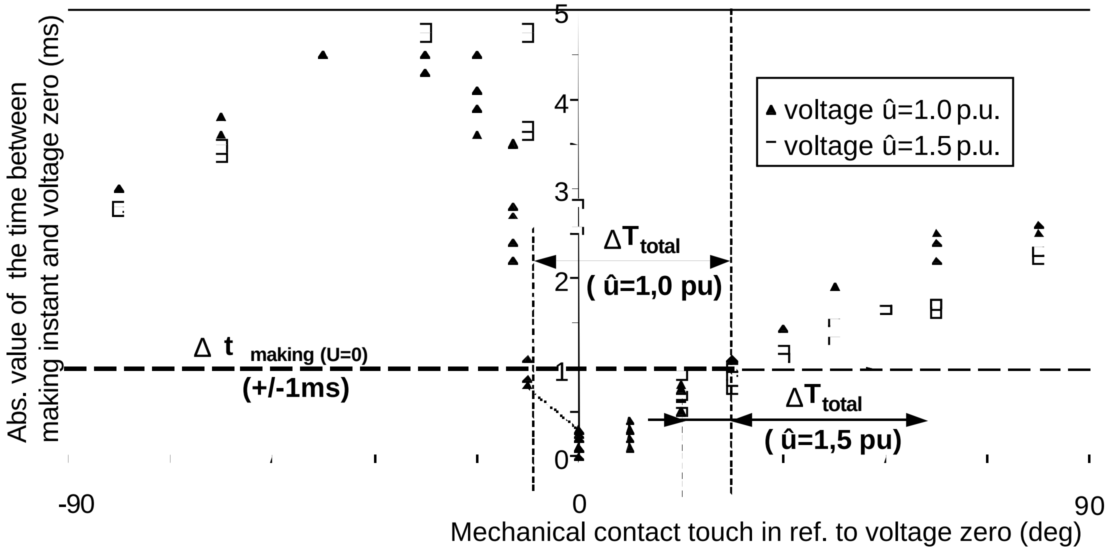


Figure 4-8 Example of making instant characteristic as function of contact touch instant

? T_{total} is defined as

$$? T_{total} = ? T_{target} + ? T_{mec} \qquad \text{eq. 4-3}$$

where ? T_{target} is obtained according to eq. 4-2. ? T_{mec} is the standard deviation of the close time scatter (random drift).

4.3.2.3 Influence of systematic variations of the RDDS on the close target

The systematic variations in RDDS described in 4.3.1.3 affect the optimal target point and it is possible to correct for such variations.

The optimal target points for different RDDS's with respect to the 2% prestrike voltage have been calculated. The results are shown in Figure 4-9. The curve has been calculated by means of a statistical model applying the standard deviations indicated in Figure 4-6.

To illustrate how to use the information shown in Figure 4-9 it is assumed that the nominal RDDS of the circuit-breaker has been determined at rated conditions (this relates to 100% of the product of the rated pressure and the rated contact velocity) and was found to be 1 pu. The optimal target point in this case is 1.2ms after reference voltage zero (Figure 4-9, circle A). For a product of pressure and contact velocity that is 75% of the product at rated conditions, the RDDS is decreased to 0.75pu and the optimal target point is 1.9ms after reference voltage zero (Figure 4-9, circle B). In the same way other systematic changes can be corrected.

The curve in Figure 4-9 can be seen as a general guideline. It allows automatic adaptation by the controller of the optimal target point with reference to systematic changes in RDDS. It also allows correction of calculated target points for a RDDS measured under different conditions of pressure and/or contact velocity. It is valid for circuit-breakers with similar statistical distributions as stated in Figure 4-6 For circuit-breakers with significantly different 3σ values from those given in Figure 4-6 it may be necessary to recalculate the curve in Figure 4-9.

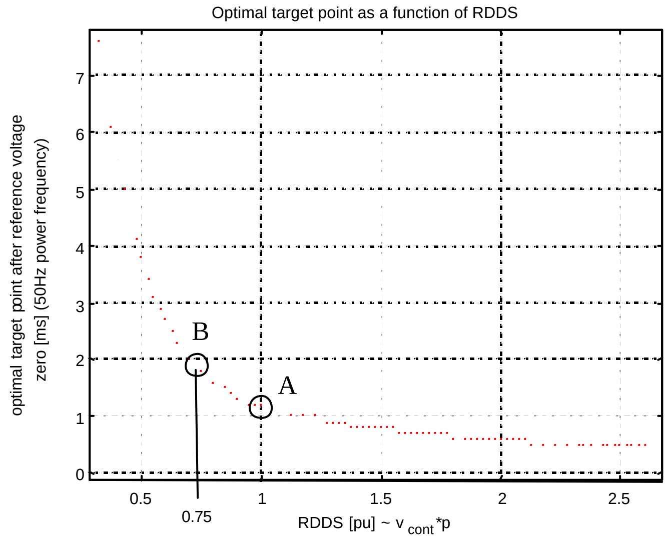


Figure 4-9 Optimal target point as a function of RDDS.

4.3.3 Determination of optimum arcing time for opening

Optimum arcing times for controlled opening applications can normally be derived from circuit-breaker Type Tests. For capacitive switching applications T_{target} may be determined from the capacitive type tests defined in IEC 60056 [2].

For shunt reactor applications T_{target} may be determined from the tests according to IEC 61233 [3]. These tests are performed at rated conditions on a new circuit-breaker. The minimum arcing time determined from these tests ($T_{arc\text{-}min1}$) is normally smaller than the minimum arcing time determined at lockout conditions ($T_{arc\text{-}min2}$) for reasons of low pressure or auxiliary voltage. Experience has shown that the difference between $T_{arc\text{-}min1}$ and $T_{arc\text{-}min2}$ can be as high as 1ms. This effect should be taken into account in the determination of T_{target} by introducing an additional security margin or by performing extra breaking tests at lockout conditions.

4.3.4 Recommended type tests for circuit-breakers for controlled switching applications

Type tests are used to verify a circuit-breaker's ability to fulfill the requirements for controlled switching under realistic operational conditions. They do not require any calculation to interpret circuit-breaker performance and therefore provide definitive proof directly. Normally the circuit-breaker properties verified by these type tests will already have been determined during the development stage.

The validity of unit tests must be carefully considered since possible discrepancies in the mechanical scatter of a single chamber can be practically impossible to extrapolate to the whole CB pole. Full pole tests are preferable.

4.3.4.1 Scatter of close and open times

The mechanical scatter is a design dependent characteristic and therefore should be verified on a type test basis. This measurement could be integrated into the mechanical endurance test series specified by circuit-breaker standards [2]. The values of the mechanical operation times are generally represented by a normal distribution. Under this assumption, the statistical scatter for close ($\sigma_{O\text{-}mec}$) and open ($\sigma_{C\text{-}mec}$) times are calculated as the standard deviation of the distribution. The set of measurements to be included in the calculation should cover all operating conditions specified for mechanical tests at normal ambient temperature (20°C). The scatter at low temperatures shall be determined separately for verification. If they differ from those at the normal temperature range and no temperature compensation is available this shall be taken into account when setting the close and open targets in the controller.

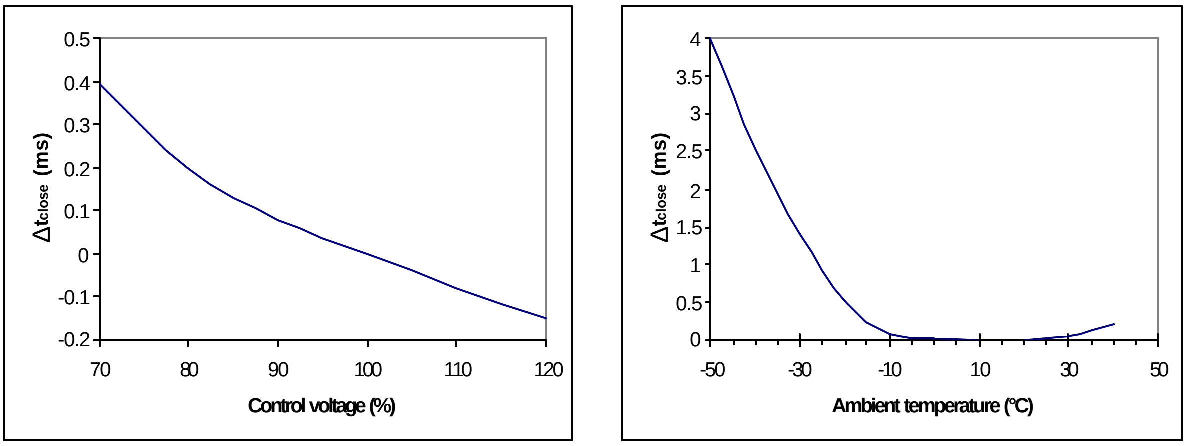
Some designs of three-pole and gang-operated circuit-breakers have a fixed delay time between poles. For these, the standard deviation of the operating times can be normally assumed to be identical for all three poles. However, if there is any doubt regarding the validity of this assumption it is recommended to determine $\sigma_{O\text{-}mec}$ and $\sigma_{C\text{-}mec}$ for each circuit-breaker pole individually.

4.3.4.2 Influence of external parameters on close and open times

External parameters may affect the circuit-breaker's close and open times. Normally such influences are reproducible and can be represented by characteristic curves which should be determined experimentally for close and open individually. In cases where a significant sensitivity to external influences exists but is not reproducible it may not be possible to demonstrate the suitability of the circuit-breaker for controlled switching. Implementation of such characteristic functions in the controller is an efficient means to compensate for variations in the circuit-breaker's operating times. The circuit-breaker design will define the relevant characteristics. Generally, the most common are:

Variation of close and open times as a function of the control voltage

Tests shall be performed covering the full range of control voltages foreseen in service. A statistically significant number of measurements shall be performed. Forty measurements over the entire range is recommended. A typical characteristic curve is shown in Figure 4-10 a) for the close time.



a) control voltage characteristic

b) temperature characteristic

Figure 4-10. Example of characteristic curves for variation of close time as a function of control voltage and as a function of ambient temperature. Δt_{close} = 0 corresponds to the rated close time.

Variation of close and open times as a function of ambient temperature

Tests should be performed for the full range of ambient temperatures over which the circuit-breaker is intended to operate satisfactorily. This temperature range will normally be that defined in the circuit-breaker standards. Special application temperatures such as –50°C shall be considered whenever specified. Refer to Figure 4-10 b) for an example of a temperature characteristic.

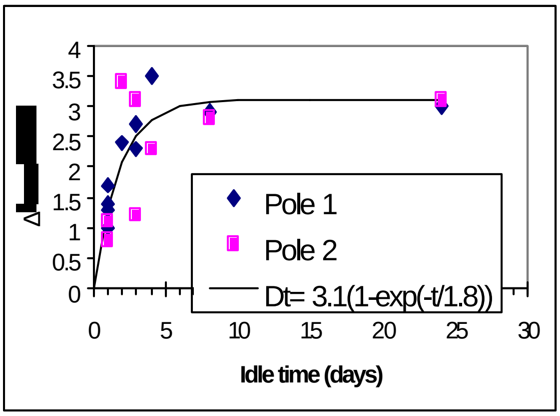
Variation of close and open times as a function of drive energy

Close and open time measurements at the minimum (lock out), maximum, and rated drive energy shall be performed. A characteristic curve shall be obtained.

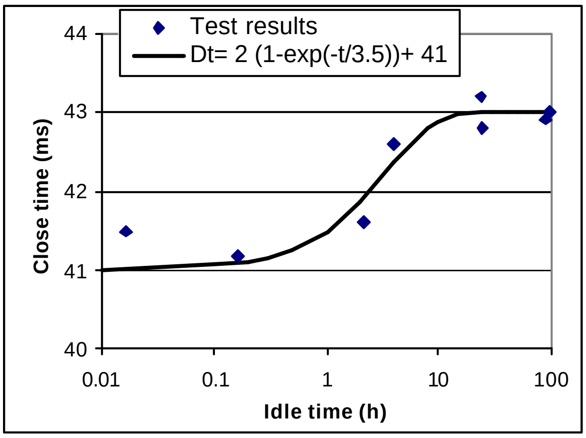
Variation of closing and opening times as a function of idle time

Investigations carried out by this working group have demonstrated that most existing circuit-breaker designs have close and open times which are affected by the idle time. This is a design dependent influence and should be taken into account for controlled switching applications. Figure 4-11 gives some examples of variations of closing time as a function of idle time for different circuit-breakers and for different type of mechanisms. These examples demonstrate that it may be necessary to take into account the idle time characteristic when choosing the set point for the close target in the controller. These examples demonstrate that all circuit-breaker designs exhibit different behaviour and that it is not possible to define generally applicable rules for idle time sensitivities.

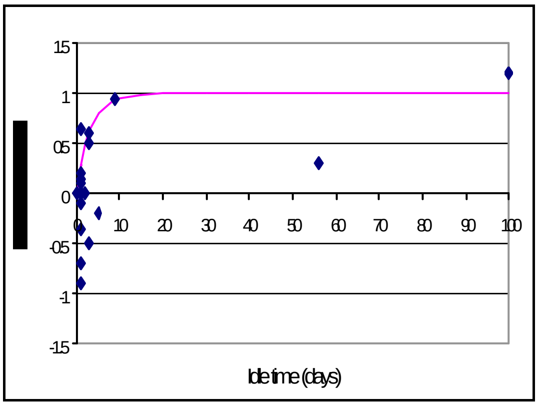
Since each circuit-breaker design has a broadly reproducible idle time characteristic this should be determined such that, if necessary, it can be compensated within the controller.



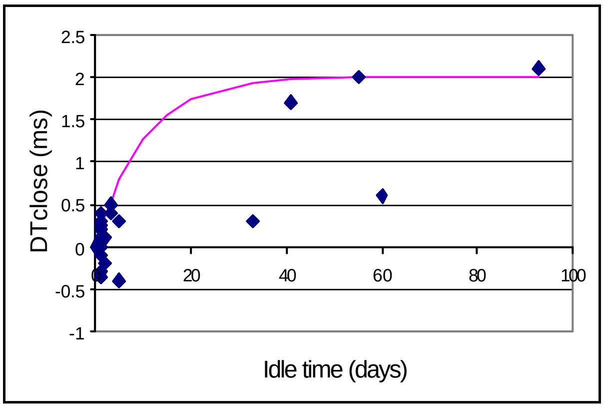
a) spring drive



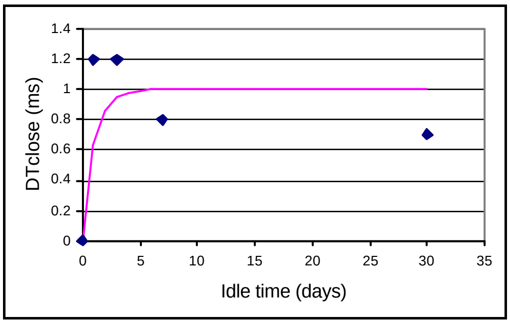
b) spring-hydraulic drive



c) spring drive



d) hydraulic drive



e) Spring drive

Figure 4-11 Example of idle time characteristic of SF_6 circuit-breaker with different drive mechanism

The following test procedure is recommended for the determination of the relationship between the idle time and the operating times.

Tests should be performed on two independent poles in order to get some statistical information. Rated conditions of control voltage and drive energy should be used and the ambient temperature should be measured such that its influence can be eliminated by compensation. Initially 20 operations should be performed in order to define the mean operating time and its standard deviation. Subsequently, depending on whether testing of closing characteristics or opening characteristics are of interest, operating cycles of C-1min-O-1min-C-1min-O or O-1min-C-1min-O-1min-C should be undertaken after idle times of :

- 1 hour
- 8 hours (one working day)
- 16 hours (one night)
- 64 hours (one week-end)
- 104 hours (one working week)
- 232 hours (one working week + two week-ends)
- 720 hours (one month)

The duty cycle has been chosen in order to determine whether the second operation after an idle time returns to the mean value.

Variation of close and open times as a function of phase spacing for three-pole operated circuit-breakers equipped with mechanical staggering

The dynamic behaviour of mechanical links between poles are generally affected by the space between adjacent poles. This influence shall be determined.

General remark

If some of the parameters, listed above, which influence the operation time are not compensated by the controller, or eliminated by any other means - e.g. coil heating at very low ambient temperatures - the corresponding variations of close and open times shall be considered for the determination of T_{target}.

4.3.4.3 Controlled switching test

This test aims to verify the controlled switching ability of the tested circuit-breaker for closing targets at voltage zero and voltage peak. Realistic voltage conditions (including phase factors) and the power frequency of the intended application case shall be applied. For example, loads with directly earthed neutral generally require 1.0p.u., ungrounded loads 1.5p.u. The RMS value of the test voltage is given by eq. 4-1. The simplified test circuit is similar to the one in Figure 4-2.

The test series should be performed at operating conditions representing those found in the network. The following items present some suggestions for these important testing requirements.

4.3.4.3.1 Operational conditions for controlled switching tests

Since operating conditions of circuit-breakers have a major impact on controlled switching performance they should be considered carefully for type test purposes. In principle, all operating conditions influencing the close/open times as well as the RDDS shall be taken into account. Exceptions can be made for those conditions that are compensated by the controller.

Even in state-of-the-art of controlled switching applications drift of the RDDS due to variations of operating conditions are not compensated by controllers. For modern SF_6 circuit-breakers two parameters which affect the RDDS are gas pressure and drive energy a discussed in 4.3.1.3. The former is an indirect measure of gas density which determines the dielectric strength of the contact gap. The latter directly affects the contact speed. Extreme conditions of these two parameters should be considered in the tests. The results of these tests should correlate well with the curve presented in Figure 4-9.

In order to simplify the test procedure those operating conditions directly affecting the close and open times can be taken into account by adding up their extreme variations. These extreme operational conditions can be simulated for testing purposes by incorporating them in the setting values of t_{target}. An overview of the most important operating conditions, together with a method of incorporating them into the controlled switching tests, are presented in Table 4-2.

		Operating conditions	
Directly considered (extreme values must be directly applied in the tests)	SF_6 gas pressure	Lockout	Rated
	Drive energy	Lockout	Rated

a) Operating conditions applied in the tests

		Minimum	**Maximum**
Indirectly considered (extreme values considered by means of close/open target)	Control voltage	$\Delta T_{1\text{-}min}$	$\Delta T_{1\text{-}max}$
	Ambient temperature	$\Delta T_{2\text{-}min}$	$\Delta T_{2\text{-}max}$
	Idle time	$\Delta T_{3\text{-}min}$	$\Delta T_{3\text{-}max}$
Extreme variations of close/open times for testing		$\Delta t_{min} = \sum_{i=1}^{3} \Delta T_{i-\min}$	$\Delta t_{max} = \sum_{i=1}^{3} \Delta T_{i-\max}$

b) Operating conditions that can be represented by variations of the close/open targets (refer to Figure 4-7).

ΔT_{i-min} = *(minimum close/open time variation from the respective characteristic curve)*
ΔT_{i-max} = *(maximum close/open time variation from the respective characteristic curve)*
Remark: parameters compensated by the controller shall not be considered.

Table 4-2. Operating conditions to be considered for controlled switching tests.

4.3.4.3.2 Recommended test procedure for close operations

The test procedure shall be performed by means of point-on-wave control of the tested circuit-breaker following the recommendations given below:

- Tests should be performed for closing at voltage zero and/or at voltage maximum adopting the various operating conditions given in Table 4-2.
- The close target for the circuit-breaker should be prescribed by the manufacturer. This recommendation is based on the information gathered during circuit-breaker testing (Subsection 4.3.1.2).
- The same number of test operations should be performed for each voltage polarity. It is recommended to perform at least 6 close operations per voltage polarity for each test series indicated in Table 4-3. This will result in 48 shots each at voltage zero and at voltage peak.
- A maximum value of pre-strike voltage should be specified as an approval criterion for the circuit-breaker. If the circuit-breaker pre-strikes at voltages higher than the specified value the target should be corrected and the whole test series repeated.
- The circuit-breaker has passed the test only if the measured making voltages in all test series and for all test conditions specified in Table 4-3 are lower than specified.
- A typical test oscillogram for closing at voltage zero after a negative last voltage loop is shown in Figure 4-12.

Test series	Close at voltage zero	Close at voltage peak
1	Lockout SF_6 pressure, rated drive energy: $t_{target\_zero} = t_{target\_zero\_rated} + \Delta t_{min}$	Lockout SF_6 pressure, rated drive energy: $t_{target\_peak} = t_{target\_peak\_rated} + \Delta t_{min}$
2	Rated SF_6 pressure, lockout drive energy: $t_{target\_zero} = t_{target\_zero\_rated} + \Delta t_{max}$	Rated SF_6 pressure, Lockout drive energy: $t_{target\_peak} = t_{target\_peak\_rated} + \Delta t_{max}$
3 (most critical case)	Lockout SF_6 pressure, Lockout drive energy: $t_{target\_zero} = t_{target\_zero\_rated} + \Delta t_{min}$	Lockout SF_6 pressure, lockout drive energy: $t_{target\_peak} = t_{target\_peak\_rated} + \Delta t_{min}$
4	Rated SF_6 pressure, rated drive energy: $t_{target\_zero} = t_{target\_zero\_rated} + \Delta t_{max}$	Rated SF_6 pressure, rated drive energy: $t_{target\_peak} = t_{target\_peak\_rated} + \Delta t_{max}$

Table 4-3. Testing conditions for close operations.

For practical application of controlled switching the setting point of t_{target} for close operations at zero or peak voltage should be the rated values adopted in the tests, i.e. $t_{target\_zero\_rated}$ and $t_{target\_peak\_rated}$, respectively.

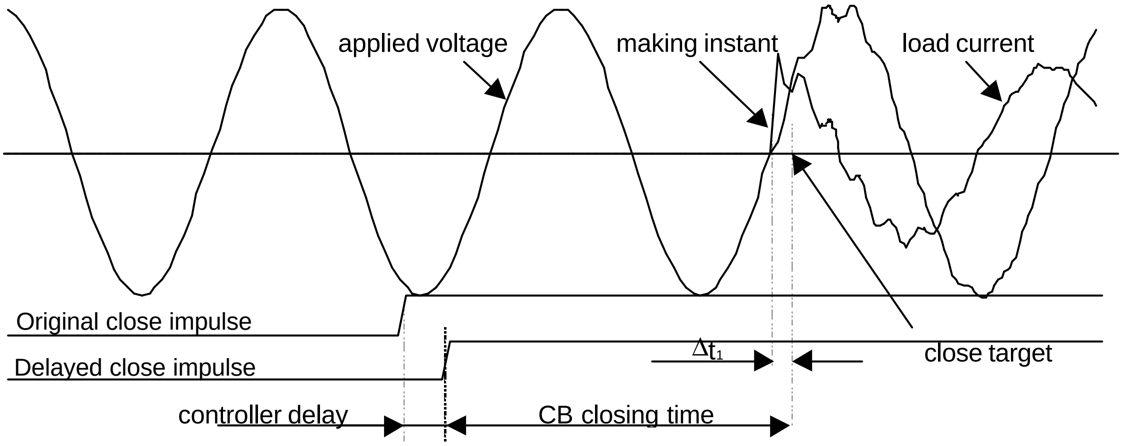


Figure 4-12. Example of test oscillogram of functional performance test of CSS. Note that the load current phase shift and shape are dependent on the test circuit.

4.3.4.4 Additional power tests for mechanically staggered circuit-breakers:

Circuit-breakers rated 100 kV and above are mostly subjected to single-phase switching tests for short-circuit conditions [2]. However, intentional pole delays and particularly mechanical staggering can lead to additional stresses. If this is the case the three-phase performance of the circuit-breaker shall be checked for the following cases:

- current making at three phase fault (100% I).
- current breaking at symmetrical and asymmetrical three phase fault (100% I).

4.3.5 Routine tests

The routine tests for mechanical operation, as specified in [2], are also applicable for circuit-breakers used for controlled switching.

For three-pole operated circuit-breakers with mechanical staggering the time delay between the poles shall fulfill the specified requirements for close and open operations. These requirements are generally defined in accordance with the relevant system studies for the intended switching application.

4.4 Complete system performance check

Confidence of the compatibility of controllers and circuit-breakers from different manufacturers can be derived from the individual test routines for these components, as described in Sections 4.1, 4.2 and 4.3. However, when implementing a particular combination of circuit-breaker, controller and sensors for the first time a performance check of the complete CSS is necessary.

In principle two categories of complete system checks are required, namely demonstration of the functional performance of the entire system and demonstration of the compatibility of the components involved (breaker, controller, sensors). These demonstrations can be achieved in a variety of ways and the following subsections propose testing regimes which meet these requirements whilst minimising the extent, and hence costs, of the tests.

Compatibility testing (4.4.1) and functional testing (4.4.2) are not considered as Type Tests in the conventional sense. Nevertheless, it is important that they are undertaken the first time a particular combination of components is supplied as a CSS. No prescriptive guidance is presented regarding when the tests are undertaken but it is recommended compatibility and functionality are demonstrated at the earliest opportunity i.e. as soon as the various sub-components are brought together in a common location. Depending on the approach being taken this may, for example, be prior to routine testing (for complete system supply from a single source) or may be immediately prior to commissioning (for retro-fit applications to existing circuit-breakers). The testing regimes recommended in 4.4.1 and 4.4.2 are based upon their being undertaken in a factory/testing station environment and where this is not possible e.g. for retro-fit applications, a compromise approach to demonstrating compatibility and functionality which is achievable will be required.

If all devices involved are available at an early stage the compatibility test (4.4.1) can be performed before the controlled switching type test of the circuit-breaker (4.3.4). If compatibility is proven at this early stage all subsequent tests can be performed on the same configuration. However, it is notable that controlled switching tests (4.3.4.3) undertaken on a circuit-breaker as part of a complete system cannot be considered applicable for the same circuit-breaker used within a different system which may possess different overall characteristics. Nevertheless, if the controlled switching test is undertaken as a complete system test it eliminates the requirement for separate functional testing as detailed in 4.4.2. The relative benefits of these options must be assessed by the suppliers of controlled switching systems but particularly by the circuit-breaker manufacturers.

4.4.1 Compatibility of circuit-breaker, controller and sensors

It is assumed that the required compatibility of circuit-breaker, controller, and sensors is defined in the specification. Nevertheless it should be verified that these three independent components inter-operate as intended when brought together. The controller shall be connected to the circuit-breaker and sensors and all necessary settings carried out. The test procedure consists of several point-on-wave close operations of the circuit-breaker by means of the controller. No primary high voltage signal is necessary since the reference signal for synchronisation can be fed to the controller from a low voltage AC source. Compatibility of the parts is verified if the circuit-breaker contact touch moment in every shot is within the close target range as defined by the closing time setting point of the controller and the mechanical scatter of the circuit-breaker. Refer to Figure 4-13. If the controller features adaptive timing adjustments a few adaptation shots can be done first.

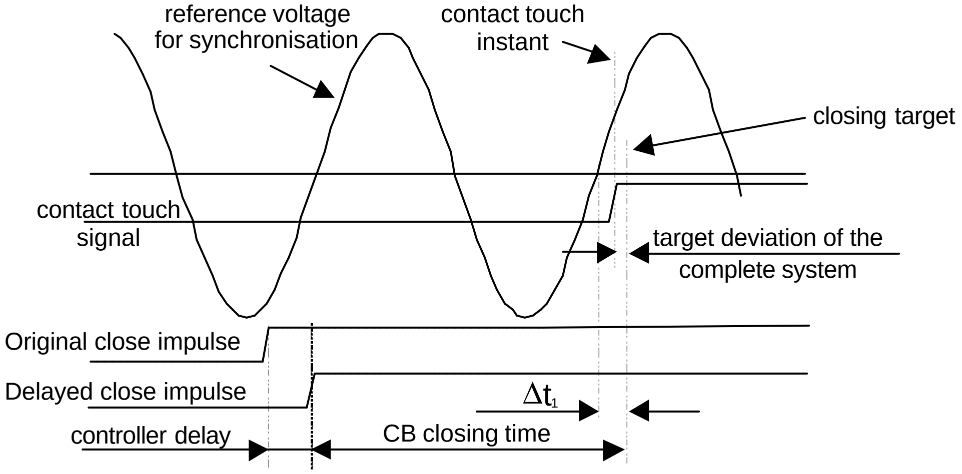


Figure 4-13. Example of test oscillogram for the compatibility test of circuit-breaker, controller, and sensors.

4.4.2 Functional performance test of the complete system

These tests consist of a repetition of those described in item 4.3.4.3, performed on the entire system with a reduced number of shots. In every case the variations of the close instant caused by external parameters should be taken into account. In practice, for each test series foreseen in 4.3.4.3, the respective value of the corrected t_{target} (t_{target_zero} and t_{target_peak}) shall be set in the controller.

If the compatibility check (4.4.1) was completed earlier, as described above, the controlled switching tests (4.3.4.3) could be carried out on the entire system of circuit-breaker, controller, and sensors. This procedure offers verification of both functional performance of the whole system as well as compatibility of the involved hardware under realistic operational conditions without the need for additional test series. In this way the overall effort for field testing can be minimised.

4.4.3 Commissioning tests

Commissioning tests shall be limited to the minimum possible in order to avoid inconveniences for network operation and associated site tests costs. The type tests and routine test procedures defined in this document take into account this strategy however, utilities must be fully aware of the importance of making provision for comprehensive commissioning tests to ensure satisfactory in-service performance.

Site tests are decisive to guarantee the successful operation of controlled switching installations. They are particularly vital to ensure precise settings for the circuit breaker open and close times. Every time the circuit breaker is re-assembled these times can suffer small variations and therefore the values to set in the controller shall be those obtained during circuit breaker commissioning at site. Fine tuning of set points of other controller parameters may also be needed. In short, site tests shall consist of

- check of the setting values for close and open time: the values obtained during circuit-breaker commissioning at site shall be adopted
- check the setting parameters
- carry out a few controlled switching operations prior to energisation of the primary circuit. These operations should be used to verify that the circuit-breaker closes at the pre-defined closing target. The test procedure as defined in item 4.4.1 and illustrated in Figure 4-13 should be used.
- repeat the test described in the previous paragraph, but with energised primary circuit. It might be necessary to fine tune the close and/or open times set points under real operational conditions[2].
- check for alarms if applicable.

Experience has shown that, due to the complex nature of controlled switching the completion of a commissioning sequence of this nature does not fully guarantee future performance. Following the initial commissioning series which, by necessity, will be of limited duration, it is strongly recommended that further performance checks are undertaken. These may take the form of periodic checks at suitable intervals or the permanent installation of simple transient monitoring equipment which, for new installations, is considered a beneficial, cost effective addition.

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[2] Real operational conditions refers not only to obvious parameters such as operating voltage but also to parameters such as extremes of the expected operating regime (idle times etc).

5 References

[1] CIGRE WG 13.07, “Controlled Switching of HVAC Circuit-breakers: Guide for Application.”, Part 1: Electra, No. 183, April 1999, pp. 43-73. Part 2: Electra, No. 185, August 1999, pp. 37-57.

[2] IEC 60056 (formerly IEC56), 1987, with Amendment 3, 1996

[3] IEC/TR2 61233 (formerly IEC 1233), 1994

[4] IEC60694 (formerly IEC 694), 1996 (under revision)

[5] IEC 60255-5 (formerly IEC 255-5), 1977

[6] Task Force 13.00.1 of Study Committee 13, “Controlled Switching – a State of the Art Survey”, Part 1: Electra, No. 162, October 1995, pp. 65-96. Part 2: Electra, No. 164, February 1996, pp. 39-61.

[7] CIGRE WG 13-09 (Condition Monitoring and Diagnostic Techniques for switching Equipment) of Study Committee 13 (Switching Equipment), “User Guide for the Application of Monitoring and Diagnostic techniques for switching Equipment for rated Voltages of 72.5kV and Above”. CIGRE Technical Brochure No. 167

Appendix A: Standards for Type Testing of Controllers and Sensors

This appendix gives references to international standards and other requirements that are potentially applicable to type testing of controllers and sensors in a CSS. Depending on the intended nature and location of each device's application, the relevant tests shall be selected, performed and documented by the manufacturer. For special applications additional tests can be performed by agreement between manufacturer and user.

In preparing the detailed test specifications the latest available edition of each standard should be used and the issuing year of the standard included in the test report.

In the lists below an indication is given whether each standard applies to controllers (column "Contr.") or sensors (column "Sensor"). If left blank, the standard does not apply.

Dielectric withstand tests

These tests verify the ability of a device to withstand high voltage signals without suffering any damage.

Test	Standards reference	Contr.	Sensor	Remarks
Power frequency voltage withstand	IEC 60255-5	y		
	ANSI C37.90	y		
	IEC 61180-1	y	y	
	IEC 60694	y	y	
Impulse voltage withstand	IEC 60255-5	y		
	ANSI C37.90.1	y		
	IEC 61180-1	y	y	
	IEC 60694	y	y	

Electromagnetic immunity tests

These tests verify the ability of a device to function properly when subjected to various electromagnetic disturbances.

Test	Standards reference	Contr.	Sensor	Remarks
General	IEC 61000-6-2	y	y	EMC immunity standard for industrial environment
1 MHz burst	IEC 60255-22-1	y		
Electrostatic discharge	IEC 60255-22-2	y		
	IEC 61000-4-2	y	y	
Radiated electromagnetic field	IEC 60255-22-3	y		
	ANSI C37.90.2	y		
	IEC 61000-4-3	y	y	

Test	Standards reference	Contr.	Sensor	Remarks
Fast transient/burst	IEC 60255-22-4	y		
	IEC 61000-4-4	y	y	
Surge	IEC 61000-4-5	y	y	not to be mistaken for impulse voltage withstand tests
Conducted disturbances induced by radio-frequency fields	IEC 61000-4-6	y	y	
Power frequency magnetic field	IEC 61000-4-8	y	y	
Pulse magnetic field	IEC 61000-4-9	y	y	
Damped oscillatory magnetic field	IEC 61000-4-10	y	y	specifically for equipment in HV substations
Oscillatory waves	IEC 61000-4-12	y	y	
Conducted, common mode disturbances	IEC 61000-4-16	y	y	
AC power quality disturbances	IEC 61000-4-11	y	y	only for AC powered devices
	IEC 61000-4-14	y	y	
	IEC 61000-4-28	y	y	
Ripple on DC power supply	IEC 61000-4-17	y	y	only for DC powered devices

Note: the tests formerly specified in IEC 801 are now contained in IEC 61000.

Electromagnetic interference tests

These tests verify that the operation of a device will not disturb other nearby equipment.

Test	Standards reference	Contr.	Sensor	Remarks
General	IEC 61000-6-4	y	y	emission standard for industrial environment
Electromagnetic emission	IEC 60255-25	y		
	CISPR 11	y	y	
Conducted EMI	IEC 60478-3	y		for input lines of stabilised power supplies

Mechanical tests

These tests verify the ability of a device to withstand mechanical forces without suffering any damage or malfunction.

Test	Standards reference	Contr.	Sensor	Remarks
Vibration (sinusoidal)	IEC 60255-21-1	y		
	IEC 60068-2-6	y	y	
Shock	IEC 60255-21-2	y		
	IEC 60068-2-27	y	y	
Bump	IEC 60255-21-2	y		
	IEC 60068-2-29	y	y	
Seismic (earthquake)	IEC 60255-21-3	y		
	ANSI C37.98	y		
Bounce	IEC 60068-2-55	y	y	
Vibration (sine-beat method)	IEC 60068-2-59	y	y	recommended for devices mounted directly on the circuit-breaker

Environmental tests

These tests verify the ability of a device to withstand environmental influences without suffering any damage or malfunction.

Test	Standards reference	Contr.	Sensor	Remarks
Cold	IEC 60068-2-1	y	y	
Dry heat	IEC 60068-2-2	y	y	
Damp heat, steady state	IEC 60068-2-3	y	y	
	IEC 60068-2-56	y		
Damp heat, cyclic	IEC 60068-2-30	y	y	
Change of temperature	IEC 60068-2-14	y	y	
Composite temperature/humidity cyclic test	IEC 60068-2-38	y	y	for devices located outdoors
Sulphur dioxide	IEC 60068-2-42	y	y	for contacts and connections
Hydrogen sulphide	IEC 60068-2-43	y	y	for contacts and connections made of silver or silver alloys
Salt mist (cyclic)	IEC 60068-2-52	y	y	

Test	Standards reference	Contr.	Sensor	Remarks
Combined cold/vibration	IEC 60068-2-50	y	y	
Combined dry heat/vibration	IEC 60068-2-51	y	y	
Protection provided by enclosures	IEC 60529	y	y	IP Codes
Fire hazard (needle flame)	IEC 60695-2-2		y	

Other tests and requirements

This section contains tests and requirements for controllers and sensors that are not standardised at the time of publication of this report. However, they are considered helpful for practical application as well as for development and integration of the components of a CSS. In any case, this information should be included in the documentation of any device.

Test or requirement	Contr.	Sensor	Remarks
Maintainability and reliability	y	y	include analysis of the less reliable objects
Precision		y	±0.25% over the full range
Recovery time	y	y	< 1 sec. With the same precision (after removal of power or the input signal)
Response time	y	y	(specified by the application)
Drift		y	< ±0.25% per year
Functional	y	y	In addition to standard functional tests, verify the system behaviour during abnormal conditions (e.g. out of range input, signal oscillation, etc.)
Reverse polarity	y	y	To verify if the equipment power input can withstand a polarity inversion
Visual inspection	y	y	First quality insurance procedure
Documentation	y	y	special option or modification description
Tests sequence	y	y	describe also if and how the tested equipment can be maintained during a test series