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**CIRCUIT-BREAKER CONTROLS
FAILURE SURVEY ON
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SYSTEMS**

**Working Group
A3.12**

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Members and Contributors of Working Group A3.12:

**Harley Wilson (Convenor), George Curcanu, Hiroki Ito, Thierry Jung,
Thomas Küng, Eva Pagán-Díaz, Gunvantray Patel, Stanislaw Pokora**

Corresponding Members:

Mark Blundell, Jens Burger, René Smeets

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1 Introduction

The CIGRE Report of the Second International Enquiry on High Voltage Circuit Breaker Failures and Defects in Service, published in 1994 (Reference 1), showed that approximately 25% of the major and minor failures of circuit breakers in service were caused by control circuit failures. This was the third highest cause of failure after operating mechanisms and leak tightness of SF₆ gas systems and associated monitoring. Since this observation is of concern to both operating utilities and manufacturers, CIGRE established Working Group A3.12 to further investigate the nature of control circuit failures and to make recommendations on how to improve the reliability and performance of circuit breaker control systems. Working Group A3.12 was formed to focus solely on circuit breaker control system reliability. The first objective of this evaluation was to determine the nature of recent control system failures and to ascertain whether the failures reported in 1994 remain as frequent with more modern technologies. The second objective was to determine the cause of these failures and to make recommendations on corrective actions which would reduce or eliminate failures. The second objective also involved looking in detail at the potential for improved control system reliability by implementing advanced electronic control systems.

In order to achieve the first objective, a limited survey concerning the frequency and nature of circuit breaker control system failures was conducted in 2002 – 2003. This gave a worldwide overview of experience with different technologies. A total of 339 failures were reported from 27 utilities representing 13 countries and 4 continents and these are summarized in References 2 and 3. Since very limited data was obtained on electronic controls from this survey, these reports did not include any analysis of electronic control systems.

This is the second and final report of Working Group A3.12 which summarizes the causes of the observed control system failures and possible corrective actions to improve circuit breaker control system reliability including the possible impact of more advanced, electronic control systems on control system reliability. The survey summarized in the first report of Working Group A3.12 identified six components which accounted for 88% of the reported failures. Although in this first report the failures were distributed approximately equally between the components, a re-evaluation of the data showed that relays were responsible for a larger percentage of the failures than any of the other components (twice as many reported failures than any other component). Potential causes of failure were summarized by the Working Group members based on their individual experiences and the data from the survey were then reviewed to determine the failure causes identified in the survey.

Since little data on electronic control systems was reported in the first A3.12 report, another limited survey of operators was conducted to determine the experience with electronic control systems. This included what benefits were expected and realized, what were the concerns with electronic systems, and what further actions would it take to cause the users to increase their use of electronic control systems. The results of this survey are also summarized in this report.

Based on the failure causes identified above, corrective actions which could improve control system reliability were identified and are summarized in this report. These corrective actions focused on both conventional technologies and improvements that could be achieved through the use of more modern electronic control systems. These corrective actions provide a guide which can be used by both users and manufacturers to improve control system reliability.

2 Data Analysis

2.1 Introduction

An initial analysis of the results of the first A3.12 survey was summarized in the first report of the Failure Survey on Circuit Breaker Control Schemes (refs 2,3). The survey was conducted to include all types of high voltage circuit breakers (SF₆, Oil, and Air Blast). Since almost all recently installed equipment reported in the survey was of SF₆ technology, it was decided to focus the remaining analysis in this report on SF₆ circuit breakers only. In developing future actions to improve reliability, additional evaluations of some aspects of the data and the previous data analysis were performed by the Working Group resulting in some modifications to the original data and analyses. These modifications included eliminating data where it was not obvious that the failure was caused by the control system and where the component that failed was initially mis-classified. These evaluations are summarized below. In addition, several key points from the previous analysis that are relevant to potential control system reliability improvement are repeated below for ease of reference. However, not all of the original evaluations and analyses from the first reports are repeated here, only those felt to be relevant to potential improvements.

In the first A3.12 report, the functions of circuit breaker control systems were summarized and a functional schematic diagram was developed. This schematic diagram formed the basis for identification of components used in the evaluation of the survey data and is used later in this report to assess the potential impact of digital control systems. This information is summarized in this document in Appendix A.

During the detailed evaluation of the data, several cases were observed where the original data appeared to be mis-classified by the organization reporting the data. All of the failure data was reviewed and all potential misclassifications identified. Each of these potential mis-classifications was reviewed by the Working Group and a re-classification was agreed upon. A total of 17 failures were re-classified and re-assigned to the appropriate component. In addition, some cases were observed where the failure did not appear to be related to the control system. These cases were removed from the database.

2.2 Failure by Component

One of the key conclusions from the first report was that six components accounted for 86% of the control system failures of SF₆ circuit breakers (as compared to 88% for all types of circuit breakers). These components and the percentage of observed failures from the first report were:

- Coils (including associated resistors and capacitors) – 11%
- Wiring and joints – 11%
- Position auxiliary switches – 15%
- Auxiliary relays – 23%
- Energy limit supervision – 12%
- Gas density monitoring (including connecting piping) – 14%

The distribution among the components was generally in the range of 11% to 15% except for auxiliary relays which had the highest percentage at 23%. During the re-evaluation, it was also noted that the previous evaluation differentiated between “relays” (component 104) and “time-delay relays” (component 107). Since both of these categories are relays, it was decided that they should be combined for purposes of this evaluation. The revised data combined components 104 and 107 into a single category of “relays”. The revised evaluation described above is summarized in the following table.

Component	Component Number(s)	Number of failures	Revised Failure Percentage
Coils	101	25	11%
Relays	104 & 107	64	28%
Density Monitoring System (with piping)	106	31	14%
Energy Limit Supervision	105	31	14%
Auxiliary Switch	103	31	14%
Wiring & joints	102	23	10%
Others	-	21	9%

As can be seen in the table, the combination of relays and time delay relays changes the results of the evaluation somewhat. Whereas before, the components all had a relatively similar failure percentage, now a single component, relays, has a significantly higher number of failures than the others (approximately twice the percentage of the next highest component). Although there are still six components which constitute a total of 91% of all the failures, relays now have significantly more failures than any of the other components. This data is displayed in Figure 2.1.

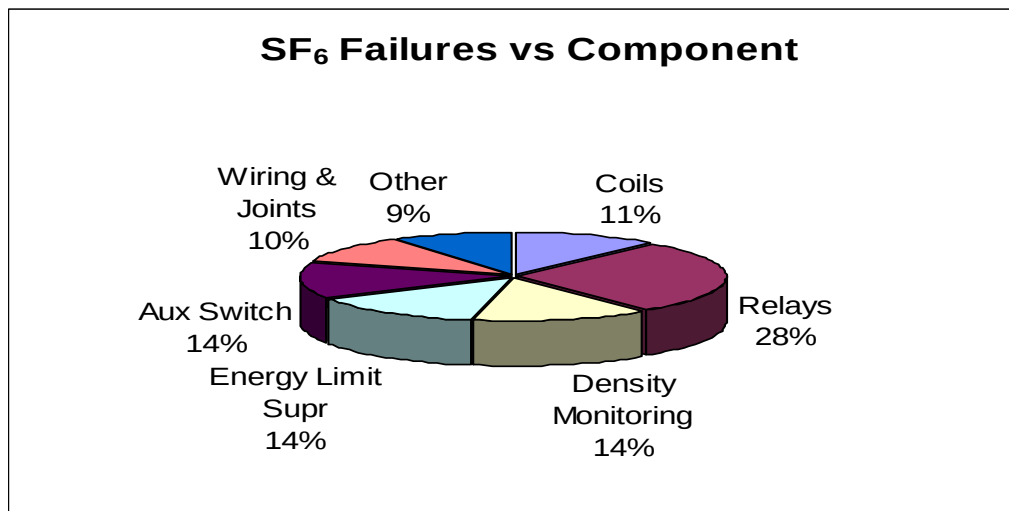


Figure 2.1: SF₆ Control Failures by Component Group (revised)

2.3 Time since Last Maintenance

One of the key conclusions from the first report was that a higher percentage of the failures in SF₆ circuit breakers are observed in the first 1-2 years after maintenance activities. These data were re-evaluated to determine the impact of the data modifications on this conclusion. It should be noted that the number

of years since the last maintenance operation was not reported for many of the data points and only data where specific time of maintenance information was reported were used in this evaluation.

The revised evaluation showed little change and is summarized in Figure 2.2. The number of failures tends to be higher in the first two years after maintenance and decreases after the first 1-2 years to a lower rate. This is observed for both the major and minor failures. Major failures are defined to cause one or more fundamental functions of the breaker to cease to operate. A major failure will result in an immediate change in the system operating conditions (e.g. require backup equipment to remove the fault), or in mandatory removal from service for unscheduled maintenance within 30 minutes. A minor failure is a failure other than a major failure. It can result in complete failure of a specific component, but does not result in a major failure of the circuit breaker.

This observation is thought to not be related to the specific activity performed, but instead, is likely related to the potential for human error during such operations. During maintenance and diagnostic activities, wires have to be disconnected and reconnected which can be an important factor in this observation. Therefore, the observation is interpreted as indicating that additional training and more detailed procedures would be beneficial whenever work is performed on a circuit breaker since there is the potential for human error during these operations. A potential reason for this observation could be that the number of skilled workers is decreasing which makes it difficult to obtain the necessary skilled workers for maintenance activities. This observation points to the need to educate and keep skilled workers in the electrical industry.

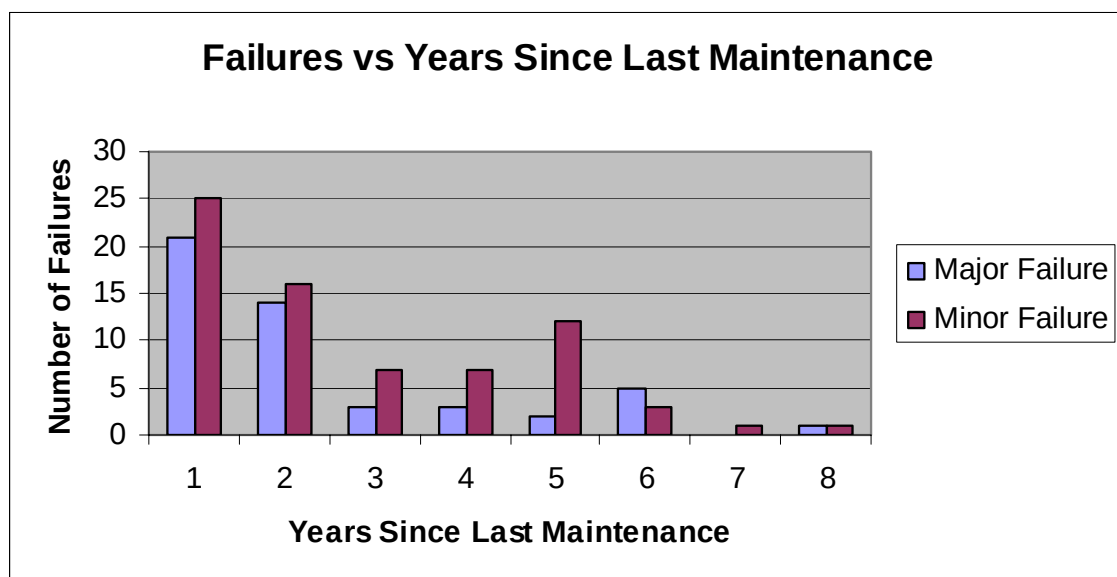


Figure 2.2: Distribution of Failures as a Function of Years since Last Maintenance

From a design perspective, devices such as multi-contact switches which would eliminate the need to disconnect wires would help reduce these types of defects. In addition, advanced monitoring functions have the potential to reduce or eliminate the need for maintenance.

2.4 Total Years in Service

The timing of the major and minor failures for the SF₆ circuit breakers is summarized in Figure 2.3. It is observed that the number of both the major and minor failures tends to be high for the first 2 years and then decreased to a lower rate. The failure rate for the major failures subsequently increased in years 10 through 13 and then decreased again. The minor failures showed a similar trend, but tended to increase at 7 years and then showed a larger increase again in years 10 - 13. It should be noted that the number of SF₆ circuit breakers with years of service greater than ~15 years is limited and this should be considered when attempting to draw any conclusions from the data beyond ~15 years.

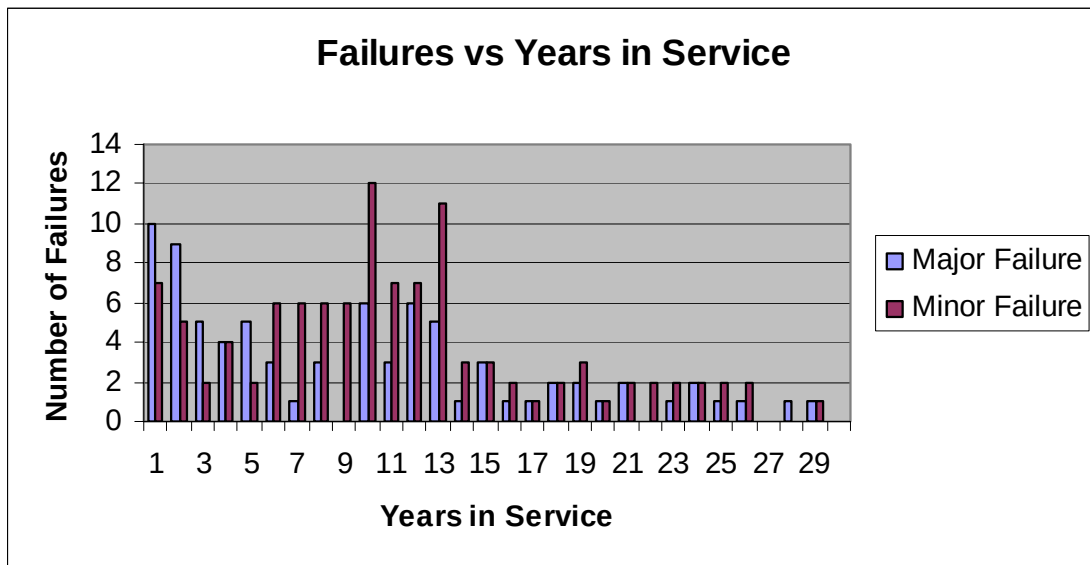


Figure 2.3: Distribution of Failures as a Function of Total Years in Service

Following the logic established in reference 4, the initial high failure rate might indicate a “teething” (or infant mortality) failure pattern. The subsequent increase in both the major and minor failures could be interpreted as indicating a “wear-out” failure pattern. However, it is known that maintenance is generally performed in the time frame of 7 to 13 years which would tend to increase the number of minor failures detected by inspection. Therefore, the increase in failure rate in years 7 through 13 could be due to maintenance activities and may not be a wear-out phenomenon. The increase in failure rate in the first few years following maintenance activities discussed in Section 2.3 is also consistent with this observation.

3 Evaluation of Main Survey Results, Failure Causes and Corrective Actions

3.1 Introduction

The survey data for the six control system components identified to be responsible for the majority of control system failures in the survey were reviewed to determine the causes of failure for each of the components. This information was then used to determine what corrective actions would help to eliminate or reduce the observed failure causes. The Working Group reviewed the available data and determined the predominant causes of failure for the individual components. In the review of the data, it was noted that, in some cases, the data tended to be somewhat limited and did not always allow as exact a determination of the root failure causes as would be desired.

The evaluation of the failure causes is divided into three main sub-sections. In order to provide background on potential failure causes for the specific components, an overview of possible failure causes for the individual components was developed based on the experiences of the Working Group members. The failure causes observed from the specific data reported in the survey were then summarized. Lastly, potential corrective actions to eliminate or reduce the observed failure causes are summarized.

In the review of the failure data, it was observed that the causes of failure typically fell into one of three general categories. The first was a design or manufacturing related issue which would occur in the design or fabrication stage of the circuit breaker and could be the result of a design flaw, improper selection of components, and/or a manufacturing related problem. The second category was related to the overall engineering co-ordination and project management of the project involving the circuit breaker. These issues would involve inadequate co-ordination between the users of the equipment and the circuit-breaker supplier or site engineering deficiencies. Examples would be failure to identify and specify the proper environmental or operating requirements or inadequate power supplies at the site. The last general category concerned the operation and maintenance of the circuit breaker after installation. The discussion of the failure causes observed in the survey and the potential corrective actions were divided into these three general categories.

As stated earlier, there was little information on the performance of digital control systems in the original survey. Potential corrective actions discussed below were identified for both the conventional technologies reported in the data and those that could be achieved with more modern digital systems. The intent of this input was to attempt to identify how digital control systems could impact the reliability of circuit breaker control systems and eliminate some of the observed failure causes.

The discussion of the causes of failure for the six critical control system components is summarized below.

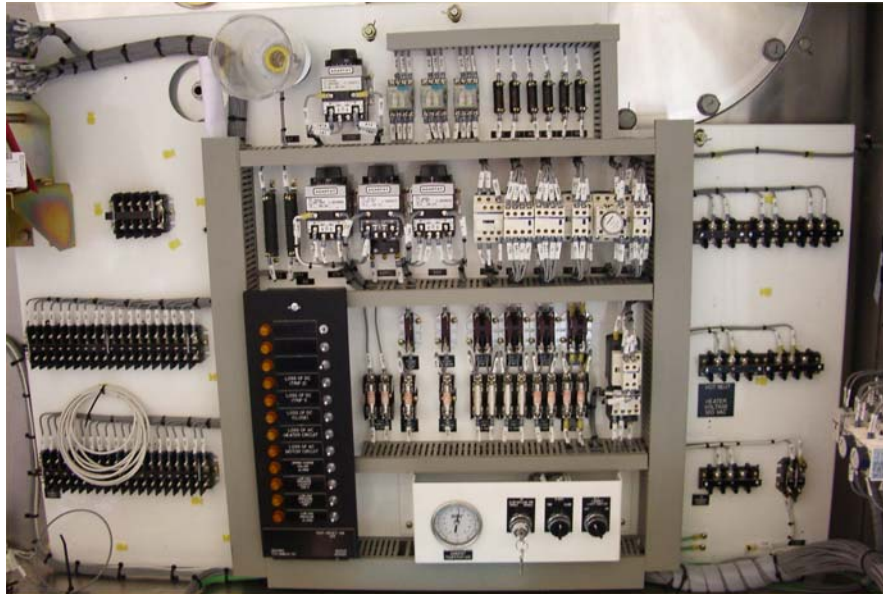


Fig. 3.1 Typical breaker control panel

3.2 Trip and Close Coils

3.2.1 Possible causes of failure

Failure of a trip or close coil will almost always result in a failure of the circuit breaker to operate and is, therefore, of great concern. Trip and close coils can cause operational problems due to several potential failure causes which are summarized below:

- The power supply to the coil does not get interrupted by the auxiliary switch and current flows through the coil for an extended period of time. Since these components are designed for a short time thermal rating, they will be thermally overloaded resulting in failure of the winding when the current flows for a longer time.
- If the winding has poor insulation, inter-turn failure can occur. The failure could be between adjacent turns or the turns of adjacent layers. The absorption of moisture in the insulation can have a detrimental effect on insulation performance.
- The coils are generally connected directly to the grounded terminal of the battery without any break. If the coil is directly connected to the ungrounded terminal of the battery without any break, when the contacts are open on the grounded terminal, the coil will remain at some potential resulting in electrolytic current flow. As a result, dust and dirt can accumulate on the winding causing degradation of the coils over a long period of time.
- Electromagnets (the coils) are mounted directly on the mechanism which experience significant vibration during operation. When care is not taken in design and/or manufacturing, the components can become loose, causing the electromagnet setting to be disturbed. This can cause the electromagnet to not pick-up and fail to operate the circuit breaker. In such cases the coil can fail due to the application of a continuous signal.

- The control voltage power supply can also cause problems. For example, low control voltage at the circuit breaker will cause the electromagnet to not to move. The circuit breaker will not operate causing the auxiliary switches to not operate and interrupt the control current which will result in thermal failure of the coil. Low control voltage can be caused by improper design of the battery distribution system (e.g. power rating of the battery, power consumption of other equipment in the substation, excessive loss due to cable length with insufficient cable size, etc).
- When a supervision relay is used to monitor the status of the coils, a very low current flows through the coil continuously. If the current limit is not selected correctly this may cause over heating of the coil resulting in coil failure. If the monitoring current is too high, it may also prevent the release of the coil once it has operated.
- Two trip coils are commonly provided to increase reliability of the trip function. These coils typically have separate magnetic circuits, however, some designs use a common magnetic circuit where the two trip coils are wound adjacent to each other on the same core. In such cases, a failure of one coil can cause failure of the second coil resulting in an inability to operate the circuit breaker and reducing overall reliability.
- In some designs, a capacitor is used in the trip circuit to increase the operational speed of the circuit breaker (a “snubber circuit”). This introduces another component into the trip circuit which is prone to failure and can prevent operation of the circuit breaker.

The above are potential failure causes for shunt coils, however, many of these potential causes are also applicable to other electromagnets in the circuit, such as relays and contactors (Section 3.5).

3.2.2 Survey results

Of the 25 coil related failures, 24 had sufficient information on the failure to allow an assessment to be made of the failure cause. The observed failure causes for trip and close coils are summarized below:

- Hardware issues (~70% of these were failures of capacitors in the trip circuit)
- Human error
- Burnt or partially burnt coils
- Signal applied for an excessive time
- Loose hardware

Since coils directly activate the circuit breaker’s moving parts, undetected coil failure very often translates into a major failure making coils a very sensitive part of control schemes. Most of the coil failures (50%) came from hardware issues and, more specifically, a significant proportion of these failures (~70%) came from failure of capacitors used in the circuit for the purpose of accelerating the coil plunger operation (“snubber circuits”). In this case, the auxiliary circuit used to accelerate tripping was the weakest link in the trip circuit. Human error and burnt or partially burnt coils were responsible for the majority of the remaining failures.

Design issues:

Since approximately half of the failures were hardware related, the quality of the specific components appears to be an issue however, it should be noted that the majority of the hardware failures were with capacitors in the trip circuits, not the coils themselves. Poor quality components or improper design are likely to be the cause of these capacitor failures. One can point to possible progressive issues concerning insulation material (aging, sometimes accelerated when coupled with the presence of water), vibration, or electrolytic corrosion in these components. In many of the reported cases, better design or better material could have prevented failure.

Engineering, co-ordination and project issues:

A few burnt or partially burnt coils were reported. The failure cause for burnt coils is usually found outside the control cubicle being due to low control voltage as discussed above.

Operation, maintenance:

Some cases were reported where safety devices intended for maintenance staff protection were responsible for failures because of improper handling during, or after, maintenance. A typical example would be where prevention pins which were inserted into the circuit-breaker to prevent inadvertent operation during maintenance operations and were left in place after the maintenance was completed. The circuit-breaker would be prevented from operating in response to subsequent commands resulting in an extended electrical signal and causing coil burn-out.



Fig. 3.2 Typical Coil Failure

3.2.3 Possible improvements

Design issues:

It appears that some progress can still be made towards better quality of the coils and associated components (e.g. capacitors) to improve resistance to

ageing, chemical oxidation and contamination by foreign materials. These issues cannot be improved by digital control or more advanced technology unless coil free control solutions are used (a motor drive for instance).

Engineering, co-ordination and project issues:

From the point of view of system reliability, a solution for the capacitor related failures would be to use better designed coils (e.g. lower pick-up voltage) which would eliminate the need for the snubber circuits and hence the need for the capacitors in the trip circuit. Indeed, many operators do not permit the use of capacitors in the trip circuits due to their lack of long term reliability. Another improvement would be to avoid the use of very long supply cable and thereby reduce the associated resistive losses. By switching the coil through a local auxiliary relay more energy can be applied to the coil. If long cables are unavoidable use of a larger cross-section conductor for the control system will reduce the voltage drop and improve reliability.

The risk of a burnt-out coil resulting from an excessive duration tripping current could also be reduced externally by setting the circuit-breaker relay timing to a short time (100-200 ms) providing that this is compatible with the protection scheme. This could also be accomplished within the control cubicle by directly operating the coils through solid state transistors and limiting the duration of the coil command to levels that would not burn the coils. In addition, the use of an auxiliary voltage supervision system would ensure that the quality of local auxiliary power supply is adequate (voltage level) so current flowing through the coil does not exceed its limits in terms of both magnitude and time.

As stated above, the coils are critical components since their failure will generally result in a failure to operate which is classified as a circuit-breaker major failure. Coil supervision relays that transmit coil status in real-time to upper level control and command systems would restore somewhat the availability of the control chain. A failure immediately detected prior to there being a failure to operate would allow for quick maintenance operation and/or immediate back-up procedures, thereby reducing the risk of major failures.

A more radical solution would be to remove the need for coils altogether by switching to a completely new solution for activating moving parts of circuit-breaker. An example would be using a motor directly coupled to the main shaft (Reference 5).

Operation, maintenance:

As is the case for other issues, keeping maintenance practices simple will reduce the potential for human error during and after the maintenance operation. Proper and up-to-date training and the use of defined procedures are necessary to help reduce the potential for errors during maintenance operations.

3.3 Wiring and Joints

3.3.1 Possible failure causes

The various control components form a logical circuit made up of wires, the termination of the wires at the various components, and the physical layout of the wiring.

Termination of wires is very important for reliability and historically, lugs have been used to terminate the wires on the components. Possible causes of failure of the lugs can be summarized as follows:

- o The lug can become loose and cause high resistance due to improper attachment. This in turn causes heating, and ultimately, failure of the joint. Accepted practice is to use calibrated crimping tools to ensure that all crimps are properly applied.
- o The lugs may be inadequately insulated causing exposed metallic connections, which can result in short-circuiting of the wiring.
- o Wire terminations have a tendency to become loose when the wired equipment is mounted in the mechanism which experiences vibrations. Special care needs to be taken to avoid loosening of the screws in these applications.

When the lay out, or routing, of the wires is incorrect, interaction with the other parts of the circuit breaker may occur. This could be with the moving parts of the mechanism or other components and, in such cases, the wires may get damaged during operation and cause a short circuit in the wiring. The presence of wires in close vicinity to heaters may cause damage to the insulation and eventual failure and a short circuit.

During maintenance, wires may be disconnected many times from their original position which carries a risk that they are not re-installed in their original position following the maintenance. This could cause mis-operation of the circuit breaker if not detected during re-commissioning.

3.3.2 Survey Results

Given the very high number of wires, screws, crimps, and clamps used in control cubicles, the fact that only 11% of all failures reported are due to these components is a testimony to the high quality of today's practices and products. The reasons for failure are varied and diffuse: no major reason can be singled out but a variety of causes were observed such as bad joints, disconnected wiring, human error, loose screws, etc. Only a few observations were made for each of the failure causes. The failure occurrences for each of the causes were very low in frequency with a maximum of 6 observations for an individual cause, with typically 1-3 failures for each cause and with no major cause or reason identifiable.

3.3.3 Possible Improvements

Design issues:

One way to reduce wiring related defects is to eliminate the amount of wiring and connections. Some users have started to avoid using lugs by connecting the wire directly onto the equipment, a practice which eliminates one extra joint and which is gaining popularity. Other innovative solutions are being adopted for terminations such as the use of spring-loaded terminals which are gaining popularity due to their special advantage in situations where vibration is a concern.

From a general point of view, the Working Group has assumed that a reduction in the number of wires to be manually connected, and the associated operations to connect wires, will lead to a reduction in the number of wiring related failures. Products or systems, such as pre-assembled bundles already fitted with connectors, that will facilitate industrial installation and tests are to be preferred. Micro-processor based programmable logic controllers (PLC) can replace external wiring by integrated circuits and since the electronic boards are individually tested during the production process (by both in situ and functional tests) a large portion of the wiring in the control cabinet or marshalling box can be replaced by a mass-produced and fully tested integrated electronic circuit. Such a digital control solution should also reduce the risk of human errors during maintenance due to faults in wiring and joints (loose screws, low quality crimps, wiring errors, etc.) by drastically limiting the numbers of wires and the number of human operations within the cubicle.

Engineering, co-ordination and project issues:

No major issues in this area are proposed. As always, attention to detail during the manufacturing process of the circuit breakers should reduce the number of failures due to this cause.

Operation, maintenance:

Improvement can be achieved by taking greater care in the organization, storage and availability of complete ("as-built") wiring documentation. In many cases it was reported that after a few years of service, accurate documentation was not easily available on site. A potential method to improve this situation would be to store all drawings in an electronic format either in a centralized data management system or in a decentralized location, perhaps in a digital device in the circuit breaker itself.

In addition, care should be taken in maintenance operations to ensure that the wiring is not damaged and, if disturbed, is always returned to its original configuration.

3.4 Auxiliary Switches

3.4.1 Possible failure causes

The auxiliary switch is a critical component which breaks the current to the operating coils and ensures proper operation of the circuit breaker and protects the coils from thermal damage. Typically, auxiliary switches consist of standard switching elements which are operated by a linkage system. They can be

categorized into two main types: those that are dependent on the velocity of the main contact and those that are independent of the velocity of the main contact.

Failure of these switches could be mechanical or electrical in nature but will result in an inability to carry or interrupt current. The number of auxiliary contacts in a switch varies depending on the needs of the user and it is clear that the load on the shaft increases when the number of switching elements is increased. This, combined with the speed of operation, can result in failure of the switch and a switch used for one application may not be able to be used for another application.

The mounting arrangement of the switch is very important. Any misalignment that occurs during or after mounting can cause undue stresses on the switch which can cause failure. The current carrying capacity of the switch may deteriorate with time due to ageing if it is not protected from adverse environmental conditions. It is frequently observed that auxiliary switches are exposed to direct rain due to damaged or poorly maintained enclosures. It is essential that the switches are protected from undue effects of extreme conditions

Since auxiliary switches are used for both coil current interruption (control) and position signaling (monitoring), failures can have different results. Failure to perform a control function would typically result in a burnt out coil or leave the control circuit permanently open and not operable. Although this would not prevent the circuit breaker from operating during the operation leading directly to the failure, subsequent operations would be impossible or would have to be made through a back-up trip circuit if one is available, with possible severe consequences for the network.

Failure to perform a monitoring function could result in improper blocking of operation or spurious operation e.g. due to a pole discrepancy relay operation. Improper indication of the state of the circuit breaker due to a mal-functioning auxiliary contact can lead to damage to other portions of the network (e.g. incorrect information for circuit-breaker failure protection).

Auxiliary switch failures are generally mechanical in nature resulting in a degradation of the steady state or switching capability which in turn leads to thermal failure during normal current carrying conditions or excessive burning of the material. Defective auxiliary contacts can occur due to contamination inside the auxiliary switch block (insufficient Index of Protection (IP) rating) which could lead to corrosion of the contacts. Self-wiping contacts have been used to address these problems and seem to have had satisfactory results.

3.4.2 Survey results:

Of the observed auxiliary switch failures, a significant percentage (32%) could not be assigned a failure cause. The most significant identifiable failure cause for these mechanical components was defective contacts which accounted for 42% of the observed failures. At least one of these failures was due to corrosion of the contacts. Failures due to being out of adjustment were also observed (19%) but very few failures due to short circuits were reported with one of them being attributed to heavy rain entering the control cabinet. It can be concluded

that present technology in this area is robust and seems difficult to improve upon, except in the area of material improvement.

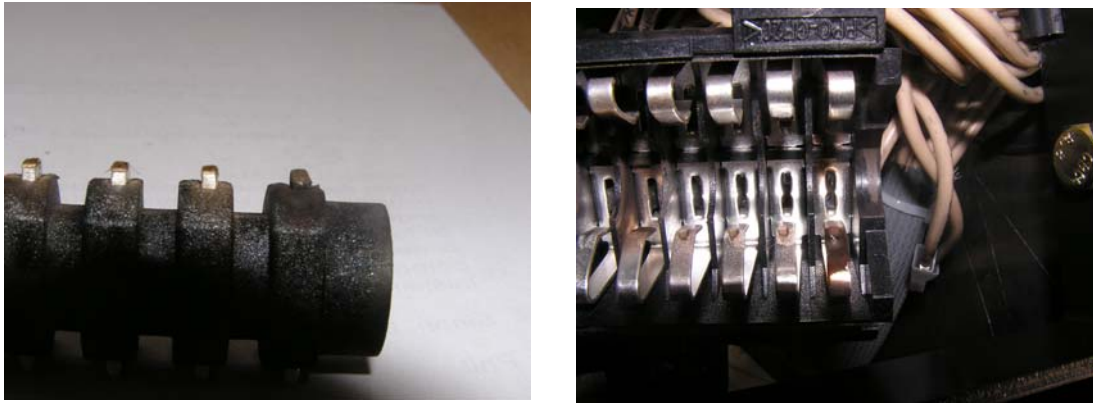


Fig. 3.3: Auxiliary Switch Failure

3.4.3 Possible improvements:

Design issues:

Redundancy of auxiliary contacts (two auxiliary contacts serially connected with the coil) is a simple way to improve the reliability of the coil current breaking function. This approach is commonly used for strategic switchgear (e.g. circuit-breakers controlling strategic high voltage transmission routes and generator circuit breakers). Although they do not improve the reliability of the individual components, the use of various monitoring systems have also been used to detect defects in the auxiliary switches and to prevent a severe failure.

The use of a coil supervision system can be used to detect auxiliary switches that have failed in the open position. More sophisticated supervision of coil energization (waveform shape and energization time) can give an indication of the ability of the auxiliary switch to interrupt the control current and can also detect sticky auxiliary switch contacts. If advanced monitoring is used in combination with conventional auxiliary switches, comparison of the auxiliary switch performance with other position/travel sensors (with self cleaning contacts directly mounted on the same shaft) may be use to detect incipient failure of auxiliary switches.

Typically, the largest percentage of auxiliary switch contacts is dedicated to signaling and conventional control schemes may use 24 (12 + 12) position indicating auxiliary contacts for a 245kV circuit breaker. Indeed some users require 48 (24+24) contacts to be used. This means at least 48 wires connected between the marshalling cubicle to the user's control interface. Alternative measurements of circuit breaker position and travel (through direct measurement using magnetic, electronic or optical sensors, or indirect measurement using motor drive characteristics, etc.) coupled with field bus (IEC-61850) serial communication could drastically reduce the amount of cabling, moving parts, screws, crimps, etc. required to perform this function. This reduction would make a major contribution to reducing failures associated with both traditional auxiliary switches and wiring.

Engineering, co-ordination and project issues:

As described above, poor environmental control in the control cabinet has caused some auxiliary switch failures. Better co-ordination of the IP rating of the auxiliary switch blocks and enclosure with the external environment would improve performance. This effort should take into account the IP rating of the control cubicle and external factors, such as humidity, salt, pollution, etc.

3.5 Relays

3.5.1 Possible causes of failure

Relays and contactors are electro-mechanical devices used in the circuit breaker control system. Relays are used to make a logical circuit to control operation of the circuit breaker, whereas contactors are used for load switching purposes (such as for motors, compressors, etc.). For the purpose of simplicity of analysis, contactors are considered to be a subset of relays in this discussion.

As noted in Section 3.2.1, many of the potential failure causes for coils are also relevant for relays however there is one significant difference between relays and operating coils; relays are designed to operate in a fully energized state for a prolonged period of time whereas trip and close coils are not designed to be permanently energized. For this reason, burnt out coils are not as large a concern for relays as for trip and close coils.

Several other factors for potential failure of relays are summarized below:

- Environment conditions (moisture levels, temperature, dust, etc.) can have a significant effect on the performance of relays. Relays with good IP protection, which are generally used for industrial applications, will have superior performance and will be less susceptible to environmental effects.
- Mass produced relays with good overall quality are generally available. However, at times, customized solutions are developed to meet specific operators' requirements and these may not be adequately tested for long term reliability. In such cases field experience will be the main indicator of reliability. The use of proven solutions with limited customization would reduce the likelihood of reliability issues.

In summary, the selection of the specific relays used in the circuit breaker, their mounting (vibration), and the design of the cabinet which houses the control components (environment exposure) all play an important role in reliable operation. An inappropriately selected relay may malfunction due to overloading or mechanical vibration. Incorrectly mounted relays may become loose and malfunction. Poor design for environmental control can cause exposure to aggressive environments and result in relay failure.

3.5.2 Survey results

Of the 64 relay failures (components 104 & 107) identified in the survey, only 36 had sufficient information concerning the failure cause to allow an assessment of the cause of failure to be made. The evaluation of failure cause was, therefore, limited to this data. The failure causes for relays observed in the survey are summarized below:

- Deterioration of contacts (environment)
- Environment effects on relays
- Hardware failures
- Burned contacts
- Misapplication of relay (not appropriate for the intended load)

It was difficult to draw any definite conclusions concerning cause. “Environmental” effects were responsible for a large fraction of the failures and many of these reports lack clarity regarding the specific cause. A large percentage (over 50%) of the relay failures were attributed to hardware related causes, many involving some contribution of environmental effects. As seen on several other components, failure of the contacts was a large contributor.

Design issues:

The deterioration of the contacts and many of the other failures were related to unfavorable operating conditions (water ingress into the control cabinet, temperature, corrosion, etc.). There are several sources of these issues including inadequate hardware (e.g. poor quality of the relays themselves) as well as inadequate protection of the equipment from environment in the design and manufacturing stage (cabinet humidity control, leaks, etc).

Engineering, co-ordination and project issues:

As was the case for several of the other components, burned contacts were responsible for a significant number of the relay failures. Failure to terminate the current in the relay contacts due to an outside cause could also lead to contact failure.

3.5.3 Possible improvements:

Design issues:

As a general observation, stronger IP requirements for the circuit breaker and resistance to mechanical vibrations at the component level would probably eliminate a lot of the relay failures. Improving the environmental conditions in the control cabinet would eliminate many of the reported failures. The use of relays intended for industrial application by the designer would be advisable since they usually have higher duty ratings and are more robust than standard relays.

The use of microprocessor based logic could greatly reduce or eliminate the need for relays. This would result in no moving parts, self testing of performance, possible software redundancy, and control panels being automatically tested at the factory. Since all electronic boards are individually tested during the production process, standardized internal logic would not be impacted by maintenance operations during the circuit breaker’s life.

Engineering, co-ordination and project issues:

Better co-ordination of the IP and vibration requirements between control cubicle and internal components would be beneficial. This would include items such as heating, ventilation, and moisture management in the control cubicle or cabinet. Monitoring of the cubicle internal temperature and anti-condensation system could provide back-up insurance if this concern was found to be a critical issue.

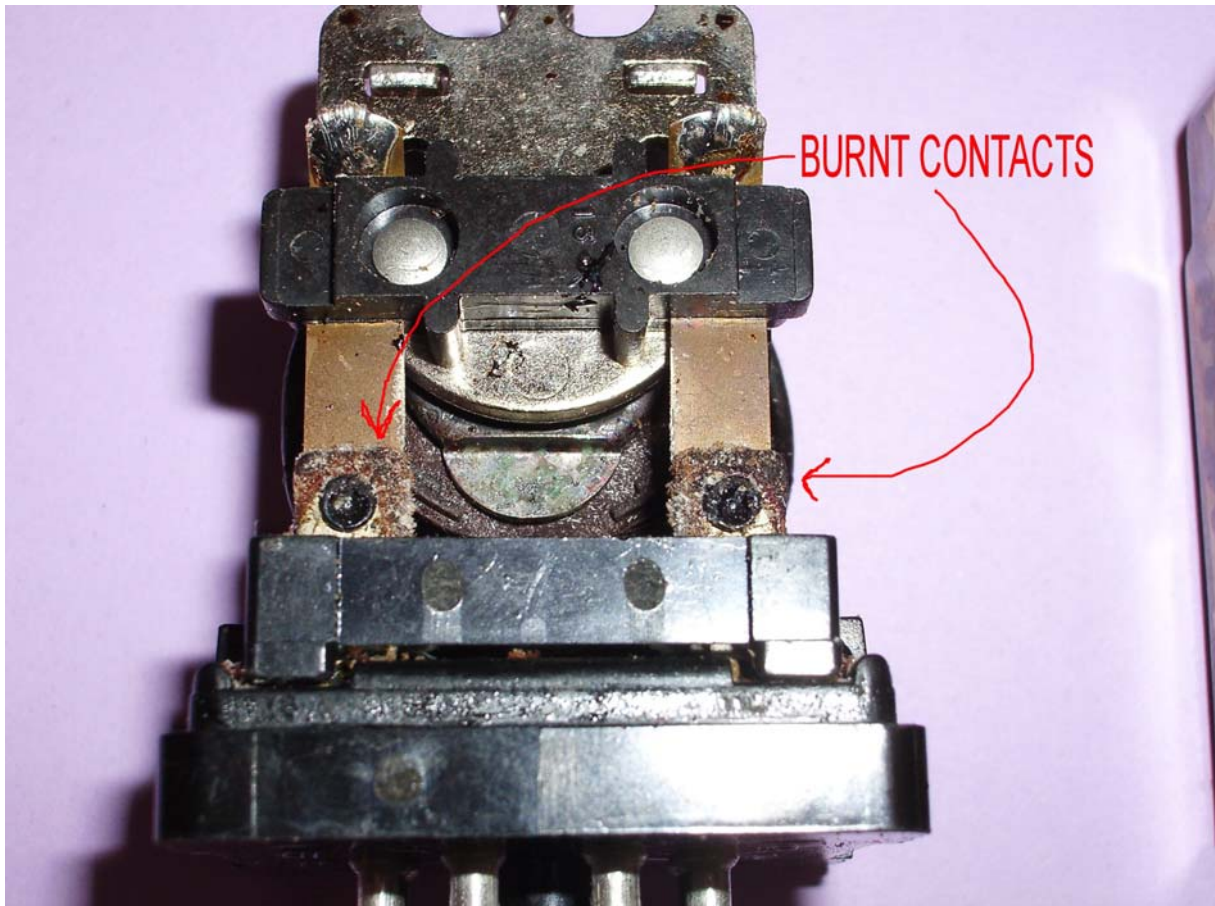


Fig. 3.4: Typical Relay Burned Contacts

3.6 Energy Sensors

3.6.1 Possible causes of failure

The type of limit switch used to manage the energy storage of a circuit breaker varies depending on the type of mechanism used. For spring mechanisms, a spring position sensing switch is typically used, whereas pressure sensing switches and sensors are used in hydraulic and pneumatic mechanisms which rely on compressed fluids (oil or air). These switches and sensors are the primary concern for the control of the energy systems but consideration must also be given to potential issues with the motors used to compress springs and drive compressors in hydraulic and pneumatic systems.

The observed problems are slightly more frequent in the case of hydraulic operated drives primarily due to leaks. The reasons for this could be the higher pressures and complexity of the hydraulic drives.

3.6.2 Survey results

The causes of failure for energy limit supervision can be grouped into the following general categories:

- Limit Switches
 - o Hardware (defective – mechanical or electrical)
 - o Adjustment

- Motors & contactors
- Contacts

The frequency of observed failures in the energy control system for hydraulic mechanisms was slightly higher than would be expected based on the overall distribution of hydraulic drives in the data base. Many of these observations were due to failures of the oil pressure sensing devices. Conversely spring drives were slightly lower than expected based on the data base distribution with all but one of the failures observed in the spring drive mechanisms involving limit switches. The frequency of observed failures in pneumatic systems was about the same as would be expected based on the data base distribution.

The predominant cause of observed failures was with limit switches (~45%). The majority of the failures were hardware related, but problems with adjustment were also observed. The hardware aspect of the problem is likely a design/manufacturing issue where either higher quality hardware should be used and/or a more robust design for the switch could be used, including the mounting arrangement.

Problems with motors and contacts were relatively low in frequency and appear to also be a hardware related issue. The relatively low number of failures would suggest that this is not a major issue.

The problem with output contacts of manometers and limit switches is an observation that was also observed in relays and density monitoring. This seems to be an issue covering at least three components (energy limit supervision, gas density monitoring and relays). The main causes are believed to be corrosion and oxidation.

In some cases, proper procedures to maintain control cubicles were probably not properly followed (open cabinet door with heavy rain or snow, pollution by salt, etc.) emphasizing the importance of proper co-ordination of IP ratings, operating conditions, and maintenance procedures is important.

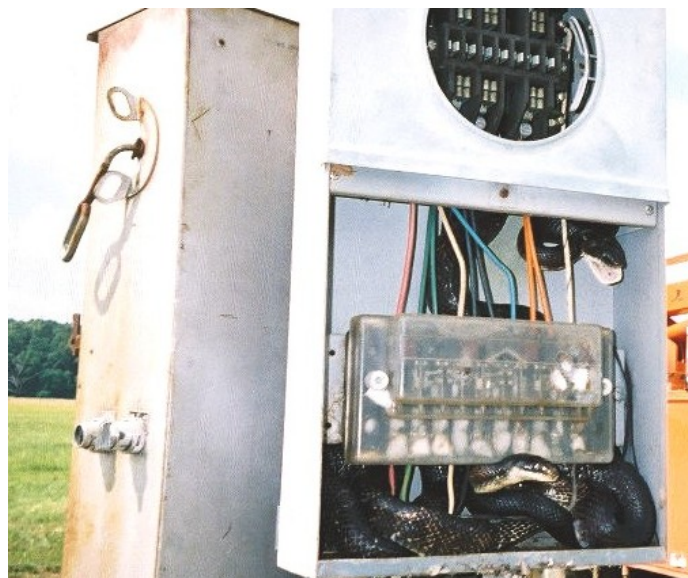


Fig. 3.5: Unwanted Inhabitants in a Control Cabinet

3.6.3 Possible improvements

Design issues:

The oil pressure monitoring of hydraulic mechanisms could be improved. This area was responsible for ~55% of the observed failures on hydraulic mechanisms.

It seems likely that a high number of hardware issues were caused by manometer set points drifting excessively over a period of years and efforts should be made to use manometers, limit switches, and contacts which are more robust in this regard. Where possible, it would be desirable to replace limit switches with more positive interlocks, sensors, etc to eliminate their need.

Simple monitoring (motor run time for spring drives, number of pump operations/day) can, if used correctly, provide an indication of the status of limit switches and contactors.

The use of other methods to detect spring position (e.g. an inductive switch requiring no physical contact) could possibly increase the reliability of this function. The use of pressure and position sensors which transmit information directly to a digital control device would eliminate the need for output contacts.

Engineering, co-ordination and project issues:

The rating of the motor contactors can be an issue and care should be taken when standardizing contactors, particularly if motor power supplies are not standardized. If not properly co-ordinated, varying power supply conditions could lead to high breaking currents which could damage the contactor.

Operation, maintenance:

Checking the run time of motor/pump operation during periodic maintenance is a very simple operation and could provide a good first indication of the switch/pump condition. More elaborate monitoring during operation, including on-line motor power consumption/motor current monitoring, would provide a more detailed status of the motor itself.

3.7 Density Monitoring System (including piping)

3.7.1 Possible causes of failure

The SF₆ gas density monitoring system has three main components, namely:

- Gas density monitor
- Gas pipes with manifold, if any
- Pressure (or density) gauge

Each of these three components will have different types of failure modes.

Gas density monitors are susceptible to the following types of failure modes.

- The density values where the switch operates can change due to disturbed mechanical settings. Vibration can cause a change in settings.
- The contacts may become corroded due to inadequate environmental protection. This could be due to poor design or the enclosures may not have been installed correctly.

- The selection of the density monitor is very important for low temperature applications and liquefaction in the reference gas volume can cause incorrect signals. Temperature compensation for the entire working range of the equipment may not have sufficient accuracy if a general-purpose solution is adopted.
- Poor brazing of bourdon tubes can lead to leakage of SF₆ gas. Environmental effects can also cause such joints to corrode and lead to leaking joints.

Gas pipes and manifolds introduce many joints in the system. These joints are often made at the site and are not as good as factory-made joints. They are also exposed to the external environment, which can cause deterioration due to corrosion or thermal cyclic loads and eventual leakage.

Pressure gauges are generally installed in the system to confirm the presence of the SF₆ gas and to monitor the gas pressure. The gauges are generally mounted outdoors, face an aggressive environment, and are connected through pipes and manifolds which are susceptible to leakage. The calibration of the gauges can become disturbed and cause the gauge to indicate an incorrect pressure after some period of operation. It may be desirable to have an indicator to monitor the pressure which is constructed in a manner to reduce the number of joints. Such indicators are available as a part of the density monitor which will reduce the possibility of leakage.

3.7.2 Survey results

The causes of failure for gas density monitoring systems observed in the survey can be grouped into the following general categories:

- Hardware issues with the gas density switches
- Leaks in SF₆ piping to the switches
- Environment related issues
 - o Corrosion of contacts
 - o Environment (temperature)

The primary cause of reported failures is with the gas density switches themselves. This is a design related issue and suggests that switches with improved reliability, or more reliable alternatives to switches, should be sought. Leaks in the SF₆ gas system also contributed to a significant percentage of the failures and appear to be a design or fabrication issue. Effects of the operating environment contributed to approximately 1/3 of the known failure causes. As was the case with other components, contacts were involved in some of these failures (~19%).

3.7.3 Possible improvements

Design issues:

Inadequate protection of connection boxes and the pressure gauge itself was found to be contributory to some failures. Whilst environmental controls were in place, poor aging performance of external components have been seen to result in leaks. At the design stage, seal design should take better account of expected operating environments, and particularly specific weather conditions, such that better long term performance can be expected.

The best stage to improve the reliability of the piping system is in the design stage. Examples of desirable practices are the use of o-ring seals instead of threaded pipe joints with compression fittings (especially in countries with high temperature variations), minimization of the number of piped and joints in the system and adequate environmental protection. In particular, maintenance of compression fittings is more problematic than with other systems. Advanced SF₆ gas density switches which reduce or eliminate the amount of piping are a major improvement.

In general, the reliability of density switches could probably still be improved.

Engineering, co-ordination and project issues:

An inadequate temperature compensation range was the cause of some of the observed failures where liquefaction occurred but was not recognized. The expected operating temperature range of the circuit breaker and ancillary equipment should clearly be checked carefully to be sure that the temperature range of the monitoring system is appropriate for the substation. It is the responsibility of the user to ensure that the operating environment is properly specified. More sophisticated temperature compensation algorithms which are part of digital control systems would also be of benefit, since they could offer temperature compensation over a wide range at no extra cost (assuming a digital control system is used).

Operation, maintenance:

Maintenance operations often require the operation of isolating valves to temporarily remove the gas density switch from the main breaker gas system in order to test the system set points. This allows the testing to be performed without impacting the gas density of the circuit breaker but care must be taken to ensure restoration of the isolating valve to its proper configuration. As these valves are a strategic part of SF₆ system, extreme care should be observed during this maintenance task (connection of pipes, valve manipulation, etc.).

4 Potential Use of Digital Controls

Digital control devices have been introduced over the past several years with varying results. As Intelligent Electronic Devices (IEDs) have been installed for some time now, it has been possible to gather some feedback from the users, including their expectations and their appraisal of existing solutions. Since modern digital control systems have the potential to improve the reliability of circuit breaker control systems, a survey was conducted by the Working Group members of users of digital control to determine their expectations for, and experience with, digital control systems to date. Although data came from a limited number of sources, since these users are evenly distributed around the world and can provide experience from a reasonably substantial circuit-breaker population, it is the feeling of the Working Group that these findings have a global application. The results of this survey and a general outline of the results are summarized below.

Controlled Switching Systems (CSS) have been installed for a relatively long time and seem to have better results than other digital systems. Whilst the reasons for this are unclear, it has been proposed that there has been good feed-back from field experience in this area which has led to much improved designs. Some negative feedback was reported from utilities that have already experimented with digital control systems and integrated control and protection systems. Reliability was a key concern with the currently installed digital systems. Some of the problems identified in the survey may be linked, to some extent, to the fact that the technologies were still in development and were early in their introduction into the market. With growing feedback and evolving technologies, it is the Working Group's expectation that many of the issues identified should substantially improve.

It was observed that many integrated communication systems are still installed but are operated as stand alone units in the field, without automated data collection or expert systems. Such applications do not take advantage of the biggest benefits one can expect from digital technology and they have been a major limitation in expanding this technology. This probably reflects the novelty of these systems and the fact that substation protocol standardization has been lagging behind technology for some time. Recent IEC efforts to define a standard protocol (IEC-61850 series) are a major step in resolving this issue however it will take some time for end users to fully modify their structure and organization to take full benefit of digital technology.

4.1 What are the user's expectations?

One aspect of the survey was to determine what functions or benefits users expect from the use of digital systems. These expectations are summarized below.

Equipment considered in the survey ranged from stand-alone monitoring systems to fully integrated monitoring and digital control systems. Since CSS systems are usually installed to reduce stress on primary equipment and

systems rather than to improve the circuit breaker control system reliability, their impact on control is somewhat unclear and can only be discussed in outline terms here.

As a general consideration, for all of these systems, it is expected that the IEDs come with integrated self diagnostic and automatic alarm functions and that the electronics are properly hardened for a substation environment (voltage transients exceeding IEC requirements, temperature, etc.). The benefits that are expected from digital control systems fall into two general categories: monitoring, and control and protection functions.

There are two specific benefits that the users expected from monitoring solutions:

- *Reduced maintenance requirements by switching to a condition based maintenance strategy.*

Maintenance requirements can be reduced either by completely deleting some parts of time and/or operation based maintenance programs, amending these, or optimizing maintenance crew activity based on information gathered. The strategy that will best suit a particular utility will depend on different factors such as labour costs, distance between substations and offices, warehouses, size and skills of crews, etc. Each case is specific and would necessitate some analysis before deciding whether to implement these IEDs. To be of real use to maintenance staff these systems must be able to transmit remotely and instantly all relevant data which implies the use of standardized or very well known communication protocols.

- Optimized lifetime management by making use of continuously available data of equipment condition. Typical expected benefits in this area are:
 - Further optimization of maintenance policies based on evolution of the installed pool
 - The ability to perform better failure analysis
 - Precise knowledge of the condition and availability of the circuit-breaker prior to any attempted operation or work activity
 - Improved planning of refurbishment, replacement, or useful life extension of considered breakers

The combination of a circuit breaker and a monitoring system has the potential to reduce overall life cycle costs however achieving this requires close co-operation between the users and manufacturers. Only by combining the technical expertise of the manufacturer with the operating experience of the user can the best result be obtained. It is generally agreed that these digital systems will show a lifetime comparable to Digital Control System (DCS) and protection, i.e. typically 15 years. This means that the users will have to replace them at least once during the life of the circuit breaker. In addition, the reliability of the IED should be high enough to not significantly compromise their expected benefits due to the occurrence of minor failures coming from new self diagnosis and alarm functions. Theoretically, Mean Time Between Failure (MTBF) calculations corrected by statistical analyses from the installed base should give a useful indication on the overall performance of the system.

Expectations for digital control systems are summarized below. The expectations generally fell into three areas: design, installation, and operation & maintenance.

Design

Traditional control functions should be expanded to include other functions such as auto-reclose protection. Due to the computing power of IEDs, this integration should translate into significant cost savings (i.e. one IED will perform at least two functions)

Improved supervision functions should include better (i.e. standardized) and faster communication protocols. It should be possible to replace parallel communication with serial communication which will reduce the number of cables required and, therefore, reduce cost. Integration of functions in the same IED should also suppress some unnecessary cabling. Of course, cost effective solutions resulting from improvements in design, engineering, installation, and commissioning are expected.

It is notable that there is a discrepancy between some users' request for low cost solutions (usually meaning standard, factory tested solutions) and customization to their own standards which reflect their past experience with conventional control systems and/or the need to co-exist with older technology. New digital control systems need to be versatile from both the hardware and software point of view to meet these sometimes contradictory requirements.

Installation

Equipment in relay and control rooms should be easy to replace and devices should be readily available from several independent manufacturers with the same, standardized interfaces. This requirement is considered to be essential to "open" the market for these new systems and to avoid users being constrained to purchase from a specific manufacturer. This is especially important when dealing with obsolescence. Considering the trend for takeovers and mergers in both the supplier community and the utilities the desire for an "open" market is understandable to facilitate integration and co-ordination. Today's practice is somewhat different from this with very few substations being fitted with new equipment from different manufacturers. However, developments such as IEC-61850 go some way to addressing this issue and should facilitate a multi-manufacturer approach.

Setup time should be optimized. Configuration costs account for a significant share of the total purchasing costs of present generation control schemes. Post setup training requirements should be reduced to a minimum and well documented Site Acceptance Tests (SAT) procedures should be available.

Operation & Maintenance

The installed equipment needs to perform reliably and not require excessive maintenance. Software and Man-Machine Interfaces (MMI) should be user-friendly. The display should show critical items in a concise format and not be difficult to interpret.

Tools developed for these new devices should be designed to minimize user's required training (i.e. visualization interface as close as possible to existing display, duplication of existing types of data.....). In addition staff skill levels and training need to be reviewed for appropriateness for their intended activity. Maintenance and operation staff need to have a clear view of how to interpret alarms regarding priority, urgency, the steps to be taken to solve the problem, and the likely cause. This result can be achieved either with training, or with built-in expert systems as an add-on layer to control and monitoring systems.

For IED systems based on digital technology it is very important that configuration, maintenance and test procedures are available and that their issue is well controlled. Multiple software releases have the potential to create a new source of failures if they are not properly managed. Users should be trained on these new products.

4.2 What is installed today?

The basic circuit breaker control scheme described in the first report and repeated in Appendix A covered only basic circuit breaker control functionality. Several manufacturers have started to introduce new systems based on digital technology to replace the basic control functions whilst incorporating extra functionality related to the circuit breaker in the substation environment. Additionally, there are cases reported of mixed conventional and digital systems.

The basic control scheme is repeated below:

Today's use of new technology generally falls into one of two main categories:

1. Additional functionality used with conventional technology
2. Replacement of conventional technology by digital technology which includes added functionality.

These two categories are summarized below:

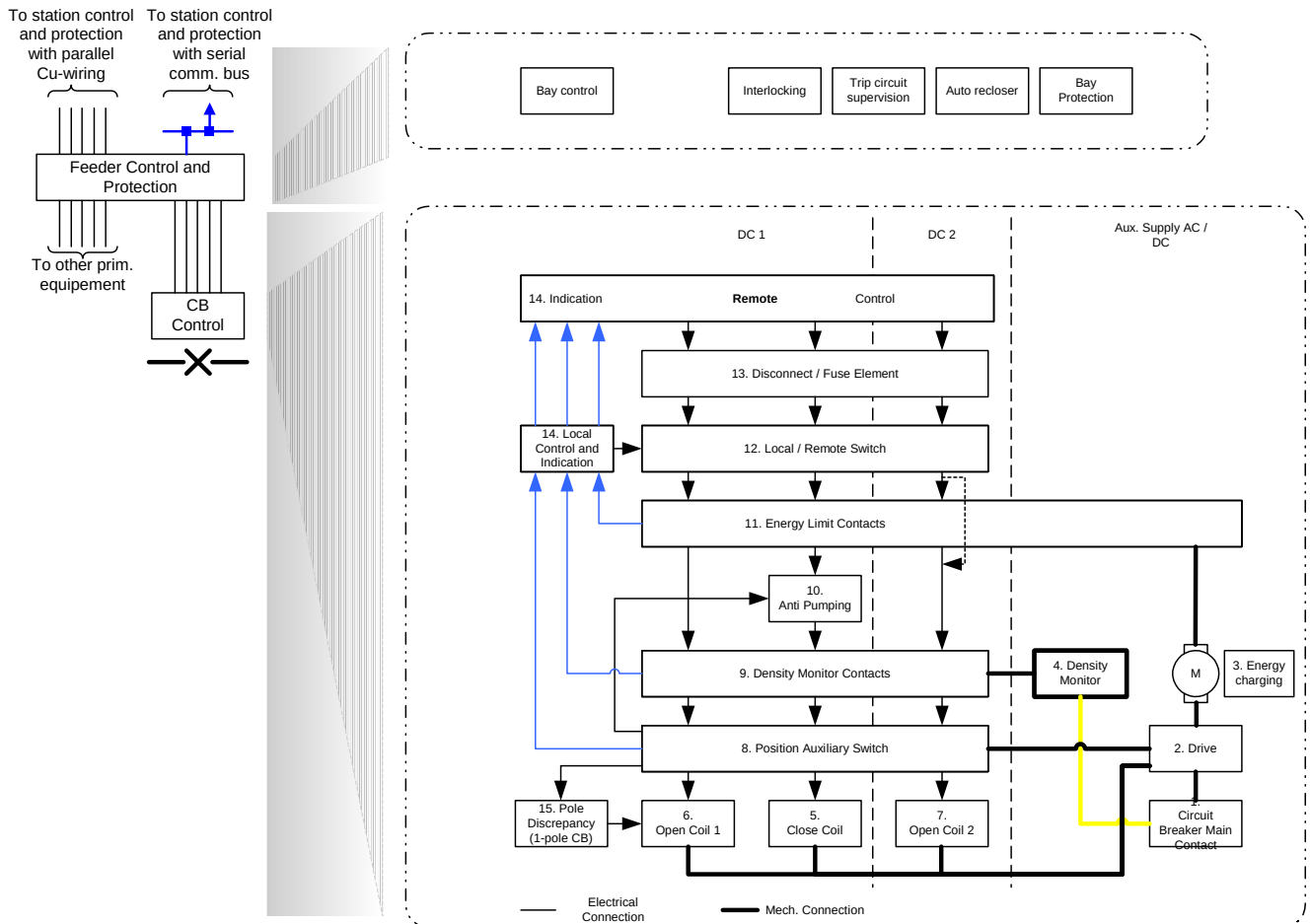


Fig. 4.1: Current Technology

4.2.1 Additional functionality with conventional technology

4.2.1.1 Control Switching System

This functionality is used to control the making or breaking point of a circuit breaker in relation to the voltage or current phase sequence so that the breaker opens or closes at the optimum point in order to minimize electrical stresses on the involved primary equipment.

4.2.1.2 Circuit-breaker monitoring

Several circuit breaker functions can be monitored. Examples are:

- Travel curve of circuit breaker
- Number of recharging system starts/day
- Maximum run time of the recharging system
- Counter of the recharging system
- Monitoring of anti – condensation device

In these applications, the CSS and monitoring functions are built in as separate, independent devices. These functions need information (e.g. actual primary voltage/current) in addition to that normally required for the circuit breaker control itself. With the exception of coil, voltage and heating supervision, these are additional benefits to improve the reliability of the secondary system.

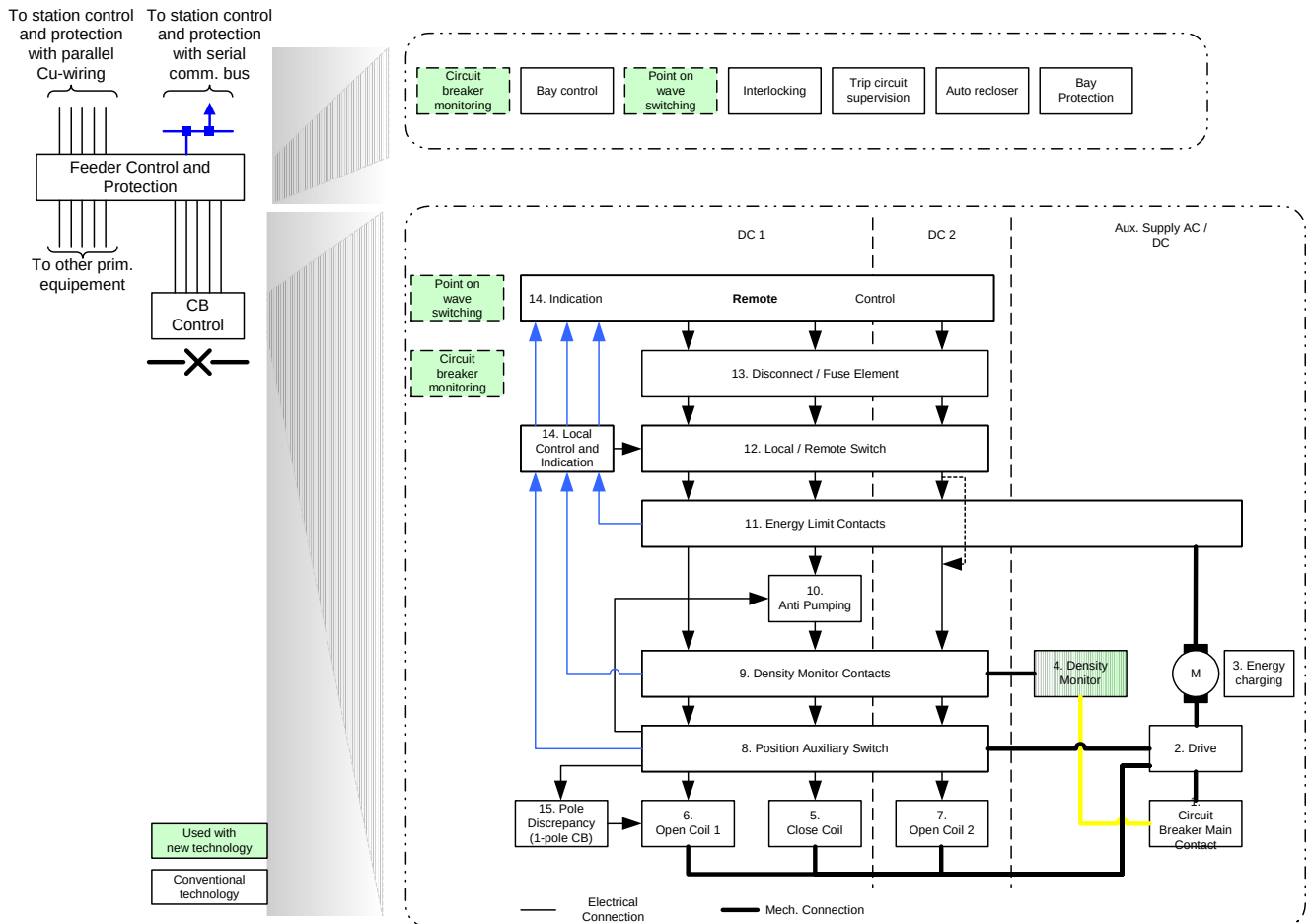


Fig. 4.2: Current Technology with Additional Functionality

4.2.2 Replacement of conventional technology

In this category, the digital control functions replace all or part of the conventional control technology. This can be considered in three technology steps:

1. Digital circuit breaker control with a conventional copper wired interface
2. Digital circuit breaker control with vendor specific interfaces
3. Integrated monitoring and control solutions (from the circuit breaker to the control room or maintenance office)

4.2.2.1 Digital circuit breaker control with conventional copper wired interface

This method of integrating digital control is used to simply replace existing functionality without the addition of significant functionality. All of the required information for substation functions are transferred by normal copper wired methods (e.g. position indication for interlocking, etc.)

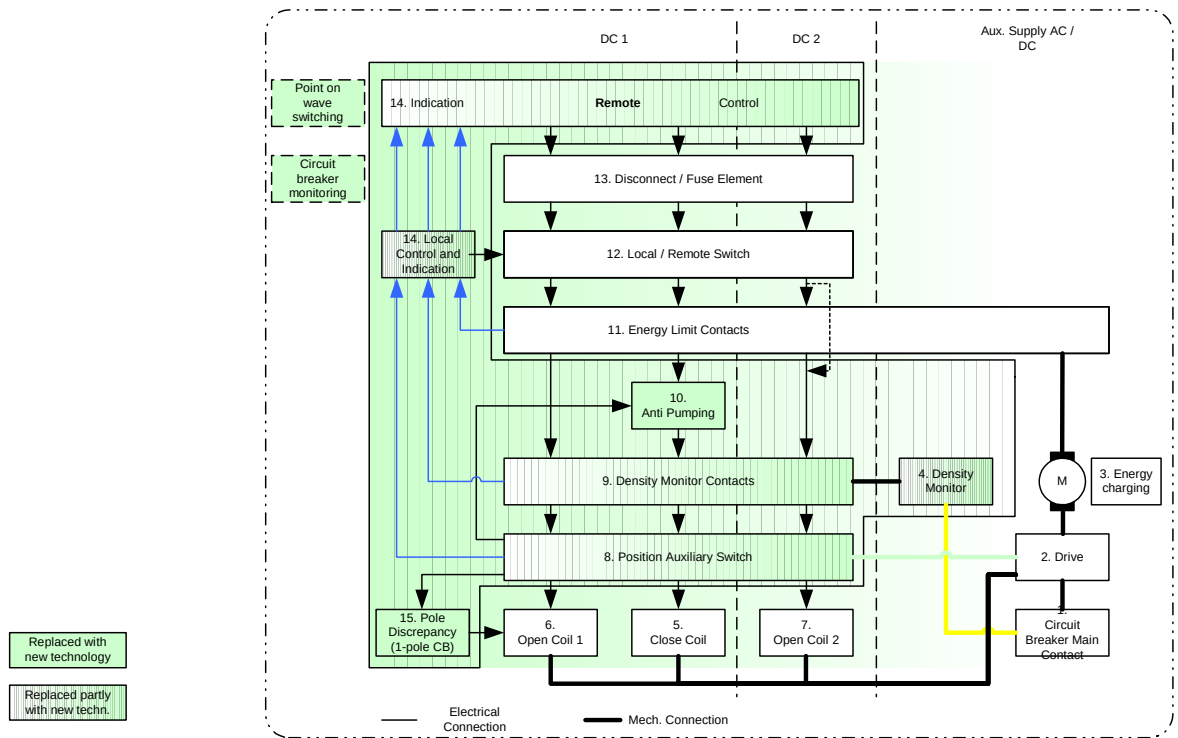


Fig. 4.3: Digital Technology with Conventional Copper Wired Interface

4.2.2.2 Digital circuit breaker control with vendor specific interfaces

In this approach, the conventional parallel copper wiring is replaced with serial fiber optic communication between the bay control and the circuit breaker control. Since this also leads to the need for digital technology in the communications, several of the basic functions are combined in one device which is housed in the circuit breaker control cabinet. Until recently, the communication protocols used to communicate with the circuit breaker control were mostly vendor specific. IEC-61850 allows a standardized protocol to be used for this communication thereby facilitating inter-operability.

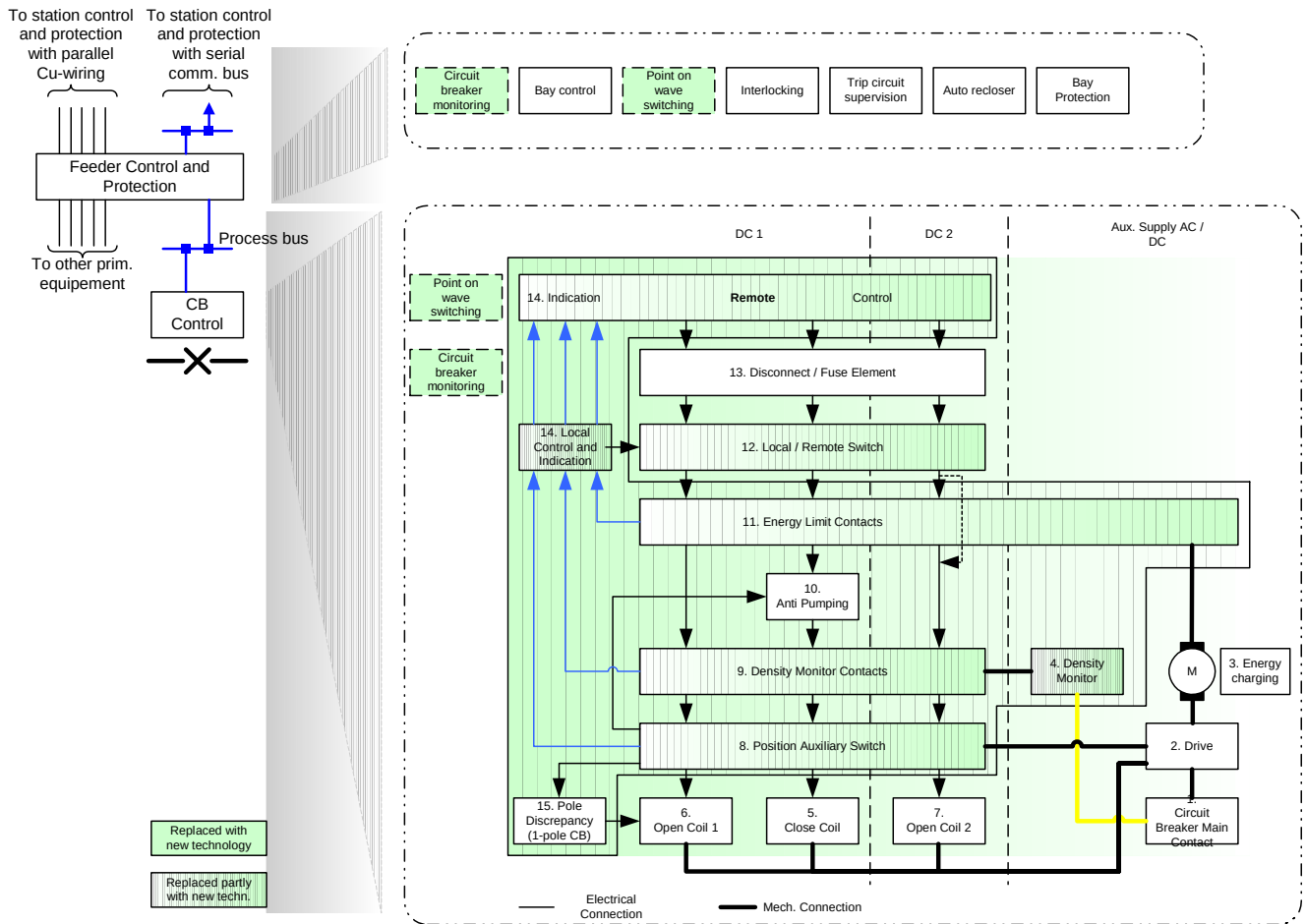


Fig. 4.4: Digital Technology with Vendor Specific Interface

4.2.2.3 Integrated monitoring solutions

In the final example, the functionality of controlled switching and circuit breaker monitoring are, in some cases, included in the digital control solution.

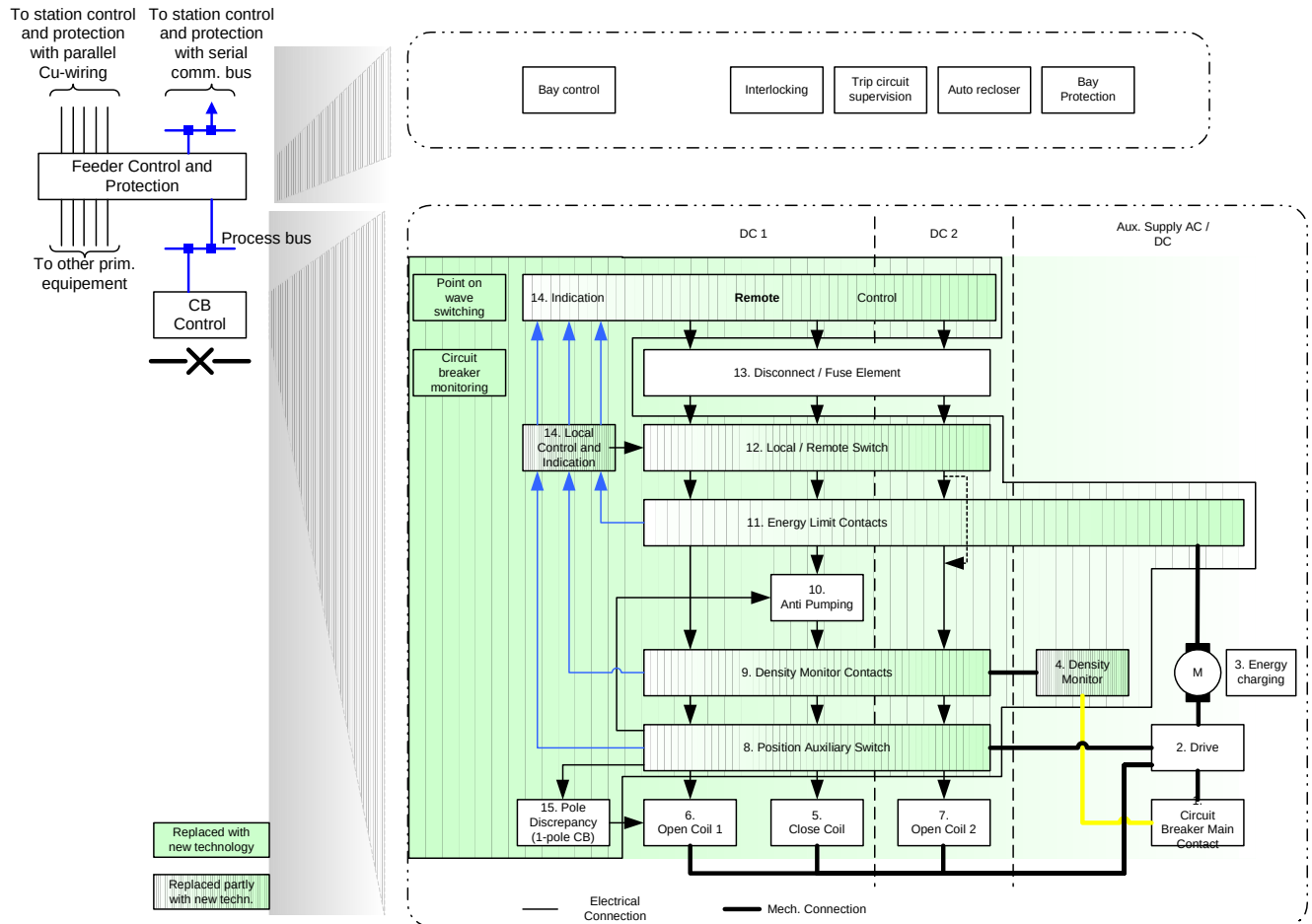


Fig. 4.5: Digital Technology with Integrated Monitoring

4.3 Expected developments in the near future

There are two primary areas to consider:

1. Using similar drive technologies as used today
2. Changes in drive technologies

4.3.1 Use of existing drive technologies

Using current drive technologies, the potential improvements are mainly based on wider use of digital control in combination with the use of the new standard IEC-61850.

In order to assess the outlook for the use of IEC-61850 for circuit breaker control, a few basics about standard 61850 –8-1 and –9-2 are described for circuit breaker control and sub-station automation (sometimes called process bus). Key characteristics are:

- Ethernet/TCP/IP based communication
- Defined protocol
 - For communication
 - For function including mandatory and optional signals per function
 - For binary signals and files transferred according IEC-61850-8-1
 - Sampled values transferred according IEC-61850-9-2

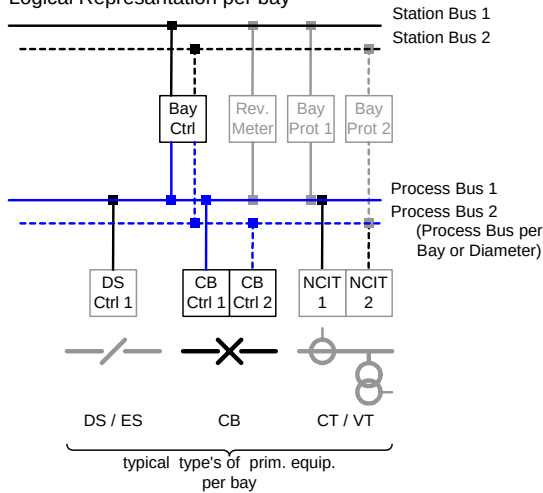
The communication infrastructure will not only be used for dedicated control related functionality but also for a possible structured distribution of monitored data, records and for remote diagnoses and maintenance. The two possible architecture structures shown in figure 4.6 demonstrate how circuit breaker control could be integrated in the whole substation.

Variant 1 shows a process bus system per bay which is separated from the station bus system. Motivation for such an approach could be to reduce the data load within the station bus and the related interfaces to the protection and control IED's.

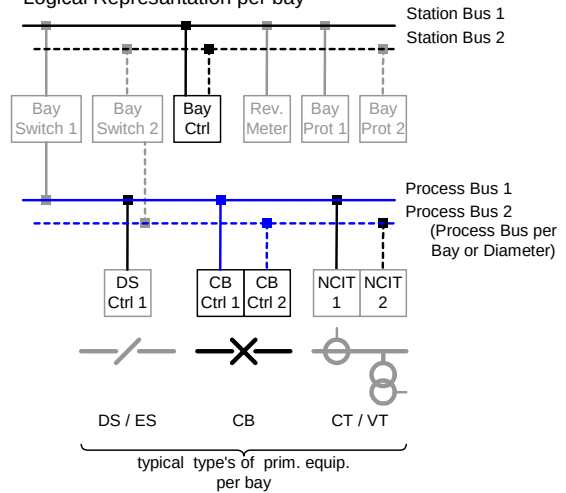
Variant 2 shows a solution where the process bus is connected to the station bus and all bay IED's receive and send their data via station bus and process bus to the circuit breaker and other primary equipment.

Both variants are shown with redundancy for both process bus and station bus. The need for redundancy in the future will be based on the required reliability for the data exchange. For protection trips there is clearly a requirement for high availability, but high reliability for the upload of data such as velocity curve reports is not critical. The selection of the best principle follows the same rules that dictate the decision to supply equipment with 1 or 2 DC supplies.

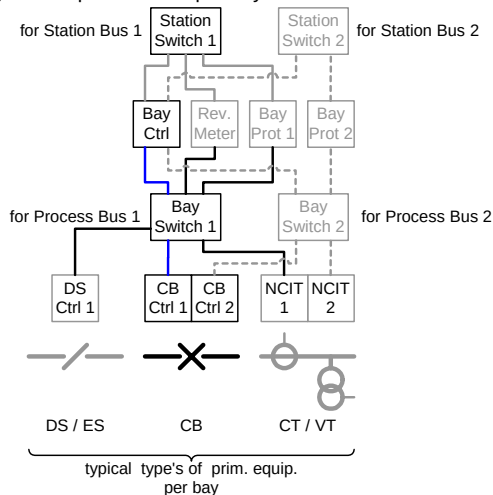
Var. 1: Process Bus without direct connection to Station Bus
=> Bay IED's connected to Process Bus
Logical Representation per bay



Var. 2: Process Bus direct connected to Station Bus
=> Bay IED's connected only to Station Bus
Logical Representation per bay



Var. 1: Process Bus without direct connection to Station Bus
=> Bay IED's connected to Process Bus
Physical Representation per bay



Var. 2: Process Bus direct connected to Station Bus
=> Bay IED's connected only to Station Bus
Logical Representation per bay

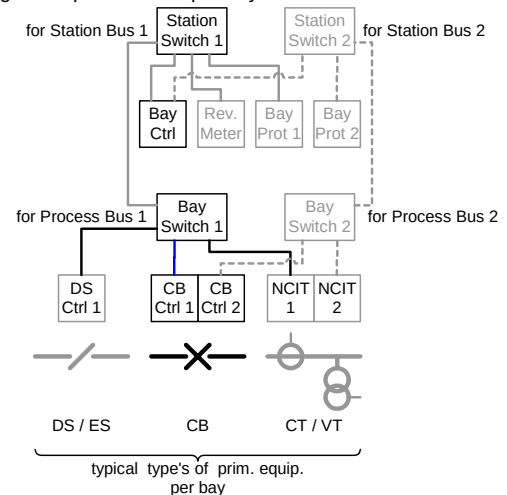


Fig. 4.6: Architecture Structures with IEC-61850

Mixed architectures are also possible e.g. digital controls with “back-up conventional control (e.g. for emergency operation). It needs to be stated that a conventional control solution will never have the same degree of self-supervision functionality as a digital control solution.

Regarding possible future architectures, unless there is an explicit need for an electromechanical solution (e.g. relays), all functions will be integrated in intelligent breakers. On an optional basis, there will also be the possibility of integrating functions which were previously stand alone devices such as circuit breaker monitoring units, controlled switching devices and also synchronous check functionalities.

The primary goal for such a solution will be to reduce or eliminate constraints which are typical for electromechanical solutions (e.g. corrosion of contacts) and have a full signal chain of self supervision in place. Relays could be reduced to a minimum by digital control since they would only be required for galvanic isolation, e.g. in case of isolation of DC supply for safety purposes.

This requirement could, itself, be eliminated from the point of the overall substation perspective if the supply interruption was controlled directly at the source (e.g. DC/AC distribution cabinet). Additional functionalities will also be added, such as under voltage trip function, auto-reclose function (Feeder Protection System).

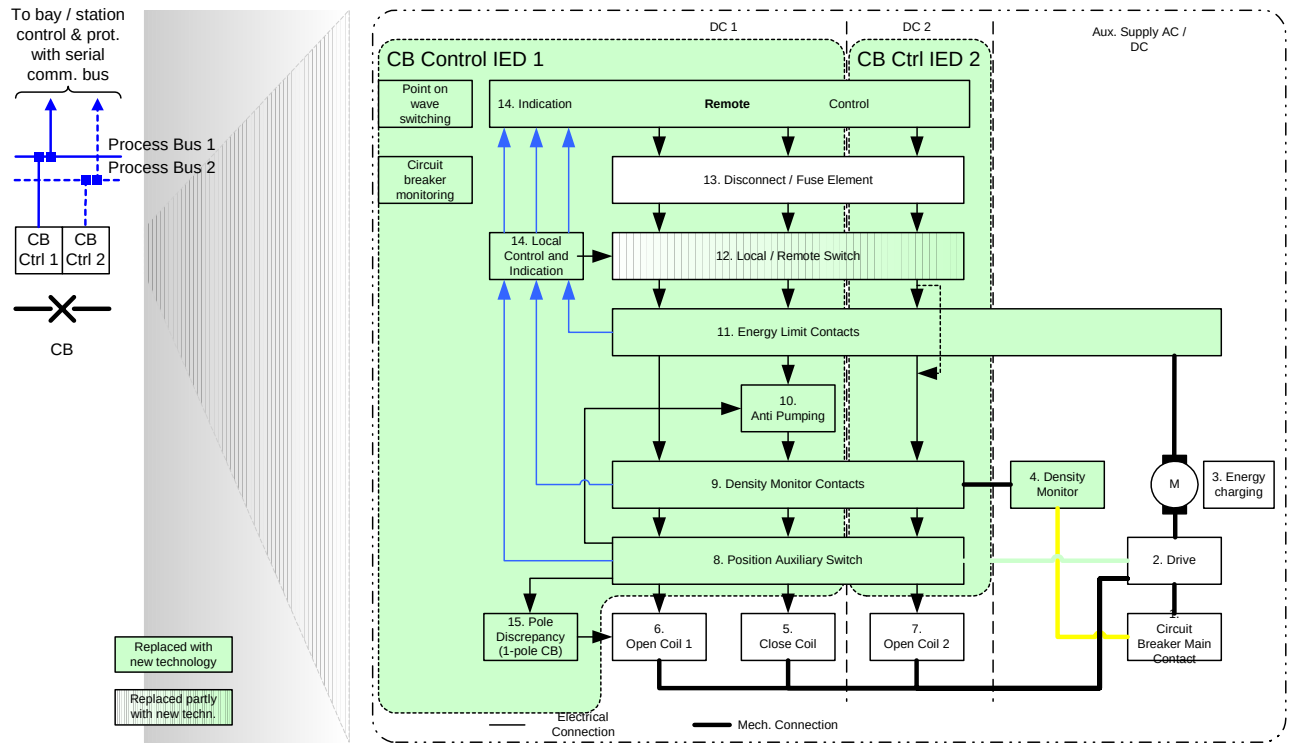


Fig. 4.7: Circuit Breaker Structure with Additional Functions

The information collected can be integrated into the technical environment in a variety of ways. The data collection philosophy could consist of no data collection, collection of data only (requiring the downloading of the data at the site), both upward and downward communication of data to/from other locations, or use of the collected data by an expert system to provide the user with “intelligent” outputs regarding maintenance information, warnings, status reports, etc. The extent to which the possible data is acquired and used will depend on the capabilities of the hardware and the goals of the user. From a reliability perspective, self-monitoring and evaluation could be performed such that failure could be detected and transmitted to an upper level immediately, or, ideally, conditions could be monitored which would identify the potential for failure with a warning which would be transmitted to the user identifying the condition and the need for maintenance prior to a failure.

4.3.2 Changes in drive technologies

The possible improvements in new drive technologies are based on improving system functionality in relation to the primary part of the circuit breaker. Digital control will adapt interfaces accordingly e.g. in a motor drive there is no need for close and trip coils but a need for open and close contacts to energize the motor.

4.4 Limitations and problems remaining to be addressed

Today, the cost of IEDs is similar to, or greater than, conventional solutions for equivalent functions whilst users' expectations are for reduced costs. There are two key considerations on this issue.

Firstly, it is usual for new products being introduced to the market to have a higher cost both due to limited market volume and due to the incorporation of new functions. This is true for digital control systems and the hence the direct comparison with conventional schemes with limited functionality is a contentious one.

Secondly, the additional functionality (and hence potential benefits) may have a negative initial cost impact, e.g. higher configuration costs, or be difficult to assess and integrate into the users' Return On Investment (ROI) calculations. The accurate assessment of the lifetime benefits of reduced cabling, function integration, size reduction, space savings and the optimized lifetime management of the equipment remains outside the capabilities of most users. Complexities of accurately calculating (predicting) life cycle costs (LCC), the difficulty of assigning a value to added functionality, pressure on costs resulting from deregulation and reducing ROI calculation periods all contribute to the difficulty in arriving at a definitive answer in this area.

A key benefit proposed by manufacturers is the integration of functions. This would include several protection algorithms within a single piece of hardware, for example CSS + monitoring + digital control integrated in one "box". However, this integration of functions might prove hard to transform into an actual benefit for the user, or may appear as a nuisance in the mid-term because of existing structures within the user's organization. Very often different departments deal with different apparatus (i.e. a primary equipment department for monitoring, a protection department for CSS switching, a tele-control department for a portion of the control system, a revenue department for digital instrument transformers, etc.) such that merging several functions into the same device translates into conflicts between existing departments. Clearly, in order to achieve the potential benefits, users need to critically review their own structures and working practices.

The limitation of circuit breaker technology can prevent or reduce the benefits of the sophisticated IEDs e.g. inconsistency of circuit breaker operating times preventing sophisticated controlled switching algorithms to perform effectively.

The issue of reliability remains open and is a major concern for users when considering further implementation. Some cases where performance was impacted by various factors, e.g. high or low temperature, power and control circuit transients, obsolescence of components, were observed in the reports. It is difficult to attribute these problems to technologies in their infancy, first implementation considerations, or design problems.

Proper estimation of the useful lifetime and the requirements for simple coast effective replacement should be made before introduction on the market. Development testing has shown that a component lifetime of ~15 years is achievable whilst early implementations of integrated control systems have demonstrated that a useful lifetime of at least 10 years (and still counting) is

achievable in the field. Stand alone CSS and monitoring systems have successfully operated even longer. Of course, some users have reported problems occurring much earlier in the lifetime and these must be a major input to future improved reliability.

Users recognize that electronics will have a shorter life than the primary equipment but are particularly concerned about the availability of replacement parts during the operating lifetime and ease of replacement at the end of life. The possibility of unavailability of a direct replacement for an IED after ~15 years is a major concern to the users. Users require a clear demonstration that manufacturers are considering these issues in the design such that direct replacement equipment will be readily available and reasonably priced in the future.

In summary, there remains a major challenge to find the best balance between the expected benefits for primary equipment, the possible increase in detected minor failures, and the changed maintenance practices which follow implementation of digital technologies. Tools taking into account all the parameters are scarce and complex and necessary data are often hard to obtain although some standards and guides to address this issue have started to be published in the past few years.

As a general conclusion, it has been noticed that even as the level of confidence in digital systems increases, redundancy with conventional systems remains the rule for critical functions, such as trip circuits and gas density monitoring.

5 Summary and conclusions

In order to evaluate control system reliability of SF₆ circuit breakers, a survey was conducted to obtain data to evaluate the causes of failures in the field. A total of 339 failures were reported from 27 utilities from 13 countries and 4 continents and these are summarized in References 2 and 3. From evaluation of this data, several global observations and conclusions can be drawn which apply to the observed control system failures, their causes, and potential improvements. These conclusions are summarized below.

- Six components of the control system were found to account for 91% of all control system failures in SF₆ circuit breakers in the data collected in the survey. These components are:
 - o Auxiliary relays
 - o Position auxiliary switches
 - o Energy limit supervision
 - o Gas density monitoring (including connecting piping)
 - o Coils (including resistors and capacitors in the trip circuit)
 - o Wiring and joints

Although most of these components had an approximately equal percentage of failures, relays were observed to be the component that had the most observed failures. Although relays were observed to have more defects, approximately two-thirds of these defects were minor failures.

- The observation was made that there was a decreasing trend of failures with years since the last maintenance operation was performed. This was thought to demonstrate the potential for human error whenever work is performed on a circuit breaker. This observation highlights the need to maintain a skilled, properly trained workforce for maintenance activities, particularly in light of aging workforce. Outsourced labor was also felt to be a potential contributing factor.
- The observation was made that there was a decreasing trend in the number of failures per year in service for the first ~2 years. After this point, the failure rate remained relatively low and then increased again after ~8 until ~15 years in service. The decrease seen in the first two years is attributed to “teething” or infant mortality failures which occur early in life. The later increase was more difficult to interpret with possible causes being “wear-out” mechanisms or the influence of maintenance activities which are typically performed in this time frame.

Failure causes and potential corrective actions to improve control system reliability were reviewed to determine the cause of failure for each of the above components however in many cases the reported data did not contain enough information to reliably determine a cause of failure. In particular, relays and auxiliary switches had a high percentage of cases where insufficient information was available to identify the nature of the failure (~40% and ~30% respectively). In order to draw some representative conclusions the survey information was supplemented with the experiences of the Working Group members and used to identify potential improvements and corrective actions that would reduce the

failure causes identified. These potential improvements covered both current conventional technologies as well as those possible with the use of modern digital technologies. Detailed recommendations for improvement are described in Chapter 3 and are summarized in Appendix B. Some of the general conclusions are listed below.

- Many of the observed failures resulted from external factors such as poor environmental control of the control cubicle (due to design, project co-ordination, and/or maintenance), site voltage conditions, and maintenance errors. Since these problems were due to design issues as well as project co-ordination and maintenance, attention in the specification and design (proper environmental ratings of the cabinets, selection of components, etc) as well as in maintenance could lead to improvement in control system reliability.
- Contact related issues were observed to some extent on all of the components which involved contacts (auxiliary switches, relays, energy supervision, and gas density monitoring). Some of these also involved poor environmental control. Use of self-wiping contacts was suggested as an improvement for some situations. Use of industrial grade components will also tend to reduce these defects.
- The fact that so many reported defects did not have a reported root cause suggests that improvements could be made in the general depth of evaluation of defects which are observed in the field. In order to improve circuit breaker reliability, identification of the root cause of failures, and hence the most appropriate corrective actions, is needed. This observation suggests that more attention needs to be paid to failure investigation in the future.

There was little information included in the survey on digital technologies, therefore, an additional, limited survey of users was conducted to determine their experiences with digital technology as well as their expectations for this technology. An attempt was made to identify what actions and/or improvements would be needed for their increased adoption in the future. The expected benefits of this technology and a description of how it could be implemented are included in the Chapter 4 of this report.

It was concluded that digital control systems have several potential benefits and could eliminate some of the observed control failure issues and, therefore, have a positive impact on control system reliability. Digital control devices would eliminate many components (relays, connections, auxiliary contacts, etc.) which would result in improved reliability. The use of devices and systems pre-tested in the factory prior to use has significant potential for reducing site installation related problems. It should be noted that the potential for similar reliability issues to those in conventional systems arising with these components cannot be excluded. In reality, the reliability of digital control systems may involve a trade-off between fewer major failures and an increased number of minor failures due to the increased complexity of the control system and better self-diagnostics.

A significant perceived benefit of digital control systems is the increase in the potential for equipment monitoring which can provide information to identify potential problems and address them before they result in an actual failure.

It was the Working Group's opinion that the major benefits of digital control systems will not be in control system reliability but rather will be at a higher level (bay level or higher). Specific benefits are summarized in Appendix B. It was concluded that the potential improvements in control system reliability alone are not sufficient to justify the use of digital technology but that, when used in conjunction with new functions, they can deliver sufficient benefits to justify their adoption.

6 References

1. CIGRE Brochure 83, Final Report on Results of the Second International Enquiry into Circuit Breaker Reliability.
2. CIGRE Brochure 259, Failure Survey on Circuit Breaker Control Systems, October 2004.
3. Wilson et al, "Failure Survey on Circuit Breaker Control Systems, Working Group A3.12, Electra, No. 16, October 2004, pp. 48-59.
4. Balzer et al, "Evaluation of Failure Data of HV Circuit Breakers for Condition Based Maintenance", CIGRE Session 2004, Paris, France, Paper A3-305, September 2004.
5. Windmar, D. et al, "Field Experience with Motor Drive as an Operating Mechanism for HV Circuit Breakers", CIGRE Conference – Present and Future of High Voltage Equipment and Substation Technologies, Tokyo, Japan, Paper 210, September 26-27, 2005.

Appendix A

Circuit Breaker Controls

A.1 Introduction to Circuit Breaker Controls

A circuit breaker is a device which opens or closes a circuit by opening or closing contacts which are driven by a mechanism. Circuit breakers are generally operated using solenoids, which release energy to the mechanical system to move the contacts. The energy required to operate the circuit breaker contacts is provided by various means e.g. spring, pneumatic pressure, hydraulic pressure, capacitor/motor, which are generally charged using motors or rectifiers. The circuit breaker is required to be capable of carrying, making and interrupting the normal and fault current. The circuit breaker is operated by receiving an external command from an external relay or an operator which actuates the mechanism to change the position of the contacts. The external command is processed by the circuit breaker control circuit to provide the proper action to activate the circuit breaker. The circuit breaker control circuit is the electrical system required to ensure that the circuit breaker responds correctly, safely & reliably to external commands. This includes operating facilities such as operating coils as well as monitoring facilities such as condition and position indication. The reliability of this control circuit is the subject of this study.

When an external operating command is sent to a circuit breaker, the circuit breaker control system is required to determine whether the circuit breaker is ready to perform the required operation. If so, the control system is responsible for implementing the required action. Conversely if the circuit breaker is not able to complete the requested operation, the control system must prevent ("block" or "lockout") the requested operation. To achieve this the control circuit monitors several conditions, such as operating energy, gas density, and the open/close position of the circuit breaker, in order to determine the operational capability of the circuit breaker at any given instant. In addition, the control system is required to monitor critical parameters and provide an alarm to the operator if these are changing such that they may cause the circuit breaker not to function in the future. This alarm function allows the operator to take action in a timely manner and prevent the circuit breaker from being unable to perform its function; a condition which may arise if changes in key parameters go unnoticed and uncorrected. In summary, the control circuit is required to supervise the operating conditions of the circuit breaker, prevent operation if the circuit breaker is outside its operational capabilities, and execute operating commands when it is safe to do so.

Control circuits vary for a variety of reasons including specific requirements in different countries, specific operator or system requirements, the type of operating mechanism, control voltage, control time, redundancy of the system, etc. However, all control circuits can be identified as having two main functions, these being:

1. Control of the circuit breaker

2. Monitoring of the condition of the circuit breaker (including auxiliary circuits) in order to:
 - Ensure safe operation of the circuit breaker
 - Provide information on the status of the circuit breaker to the operator

A.2 Control Circuit Functions

By reviewing typical control circuit schematics from a variety of suppliers participating in the Working Group a common logic for circuit breaker control circuits has been identified. This logic is more or less consistent regardless of the details of the schemes and the components used and has been translated into a block diagram showing the essential functions of the control circuit which is shown in Figure A.1. This diagram is the basis for the reliability study which has been undertaken. The specific components of this “standard” control schematic are described below. This basic schematic is appropriate for both single pole or three pole (Independent Pole Operation or “IPO”) tripping and closing. The components are related to the numbers shown in the schematic in Figure A.1.

1. Circuit Breaker Main Contacts: The main contacts of the circuit breaker (not part of the control circuit).
2. Drive or operating mechanism: The mechanical device which releases the energy to move the main contacts (open and close) (not part of the control circuit).
3. Energy charging system: The device which provides energy to the operating mechanism in advance of operation to assure that the circuit breaker has adequate energy to close and/or open. In the case of hydraulic, spring, or pneumatic energy storage systems, this is an electric motor or a motor operated pump or compressor.

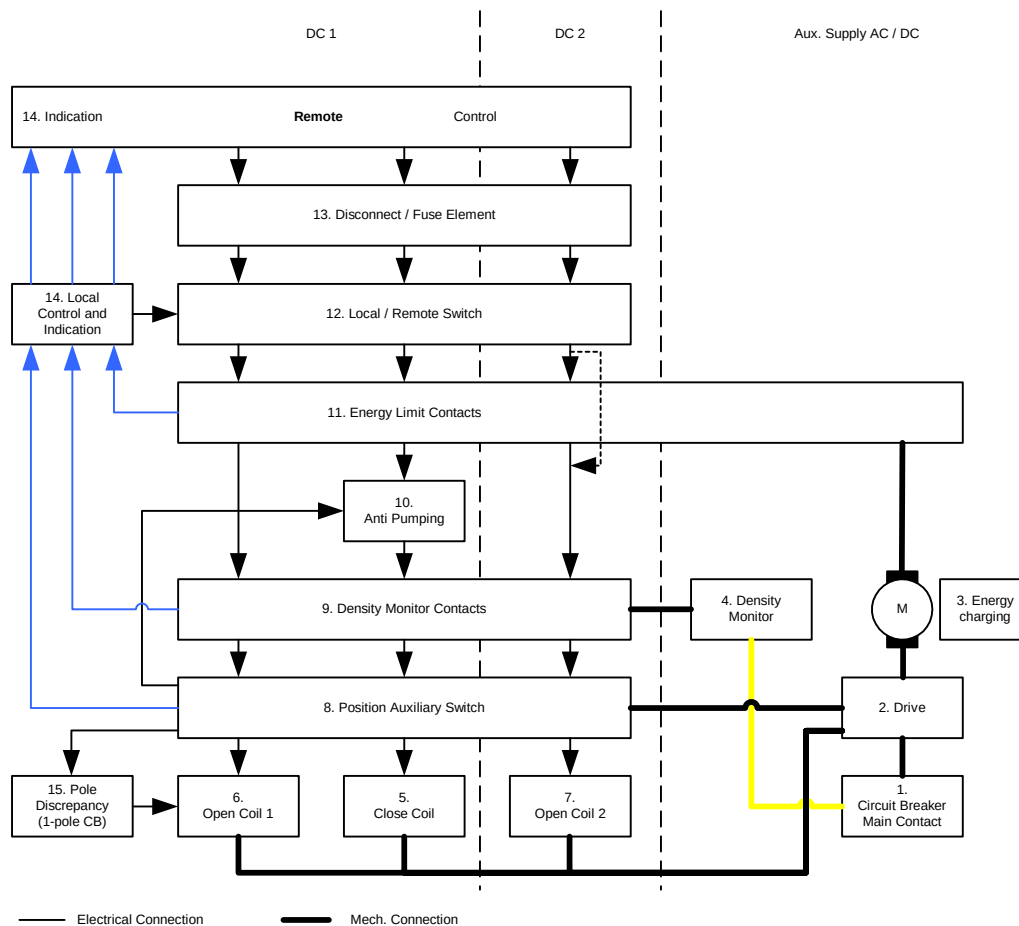


Figure A.1 – Generalized Circuit Breaker Control Schematic

4. & 9. Density monitor and density monitor contacts: These devices provide the means for supervision of the insulation and/or arc extinguishing media; typically SF_6 or mixed gas in modern circuit breakers. Temperature compensated pressure switches are commonly used which operate auxiliary relays to prevent the tripping or closing of the circuit breaker if the SF_6 gas density in the enclosure falls below critical levels. There are two functions that are performed by these switches and contacts:

1. To provide a warning or alarm in case of reduced SF_6 gas density in the enclosure before the lockout level is reached. This is an alarm only and provides time for the operator to correct the problem before the circuit breaker locks out and loses functionality.
2. To interlock or prohibit operation of the circuit breaker when the SF_6 gas density reaches a level (“lockout level”) where it will not operate safely. Typically the operator has the option of requiring the circuit breaker to automatically trip and lockout when this level is reached (“forced trip”) or having the circuit breaker lockout in the current position. The former option carries some safety risks.

5. Close coil: These are solenoid devices which are energized in the event of a valid closing signal being received by the circuit breaker. Energization releases the mechanism thereby closing the main contacts of the circuit breaker. Once the circuit breaker reaches the closed position, auxiliary switch contacts in the

closing circuit open and de-energize the closing coils. Typically, there is only one closing coil in the control circuit.

6 & 7. Open coils: These are solenoid devices which are energized in the event of a valid opening signal being received by the circuit-breaker. Energization releases the mechanism thereby opening the main contacts of the circuit breaker. Once the circuit breaker reaches the open position, auxiliary switch contacts in the trip coil circuits open and de-energize the trip coils. There are typically two trip coils that operate from independent power supplies. The operation of only one trip coil is sufficient to operate the circuit breaker. Two coils are provided in order to minimize the risk of a failure to trip.

8. Position auxiliary switch: These contacts, which are driven by the operation of the circuit breaker, are used to interrupt the current of the close and trip coils to de-energize them when the operation is complete. They are also used for indication and monitoring of the circuit breaker position and to interlock control & protection operations at the bay or station level to prevent an incorrect switching operation. These switches can be used for any function where the position of the circuit breaker is a required parameter.

10. Anti-Pumping: Anti pumping refers to the prevention of a re-closing operation in the situation where a previous close command is still applied to a circuit breaker that has been opened. This prevents the circuit breaker from repeatedly closing and opening. Typically the close command energizes an anti-pumping relay via an auxiliary switch contact (a Normally Open (NO) contact). One contact of the anti-pumping relay interrupts the circuit to the close coil. A second contact is used to latch or "seal in" the anti-pumping relay until the close command is removed from the circuit.

11. Energy limit contact: The energy limit contacts are set to operate when the stored energy in the mechanism is depleted either by operation or losses. Typically they start a motor in order to restore the energy of the mechanism to its normal operating level e.g. spring position, hydraulic/pneumatic pressure. For spring mechanisms recharging is typically after every close operation whilst other mechanism types may be able to perform several operations before recharging is required. Pneumatic & hydraulic systems have a switch which monitors the pressure and energizes a compressor when it falls below a critical level. When the energy level is restored, a switch opens, which stops the motor. The motor typically has protection against thermal overload and a time limit relay, which will stop the motor (or a motor operated pump or compressor) in the event of a malfunction. The switches or contacts monitoring the stored energy, therefore, perform the following functions:

- Lock out the close operation if the circuit breaker does not have enough energy to close and re-open safely.
- Lock out the open operation if the circuit breaker does not have enough energy to open safely. This is typical for hydraulic or pneumatic circuit breakers but not for spring operation where a successful closing charges the opening spring(s).
- Control (start and stop) the charging circuit of the energy storage device (e.g. spring).

12. Local/remote switch: This is a selector switch which allows the operator to interrupt remote control and only operate the circuit breaker locally. This is a safety feature to prevent remote operation of the circuit breaker while it is being serviced.

13. Disconnect/Fuse element: These devices are used to interrupt the power to the control system during maintenance work or during a fault to the control circuit. Disconnection is typically provided by knife switches or removable fuses/links which provide visual confirmation that the control circuit is open and which may be locked open to prevent unauthorized re-instatement. Where protection against short circuit is required, Mini Circuit Breakers (MCB) may be used as an alternative to simple fuses.

14. Local control and indication: This function provides an indication of the position of the circuit breaker and the status of the local/remote control facility. These indicators are for maintenance or emergency operations (depending on local safety rules).

15. Pole discrepancy/pole disagreement circuit: For Independent Pole Operation (IPO) circuit breakers (one mechanism for each phase); it is possible for one phase of the circuit breaker to not have the same position (open or close) as the other phases. This situation is called pole discrepancy or pole disagreement and can result in an unsymmetrical primary current. Auxiliary switch contacts in each phase are used to energize a time delay relay in the event that a pole discrepancy occurs. Assuming the discrepancy condition is persistent, after the preset time delay, an attempt will be made to trip all phases of the circuit breaker. In the event that the pole discrepancy was due to a failure to close of one pole, this trip is likely to succeed. However, if the initial discrepancy was due to a failure to open, the failed pole is unlikely to respond to subsequent opening commands and opening of other circuit breakers may be necessary. The preset time delay is normally between 1.5 to 5 seconds. The time depends on the specific grid conditions and how long the primary circuit could have operated asymmetrically (should be longer than 1 phase auto reclose time and shorter than the negative phase sequence protection of generation).

16. Heating: Space heaters are often provided in each of the operating mechanism and control housings to reduce condensation.

Appendix B

Summary of Detailed Observations and Recommendations

The detailed conclusions on failure causes of the six components responsible for 91% of the control system failures were discussed in Chapter 3 and the key conclusions on the failure causes and potential actions are tabulated in summary form below. In addition, the key conclusions concerning the future use of digital control systems and its impact on control system reliability are also summarized below.

B.1 Specific Observations and Recommendations for the Individual Components

The key observations and recommendations for the individual components are summarized below.

Coils

Observations:

- Coil failures are an important issue since almost 100% of the coil failures result in a major failure.
- There is a relatively low incidence of failure of these components. Also, coil failure is frequently indicative of another problem in the control circuit (failed auxiliary switch, low control voltage etc.) which causes the coils to fail.
- A large number of the observed coil failures involved capacitors used to improve the coil response time.

Recommendations:

- The use of capacitors in trip circuit to improve response can be eliminated through better coil design or the use of inherent cable capacitance.
- Improvements in the control cables at the site can reduce low voltage situations (e.g. larger cable sizes for long cable runs, etc.).
- Hardware improvements in the coil itself are possible (e.g. improvements to reduce inter-turn failures) however, the coil itself is not a major quality issue.
- Motor drives can eliminate this component but the potential for other, similar reliability issues can not be excluded.
- Digital controls can be used to monitor the coil condition, limit the control voltage, and limit the signal duration.

Wiring & Joints

Observations:

- Wiring defects were very limited in number and not a major issue.
- No major failure cause was identified. Instead, there were a series of smaller issues.

Recommendations:

- Improvements in conventional technologies are available (spring loaded terminals, etc)
- Attention to insuring that wiring is restored to its proper condition after maintenance would be beneficial.
- Digital controls have the potential to reduce wiring related defects by reducing the number of connections and using pre-tested systems that do not need to be disturbed later in life.
- Monitoring will improve the ability to detect loose or disturbed connections. Monitoring will also reduce/eliminate the need to replace wires during maintenance operations, thereby reducing the potential for loose wires.

Auxiliary Switches

Observations:

- Auxiliary switch failures are critical since they can cause other major components to fail (notably, coils). Improper signaling can also result in spurious minor failures as well as improper operation in other areas of the network.
- Performance was generally good. The major failure causes were being mechanically out of adjustment or environmental related effects. Some contact problems were observed due to poor IP control.

Recommendations:

- The use of self wiping contacts has improved performance of this component.
- Proper mounting, especially in areas of high vibration, is important to avoid being out of adjustment

Relays

Observations:

- Relays were the largest contributor to the overall failure statistics.
- For a high percentage of the reported data, insufficient data was available for a detailed assessment of the failure cause.
- Many of the failures were hardware issues with the relays themselves, many involving contacts. Poor environmental control of the cabinet was a contributor in some cases.

Recommendations:

- There were several improvements that could be made with the selection and specification of the relays that would reduce the potential for failure.
 - o Industrial grade relays that are more robust and appropriate for the application should be used.
 - o It is best to use relays that have been fully qualified whenever possible even when the user requests a custom solution.
 - o The contact ratings should be appropriate for the projected load current and consistent with specifications. This is especially important for motor contactors since the motor power supply can vary by site.
- As seen in several of the components, appropriate control of the cabinet environment can reduce the potential for relay problems. The

enclosure housing the controls needs to be appropriately designed. In addition, the environmental requirements need to be appropriately defined by the user.

- The use of microprocessors would eliminate a large number of the relays in the control system and, therefore, reduce the potential for failures. In addition, they can also be factory tested and reduce the potential for damage during installation and maintenance.

Energy sensors

Observations:

- There were two main problems observed which accounted for approximately half of the observed failures. These were: 1) pressure sensing gauges for hydraulic mechanisms, and 2) limit switches for spring mechanisms. Most of the problems were hardware, but some adjustment problems were also observed.
- Some contact problems were observed similar to those seen in other components (~16%). These relate to environmental control issues.
- Hydraulic mechanisms appeared to have a higher failure frequency than other mechanisms. Approximately half of these defects involved the hydraulic fluid pressure monitoring.
- Motor failures were relatively low in frequency.

Recommendations:

- Improvements can be made in the limit switches and pressure sensors used.
- The designers should pay attention to the mounting arrangement of the switches to avoid excessive vibration.
- Improvements can be made in the hydraulic pressure monitoring.
- Monitoring of the motor run time and motor current could provide an early warning to motor related problems.

Gas monitoring

Observations:

- The primary causes of failure were gas switch hardware and piping leakage issues.
- Some failures were related to contact issues (~20%).

Recommendations:

- There is potential for reliability improvement in the gas density switches themselves.
- Improvements can be made in controlling leaks in the gas piping of the gas density systems in the design stage. In particular, the use of o-rings in the gas system is a desirable practice.
- The designers should ensure that the hardware has the environmental control required for the application, particularly if the hardware is located outside.
- Following maintenance operations, care should be taken to ensure that all isolation valves are restored to their proper position if they were changed during the maintenance.

- The use of modern digital monitoring would enable improved temperature correlation algorithms to be used. In addition, monitoring has the potential to reduce/eliminate the amount of gas piping required

B.2 Benefit of Digital Controls on Control System Reliability

It was the Working Group's opinion that the major benefits of digital control systems will not be in control system reliability. Instead, the benefits of digital control systems will be at a higher level (bay level or higher). Examples of these benefits are:

- The potential for increased monitoring will result in an increased knowledge of the condition of the breaker resulting in fewer major failures.
- The ability to rapidly transmit alarms to a higher level will provide a base for application of an expert system to the network.
- Digital controls and the increased monitoring can provide invaluable support for a Condition Based Maintenance program. This would have the potential to eliminate the current practice of time and operations based criteria for required maintenance and replace them with a condition based criteria some of which could be continuously monitored.
- Implementation of an overall monitoring system would allow full loop self-supervision within the sub-station rather than individual pieces of equipment.
- Digital controls have the potential to reduce both global engineering and installation costs. This would result from items such as a reduction in required cabling which will reduce the amount of control wiring required in the sub-station reducing both material and labor costs.

Digital technology is an emerging technology within the substation environment. There are practical issues that must be considered when implementing digital control systems.

These would include integration into the existing network, new training and skills for the workforce. One of the key issues with users is the current inability for equipment supplied by different vendors to communicate easily with each other and to function compatibly. The implementation of IEC-61850 will address this issue and make implementation easier.

The users' initial experience has identified several issues that need to be addressed for a more wide-spread implementation of digital systems. Some of the key issues identified by the working group which need to be addressed are:

- The reliability of the digital systems has been an issue with the users surveyed. In some cases, the monitoring and control devices were less reliable than the base equipment they were monitoring. Although the Working Group felt that these issues are being addressed, this will be one of the major considerations for increased use of these systems.

- Replacement of digital devices is expected to occur within approximately 15 years of installation. This will be before the end of life of the circuit breaker itself. This was recognized by and acceptable to the users provided that a readily available, reasonably priced direct replacement was available that would not require significant modification to the circuit breaker or other equipment.
- Digital systems have an increased complexity on implementation. These systems require increased technical co-ordination and planning before and during installation.
- Digital systems are more technically complex than conventional technologies. Therefore, the planning, installation, and maintenance of these devices required to implement these systems into the overall system may require additional training & skills of the users' staff.