MASTER

# Controlled switching in high voltage power networks : case studies in the South African and Dutch transmission networks

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*Award date:*
1993

7094

EG/93/699

FACULTY OF ELECTRICAL ENGINEERING

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# CONTROLLED SWITCHING IN HIGH VOLTAGE POWER NETWORKS.

## Case studies in the South African and Dutch transmission networks.

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A thesis submitted to the Faculty of Electrical Engineering - Group Electrical Energy Systems, University of Technology, Eindhoven, The Netherlands, in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

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Eindhoven, December 1993.

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# Preface

In order to increase the voltage stability of HV power networks, shunt capacitors and shunt reactors are often applied at line terminals. At varying load conditions, switching of these reactive elements may require frequent (daily) switching operations. For shunt capacitor banks the very high inrush currents with the inherent busbar voltage collapse can be a serious problem. Single bank switching represents the worst case condition for the power system, back-to-back switching for the circuit breaker itself. With controlled energizing it is possible to reduce these transients to an absolute minimum. On shunt reactor de-energizing the circuit breaker may reignite at short arcing times. This may lead to multiple reignitions and voltage escalation. The inherent large rate of rise of the resulting reignition transients may damage the shunt reactors insulation. By controlled opening, current interruption at short arcing times can be avoided.

In the project, items such as the reactive power installed and planned, considerations on applying controlled switching, experience of users and experimental field tests are discussed.

The investigations have lead to the conclusion that at present controlled switching is not applicable in general yet. Only in certain installations it is recommended to apply controlled switching.

For shunt capacitor banks a discrepancy should be made between critical and non-critical installations. For the non-critical installation a series damping network is usually sufficient. For critical installations a combination of controlled switching and a series damping network is recommended. Controlled interruption of shunt reactor currents is especially recommended for the highest system voltages.

# Acknowledgements

I would like to express my sincere thanks to the following people:

All the staff of ESKOM's Transmission Substation Technology Department, in particular Enrico Francocci, Richard Hopkins, Piet Goosen and Willem Meintjies. Everybody that enthousiastically assisted during the field measurements at Apollo Substation. The measuring team for all their assistance. Mr Piet Faling for all his generous support. Also thanks to the workforce of ROTEK's Switchgear Department, especially Albert van Oudheusden and Ray Cooper. At the Rand Afrikaans University - Industrial Electronics Research Laboratory, I am particularly indebted to Prof JD van Wijk, Prof PH Swart and Prof M Case.

Prof Rietjens, Prof Damstra and Dr Smeets of the Group Electrical Energy Systems of Eindhoven University of Technology for all their support and advice. The team at the Computing Centre's Helpdesk for their assistance.

Mr J Maas and Mr S Sinke of Delta Nutsbedrijven for being so kind as to offer me free entrance to all their premises at Borssele during the field tests. Dr Rune Alvinsson of ABB, Sweden thanks for the interesting discussions. Mr E Kleyer, Mr P de Graaf and Mr D van Aartrijk of KEMA for all their assistance.

I would also like to thank my parents, Edwin and Jackie for all their patience and support during my studies.

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# Abbreviations

| | |
|---|---|
| SVC | Static Volt-Ampere-reactive Compensator |
| TCR | Thyristor Controlled Reactor |
| TSC | Thyristor Switched Capacitor |
| CB | Circuit Breaker |
| CIGRE | Conference International des Grand Resaux Electriques (International Conference on High Voltage Engineering) |
| SAIEE | South African Institute of Electrical Engineers |
| ISBN | International Standard Book Number |
| ESKOM | Republic of South Africa's National Power Utility |
| ABB | Asea Brown Boveri |
| NA | Not Applicable |
| HVDC | High Voltage Direct Current |
| IEEE | Institute of Electrical and Electronics Engineers |
| pp | pages |

# List of definitions

*Arcing contact* - A contact on which the arc is intended to be established. An arcing contact may serve as a main contact. It may be a separate contact so designed that it opens after and closes before another contact which it is intended to protect from injury.

*Arcing time of a pole* - The interval of time between the instant of the first initiation of the arc and the instant of final arc extinction in *that* pole.

*Arcing time of a multipole circuit-breaker* - The interval of time between the instant of an arc and the instant if final arc extinction in *all* poles. For circuit-breakers which embody switching resistors, a distinction should be made between the arcing time up to the instant of the extinction of the main arc and the arcing time up to the instant of the breaking of the resistance current. Unless otherwise stated, the arcing time is the time up to the instant of the extinction of the main arc.

*Arc instability* - Any abrupt change in the conductivity of the gas discharge between the contacts of a circuit-breaker, occurring away from the natural current zero in the current loop and having its origin in the discharge characteristics and/or quenching medium. Arc instability may appear as a discontinuity and/or a high-frequency oscillation in the voltage across and/or the current through the circuit-breaker.

*Auxilliary circuit* - All the conducting parts of a circuit-breaker intended to be included in a circuit other than the main circuit and the control circuits. Some auxilliary circuits serve supplementary requirements such as signalling, interlocking, etc. and as such they may be connected to the control circuit of another switching device.

*Auxilliary contact* - A contact included in an auxilliary circuit and mechanically operated by the circuit-breaker. The term "mechanically" implies any link by mechanical, pneumatic or hydraulic means.

*Breaking current* - The current in a pole of a circuit-breaker at the instant of initiation of the arc during a breaking operation.

*Breaking capacity* - A value of prospective breaking current that a circuit-breaker is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.

*Break time* - The interval of time between the beginning of the opening time of a circuit-breaker and the end of the arcing time.

*Capacitor bank breaking capacity* - A breaking capacity for which the specified conditions of use and behaviour include the opening of a capacitor bank.

*Chopping current* - Instantaneous value of the power-frequency current through the interrupting pole of the circuit-breaker at the moment of current chopping. This current may be different compared with the current through the main inductance.

*Chopping level* - Maximum recorded value of the chopping current due to true current chopping in a specific circuit under rated voltage and normal operating conditions.

*Circuit breaker* - A mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit. A circuit-breaker is usually intended to operate infrequently, although some types are suitable for frequent operation.

*Closing operation* - An operation by which the circuit-breaker is brought from the open position to the closed position.

*Closed position* - The position in which the predetermined continuity of the main circuit is secured.

*Closing time* - The interval of time between the initiation of the closing operation and the instant when the contacts touch in all poles. The closing time includes the operating time of any auxilliary equipment necessary to close the circuit-breaker and forming an integral part of the circuit-breaker. For circuit-breakers which embody switching resistors, it may be necessary to make a distinction between the closing time up to the instant when the contacts in series with the switching resistors touch and the closing time up to the instant when the primary arcing contacts touch. Unless otherwise stated the closing time is the time up to the instant when the primary arcing contacts touch.

*Contact* - Two or more conductors designed to establish circuit continuity when they touch, and which, due to their relative motion during operation, open or close a circuit.

*Control circuit* - All the conducting parts of a circuit-breaker, other than the main circuit, used for controlling the closing operation or opening operation or both.

*Control contact* - A contact included in a control circuit of a circuit breaker and mechanically operated by the circuit-breaker. The term "mechanically" implies any link by mechanical, pneumatic or hydraulic means.

*Current chopping* - An abrupt current interruption in the circuit-breaker away from the natural power-frequency current zero of the circuit connected to the circuit-breaker. Current chopping may be originated by arc instability or by transients in the circuitry. The current interruption can be incomplete due to post arc conductivity.

*Earthed neutral system* - A system in which the neutral is connected to earth, either directly, or through a resistance or reactance of low enough value to reduce materially transient oscillations and to ensure a current sufficient for selective earth-fault protection.

*First parallel oscillation* - Oscillation occurring in the current through the circuit-breaker immediately after a reignition and having its energy sources in the capacitances of the direct vicinity of the circuit breaker. The frequency of the first parallel oscillation is in the MHz-region. The discharge is a transient to a new (quasi) steady state or a new current zero. The capacitances involved are the inherent "stray" capacitances of the circuit breaker pole and the few metres of conductors connected. The first parallel oscillation can only develop when a rapid transition from current zero to a low resistance gas discharge is possible and therefore often does not appear during a thermal reignition but rather during a dielectric breakdown. If occurring, the oscillation may be strongly damped by the transient discharge itself.

*First-pole-to-clear factor (of a three-phase system; and at the location of a circuit-breaker)* - The ratio of the power frequency voltage between a sound phase and the other two phases during a two-phase short-circuit, which may or may not involve earth, at the location of the circuit-breaker, to the phase-to-neutral voltage which would be obtained at the same location with the short-circuit removed.

*Impulse withstand voltage* - The peak value of the standard impulse voltage wave which the insulation of the circuit-breaker withstands under specified test conditions. Depending on the shape of wave, the term may be qualified as "switching impulse withstand voltage" or "lightning impulse withstand voltage".

*Inductive current* - Power-frequency current through a circuit-breaker drawn by an inductive circuit having a power factor 0,5 or less.

*Instability Oscillation* - Arc instability appearing in the discharge current as a high frequency oscillation with an increasing amplitude during at least a part of the oscillation.

*Insulation Level* - The values of the impulse withstand voltage and the power frequency withstand voltage, which together characterize the insulation of the circuit-breaker with regard to its ability to withstand the electric stresses.

*Isolated neutral system* - A system which has no intentional connection to earth except through indicating, measuring, or protective devices of very high impedance.

*Load side oscillation* - Oscillation of the interrupted load side network after current chopping or natural current zero.

*Main circuit* - All the conducting parts of a circuit-breaker included in the circuit which it is designed to close or open.

*Main contact* - A contact included in the main circuit of a circuit-breaker, intended to carry the current of the main circuit in the closed position.

*Main circuit oscillation* - Oscillation induced by one or more arc voltage discontinuities or reignitions and having its energy sources in the generators, capacitances and lumped inductances of the supply side and load side networks. The frequency of the main circuit oscillation is generally much lower than that of the second parallel oscillation. Parallel oscillations and main circuit oscillations can be seen as current transients which may successively follow after a breakdown in the period between current zero and a new power-frequency current flow. The oscillations are often multi-frequency. They often cause current zeros and may consequently originate virtual current chopping.

*Make time* - The interval of time between the initiation of the closing operation and the instant when the current begins to flow in the main circuit. The make time includes the operating time of any auxilliary equipment necessary to close the circuit-breaker and forming an integral part of the circuit-breaker. For circuit-breakers which embody switching resistors, it may be necessary to make a distinction between the make time up to the instant at which current is first established through the resistors and the make time up to the instant at which full current is established. The make time may vary due to the variation of the pre-arcing time.

*Making capacity* - A value of maximum prospective peak current that a circuit-breaker is capable of making at a stated voltage under prescribed conditions of use and behaviour. The conditions of use and behaviour are prescribed in the specification.

*Multiple (parallel) capacitor bank (back-to-back capacitor bank)* - A bank of shunt capacitors or capacitor assemblies each of them switched independently to the supply system, the inrush current of one unit being appreciably increased by the capacitors already connected to the supply.

*Normal current* - The current which the main circuit of a circuit breaker is capable of carrying continuously under specified conditions of use and behaviour.

*Open position* - The position in which the predetermined clearance between open contacts in the main circuit is secured.

*Opening operation* - An operation by which the circuit-breaker is brought from the closed position to the open position.

*Opening time (until separation of the arcing contacts)* - The opening time until separation of the arcing contacts of a circuit breaker is defined according to the type of its opening release as stated below and with any time delay device forming an integral part of the circuit-breaker adjusted to its minimum setting or, if possible, cut out entirely:

a) For a circuit-breaker tripped by any form of auxilliary power, the opening time is measured from the instant of application of the auxilliary power to the opening release of the circuit-breaker when in the closed position, to the instant when the arcing contacts have separated in all poles.

b) For a circuit-breaker tripped by a current in the main circuit without the aid of any form of auxilliary power, the opening time is measured from the instant at which, the circuit-breaker being in the closed position, the current in the main circuit reaches the operating value of the over-current release, to the instant when the arcing contacts have separated in all poles.

For circuit-breakers which embody switching resistors, it may be necessary to make a distinction between the opening time up to the instant of the separation of the arcing contacts and the opening time up to the instant of the separation of the contacts in series with the switching resistors. Unless otherwise stated, the opening time is the time up to the instant of separation of the primary arcing contacts.

*Overvoltage* - A voltage to earth, expressed as a peak voltage, which is greater than the normal peak voltage corresponding to the highest system voltage.

*Peak current* - The peak value of the first major loop of current during the transient period following inition.

*Pole* - The portion of a circuit breaker associated exclusively with one electrically separated conducting path of its main circuit and excluding those portions which provide a means for mounting and operating all poles together. A circuit-breaker is called single pole if it has only one pole. If it has more than one pole, it may be called multipole (two-pole, three-pole, etc.) provided the poles are or can be coupled in such a manner as to operate together.

*Power factor (of a circuit)* - The ratio of the resistance to the impedance at power frequency of an equivalent circuit supposed to be formed by an inductance and a resistance in series.

*Power frequency recovery voltage* - The recovery voltage after the transient voltage phenomena have subsided.

*Power frequency withstand voltage* - The r.m.s. value of the sinusoidal alternating voltage at power frequency which the insulation of the circuit-breaker withstands under specified test conditions.

*Pre-arcing time* - The interval of time between the initiation of current flow in the first pole during a closing operation and the instant when the contacts touch in all poles. The pre-arcing time depends on the instantaneous value of the applied voltage during a specific closing operation and therefore may vary considerabely.

*Prospective current (of a circuit, and with respect to a circuit-breaker)* - The current that would flow in the circuit, if each pole of the circuit-breaker were replaced by a conductor of negligible impedance.

*Prospective transient recovery voltage (of a circuit and with respect to a circuit-breaker)* - The transient recovery voltage following the breaking of a prospective current without any direct current component by an ideal circuit-breaker. The definition assumes that the circuit-breaker for which the prospective transient recovery voltage is sought is replaced by an ideal circuit-breaker, i.e. with instantaneous transition from zero to infinite impedance at the very instant of zero current (i.e. at the natural current zero). For three-phase circuits, the definition further assumes that the breaking of the current by the ideal circuit-breaker takes place only in the first pole to clear.

*Rated value* - A stated value of any one of the characteristic values that serve to define the working conditions for which the circuit-breaker is designed and built.

*Recovery peak* - Maximum in the voltage across the circuit breaker having a polarity opposite to the previous arc voltage polarity and occurring after definite polarity change of the recovery voltage. Suppression peak and recovery peak are not necessarily the absolute maxima in the transient recovery voltage. Previous breakdowns may have appeared at higher voltage values.

*Recovery voltage* - The voltage which appears across the terminals of a pole of a circuit-breaker after the breaking of current. This voltage may be considered in two successive intervals of time, one during which a transient voltage exits, followed by a second one during which power frequency voltage alone exits.

*Reignition* - A resumption of current between the contacts of a circuit breaker during a breaking operation in a time interval of zero current of less than ¼ cycle of power frequency.

*Restrike* - A resumption of current between the contacts of a circuit breaker during a breaking operation in a time interval of zero current of ¼ cycle of power frequency or longer.

*Restrike-free circuit-breaker* - A circuit-breaker that interrupts without restrike during the capacitive current-breaking test duties specified in standard IEC 56 - 1987.

*Second parallel oscillation* - Oscillation in the current occurring after a reignition and having its energy sources in the capacitances of the supply side and load side networks connected to the circuit-breaker pole terminals. The frequency of the second parallel oscillation is generally much lower than that of the first parallel oscillation. This discharge has a (quasi) steady state character.

*Single capacitor bank* - A bank of shunt capacitors in which the inrush current is limited by the inductance of the supply system and the capacitance of the bank of capacitors being energized, there being no other capacitors connected in parallel to the system sufficiently close to increase the inrush current appreciably.

*Small (capacitive or inductive) currents* - The steady state shunt capacitor or shunt reactor currents are small compared to high voltage circuit breaker fault interrupting capability.
*Supply side (or source side) oscillation* - Oscillation of the supply side part of the main circuit after current chopping or natural current zero.

*Suppression peak* - Maximum in the transient voltage across the circuit-breaker, having the same polarity as the previous arc voltage and occuring before definite polarity change of the recovery voltage.

*Switching device* - A device designed to make or break the current in one or more electric circuits.

*Transient recovery voltage (TRV), restriking voltage* - The recovery voltage during the time in which it has a significant transient character. The transient voltage may be oscillatory or non-oscillatory or a combination of these depending on the characteristics of the circuit breaker. It includes the voltage shift of the neutral of a polyphase circuit. The transient recovery voltage in three-phase circuits is, unless otherwise stated, that across each of the other two poles.

*True current chopping* - Current chopping originated by arc instability in the circuit-breaker discharge.

*Virtual current chopping* - Current chopping originated by transients in (parts) of the circuit. The transients may be originated by the previous history of the switching process and/or by reignition in another pole of the same circuit-breaker.

*Voltage escalation* - Increase in the amplitude of the prospective recovery voltage of the load circuit, produced by the accumulation of energy due to repeated reignitions.

# Chapter 1 - Reactive Power Control

## *1.1 Introduction*

Electric (loading) power or apparent power S comprises only two real orthogonal divided components: active power P and fictitious power F. Fictitious power is subdivided into the orthogonal components reactive power Q and the deactive or distorsion power D. This subdivision is based upon the fact that these two components are generated differently [1.1], [1.2], [1.3].

The apparent power S is defined in terms of the product of effective values of voltage and current over a certain time interval. Active power P is the average rate of energy transfer from source to load over a defined time interval. If the voltage and current are periodic, reactive power Q can be subdivided into fundamental or displacement reactive power $Q_f$ and residual or distorsion reactive power $Q_r$. This subdivision has the distinct advantage in that fundamental reactive power can be compensated and analyzed by means of passive inductive or capacitive elements such as shunt reactors and shunt capacitors. Residual reactive power can be compensated by means of tuned harmonic filters or dynamic power filters. Static VAr Compensators and tuned filters are applied within the power systems of many utilities. Loads with high dynamic natures present a problem for Static VAr Compensators and tuned filters Aperiodic currents can not be compensated for by passive filters alone. When load voltage distorsion or aperiodicity is present, Active Power Filters are employed. An Active Power Filter can be seen as a current source that supplies the distorted part of the current drawn by the load in negative phase relation, it acts as a filter eliminating all non-active currents. This results in a pure sinusoidal current being drawn from the source. The power factor is improved in this way because the source is no longer required to supply this distorted current. Active Power Filters as large as 100 kVA are economically viable at present, the constraint is the switching technology which is used.

By minimising the amplitudes of the reactive power Q and the deactive power D, the amplitude of the apparent power S can be minimised. This means that the installed transmission capacity of a system can be utilised in a better way, it is possible to send more active power over that system.

Reactive power compensation and voltage control for a power system is necessary in normal as well as emergency conditions. Voltage constraints are usually the main criteria. In the presence of long transmission lines, the limitation of overvoltages

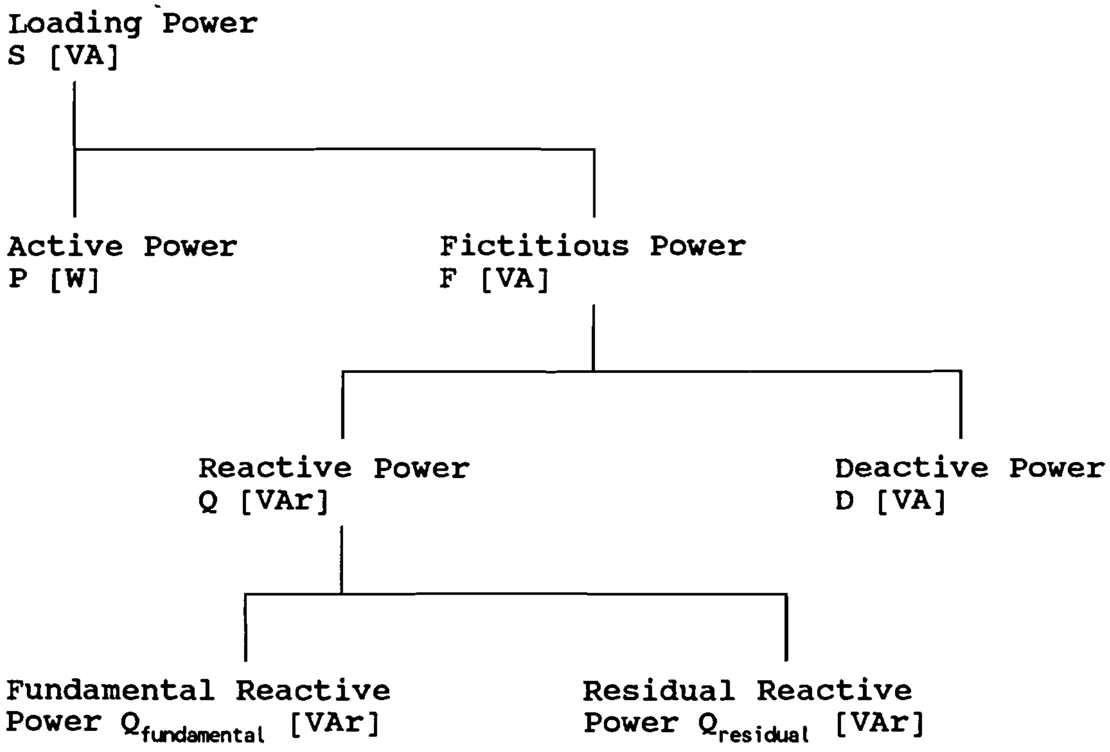

**Figure 1** - *Representation of power components [1.1], [1.2], [1.3].*

under load rejection conditions determines the need for reactive compensation. Also the maximum transmission capability, the steady state and transient stability as well as the prevention of overloading of generators are factors that have to be taken into consideration. In networks which contain Direct Current links, the reactive power requirements are heavily influenced by the operational requirements of the converters. After the technical criteria one also has to consider the economics of planning and operating of the power system, in order to minimize investments and series active losses. The value of the transmission capacity released by reduced reactive power loading or the delay of the installation of new transmission and transformation capacity is an important factor. Outages of lines, transformers, generators and compensators has to be taken into account when reactive power is planned. Generally voltages may vary in the range of 5 to 10 percent from the nominal voltage. Overvoltages can give flashovers or lead to the breakdown of insulation. Saturated transformers under overvoltage can produce currents rich of harmonics, also the risk of ferroresonance is a possibility. Causes for overvoltages are (sudden) reduction of load, line switching, faults and lightning. Undervoltages give degradation in the performance of loads. Undervoltages are usually associated with heavy loading or a shortage in generation capacity. Sudden overvoltages can result from the connection of very large loads.

## *1.2 General Characteristics of the ESKOM Power Supply System*

ESKOM, South Africa's national electricity utility, supplies more than half of the total electricity consumed on the African continent [1.11], [1.12]. ESKOM's power stations have a **nominal capacity of 39.060 MW.** They include the world's largest dry-cooled power stations and the only nuclear power station in Africa. Electricity is distributed country-wide and is exported to all neighbouring countries. ESKOM imports power from Namibia when available. Industry and commerce use 50% of the electricity generated in South Africa, mines 25%, households 16%, the railway system 4% and other 5%. Most mines and many industrial users are supplied directly. About 46% of its electricity is sold to local authorities and neighbouring countries who re-sell it to end-users. Approximately two thirds of South Africa's population does not have electricity at home. ESKOM's marketing thrust is towards bringing electricity where appropriate and cost effective, to households and other consumers which are still using other energy sources. The number of direct ESKOM customers increased from 278.033 in 1991 to 541.866 in 1992. This 95% growth is due to three factors, namely the connection of new customers as part of ESKOM's traditional business, the electrification of more houses under ESKOM's electrification programme, and the transfer of existing customers from local authorities to ESKOM. Electrification made the largest contribution to this growth.

The **total net maximum generating capacity** of ESKOM's **Power Stations** in service at 31 December 1992 was **36.846 MW.** The difference between nominal and net maximum capacity reflects auxiliary power consumption and reduced capacity caused by age of plant and/or low coal quality.

In figure 2, a map of South Africa is given on which the power stations and the main transmission system are shown.

An overview of ESKOM's power generating sources, expressed as net maximum capacities:

| | |
|---|---|
| Coal fired power stations | 32.698 MW |
| Gas turbines and diesel-sets | 368 MW |
| Hydro-electric | 540 MW |
| Pumped storage schemes | 1.400 MW |
| Nuclear power station | 1.840 MW |

Most of ESKOM's Power Stations are located in the Transvaal-area, this is area's D and part of E in figure 2. The Nuclear Station is near Cape Town. The coal fired stations are the base-load stations. Some of the older coal fired stations with relatively small units are mothballed. The gas turbine and diesel stations are used for peaking or emergency supplies, there are three stations, one in Cape Town, one in East London and one in Walvis Bay (not in figure 2). The hydro-electric stations are both located in the Orange Free State, their use is restricted to peaking and emergen-

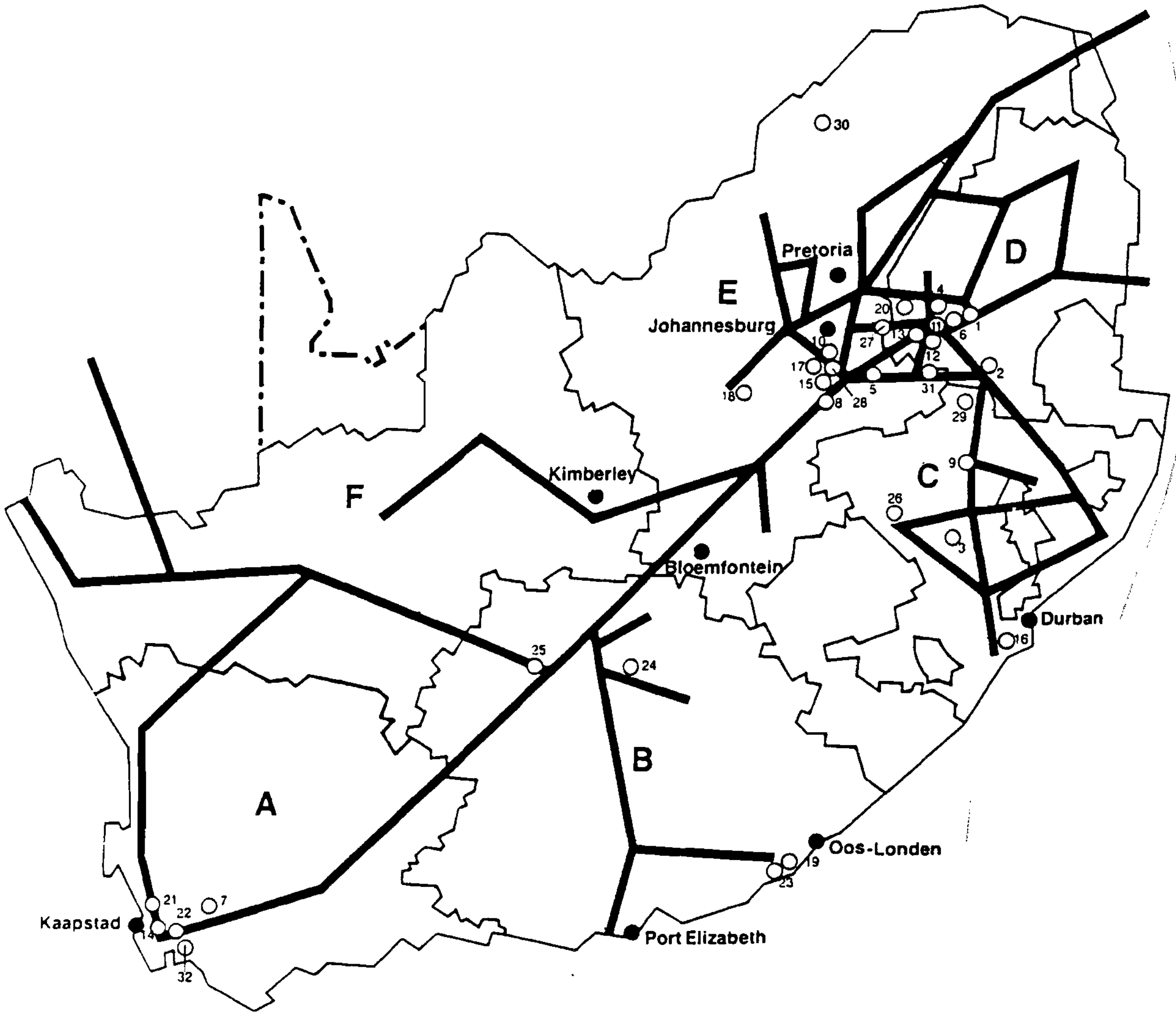

**Figure 2** - *The location of ESKOM's Power Generating Stations and the Main Transmission System [1.10].*

cies and availability of water in the dams. Pumped storage facilities are available in the Cape and in Natal. These facilities are net users of electricity and are used for peaking. Water is pumped during off-peak periods to generate electricity during peak periods.

Legenda on figure 2:
A = West Cape
B = Eastern Cape
C = Natal
D = Eastern Transvaal
E = Rand and Orange Free State
F = Northern Cape

The Power Stations are indicated as the small circles, and the Main Transmission System is represented by the fat lines. Numbers 1 and 2 indicate the locations of Stikland and Apollo Substations respectively. Tests have been carried out at these sites.

In 1992 the maximum simultaneous one-hour demand on the total ESKOM system was 22.640 MW. Since 1988 there is an average yearly increase of 2,5% in the maximum one-hour demand.

It is important to have some background on the power systems generating sources, the main transmission system and the relation between the minimum and peak demand:

1) The power systems is build up from different type of generating sources, this influences the overall distribution and cost of producing reactive power.
2) The interconnection capacity of the system to other countries and utilities and its relationships to overall system demand. This influences the overall distribution and cost of producing reactive power but also the range of reactive power production and compensation.
3) The difference between minimum and peak system demand is an important factor in determining the range of reactive power production and compensation.

The reactive absorption capability of generators is constrained by stability limits. In South Africa manual on-load tap-changers on generator transformers to regulate power flows and busbar voltages are used.

### *1.2.1 Transmission System Characteristics*

An increase in the maximum overhead line lengths is inevitable if ESKOM establishes a southern and central African electricity grid. Dr Ian McRae, chief executive of ESKOM, has since the mid 1980's been working on the establishment of such a Subsaharan Grid [1.13].

The ESKOM transmission and distribution system consists of the following voltages with their respective circuit kilometres:

**Table 1** - *Transmission and Distribution Lines in Service [1.11].*

| SYSTEM VOLTAGE (kV) | CIRCUIT LENGTH (km) |
|---|---|
| MAIN TRANSMISSION SYSTEM LINES | |
| 765 | 871 |
| 533 DC Monopolar | 1 030 |
| 400 | 13 782 |
| 275 | 7 199 |
| 220 | 1 243 |
| 132 | 491 |
| DISTRIBUTION LINES | |
| 165 - 132 | 16 910 |
| 88 - 33 | 21 099 |
| RETICULATION LINES | |
| 22 and lower | 170 484 |
| CABLES | |
| 165 - 132 | 56 |
| 88 - 33 | 313 |
| 22 and lower | 4 710 |

The total circuit kilometres of all lines is: **233.109 km**. The total length of all cables is: **5.109 km** of cables. The more expensive underground cables are used in the sub-transmission networks within cities. Sub-transmission networks [1.9] are those networks that were established prior to the introduction of transmission networks to the early established load points. Due to load growth and change of generation sources, these early networks are overlaid and strengthened with higher voltage sub-transmission systems. The third group of sub-transmission networks are those which are introduced to transport power from the transmission systems to the load centres.

In South Africa in the Transvaal, generation sources are close to load centres, which is clear from figure 2. Long transmission lines are used to transport power to the rest of the country. In the future when the Subsaharan grid becomes reality there will be more remote generation as well as an increase in transmission circuit kilometres. Especially in Zaire there is scope to generate up to 100.000 MW [1.13] by means of hydro power. An increase in the power transmission distances will give an increase in reactive power compensation requirements.

### *1.2.2 System Short-Circuit Characteristics*

The following table gives the maximum phase value of current rupturing capacities corresponding to a one-phase and a three-phase fault on a busbar at various network voltage levels.

**Table 2** - *Breaker Rupturing Capacities for the Highest Voltages in the Main Transmission System [1.7].*

| Busbar Voltage (kV) | Single-Phase Rupturing Capacity (kA) | Three-Phase Rupturing Capacity (kA) |
|---|---|---|
| 765 | 50,0 | 50,0 |
| 400 | Min.: 24,0 | Min.: 24,0 |
| | Max.: 63,0 | Max.: 63,0 |
| 275 | Min.: 14,5 | Min.: 14,5 |
| | Max.: 57,5 | Max.: 50,0 |
| 220 | Min.: 19,7 | Min.: 19,7 |
| | Max.: 40,0 | Max.: 40,0 |

A complete picture will be obtained together with the fault level at the substation were the breaker is applied [1.7].

The maximum switchgear ratings provide an indication of system stiffness. The actual amount of reactive power required to achieve a given level of voltage control is dependent upon the average fault levels existing in the network under particular demand and generation conditions.

Usually the switchgear ratings are chosen in such a way that under peak demand conditions there is room to manoeuvre.

It is also possible that a much higher breaker capacity is chosen if it is difficult to estimate the exact switching duties for the circuit breaker.

### *1.2.3 Network Transformer Characteristics*

The installed capacity, reactance and tap-changer characteristics of network transformers, which are installed between the different transmission voltage levels within a network provide an insight to the co-ordination of reactive power and voltage control functions together with short-circuit limitation considerations in the network.

The type and range of the tap-changer gives an indication of the expected voltage regulation due to reactive power exchanges between network voltage levels within the system. In South Africa use is made of an interconnected high voltage bulk transmission network to networks of lower regional voltage.

The most important transformers in this system are therefore provided with on-load tap-changers, usually on the high-voltage side. These transformers have a large influence on reactive power exchanges within the interconnected system. There are a total of **141.407 transformers in service**, with a **total capacity of 164.805 MVA.**

### *1.2.4 Reactive Compensation Plant Characteristics*

In the following, an overview will be presented on the different means of compensation of reactive power, in general and in the ESKOM Power Supply System [1.4], [1.5], [1.8].

#### *1.2.4.1 Shunt Reactors*

Shunt reactors are generally installed in networks to compensate the capacitive reactive power. Shunt reactors are either directly connected to the substation bus (busbar reactors), to a transmission line (line reactors), or connected through the delta connected tertiary windings of transformers. In the last case the reactors are usually switched at the medium voltage (tertiary) side. A tertiary switched reactor is often preferred above a directly connected (line or bus) high voltage reactor, due to the switching and insulation advantages offered by medium voltage reactors. Small amounts of shunt reactors are used in lower voltage levels.

Shunt Reactors are used to control:
1) The capacitive gain of highest voltage transmission networks by direct connection to these networks, as a line or as a busbar reactor.
2) The reactive exchange between the three main highest voltage transmission networks by tertiary connection to the transformers connecting these networks.

The total operational shunt reactor power is 5.800 MVAr.

**Table 3** - *The Shunt Reactor Banks Installed in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Rating (MVAr) | Number of Banks | Total Power (MVAr) |
|---|---|---|---|
| 765 | 400 | 6 | 2.400 |
| 400 | 100 | 26 | 2.600 |
| 330 | 60 | 2 | 120 |
| | 30 | 2 | 60 |
| 275 | 47 | 1 | 47 |
| 220 | 90 | 4 | 360 |
| | 40 | 2 | 80 |
| | 15 | 2 | 30 |
| 132 | 30 | 3 | 90 |

Only the three-phase power rating is given, irrespective of the fact if it is a single or a three-phase unit in the case of the shunt reactors. For example at 765 kV the 400 MVAr shunt reactors are three single-phase units. In the ESKOM transmission system, only line and busbar reactors are applied. No use is made of tertiary reactors.

### *1.2.4.2 Shunt Capacitors*

All the shunt capacitors in ESKOM's transmission system are connected to the substation bus. The bulk of the shunt capacitive power is installed at the 88 kV, 132 kV and 275 kV transmission voltage levels. No shunt capacitors are connected via the tertiary of the transformers interconnecting the main transmission networks. Most of them are switched on a daily or weekly basis.

The total operational shunt capacitor power is 6.600 MVAr.

**Table 4 -** *The Shunt Capacitor Banks Installed in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Rating (MVAr) | Number of Banks | Total Rating (MVAr) |
|---|---|---|---|
| 400 | 50 | 2 | 100 |
| 275 | 168 | 2 | 336 |
| | 156 | 1 | 156 |
| | 150 | 7 | 1.050 |
| | 144 | 5 | 720 |
| | 141 | 1 | 144 |
| 132 | 100 | 1 | 100 |
| | 72 | 32 | 2.304 |
| | 48 | 1 | 48 |
| | 36 | 13 | 468 |
| | 18 | 2 | 36 |
| 88 | 48 | 20 | 960 |
| | 24 | 1 | 24 |
| | 20 | 1 | 20 |
| | 16 | 3 | 48 |
| | 12 | 3 | 36 |

### *1.2.4.3 Synchronous Compensators*

Synchronous condensers were the major reactive power compensators at the beginning of this century. Nowadays they have been mainly replaced by shunt capacitors. The advantage over capacitors is that they can maintain or even increase their output at reduced system voltage. Synchronous compensators can be applied with High Voltage Direct Current power transmission were they supply a portion of the reactive power, but also provide system reinforcement at these stations if the local short-circuit capacity is low. They are used to maintain voltage within certain limits and to improve system stability. Sometimes declutched generator capacity is utilised as synchronous compensators.

### *1.2.4.4 Static (Shunt) VAr Compensators (SVC)*

South Africa will install some large static var compensators in the near future. Static means that there are no moving parts like in a generator or synchronous compensator. They are used to maintain voltage at or near a constant level, improve power system stability, improve the power factor and correcting phase unbalances. It is usuall to have fixed shunt capacitors parallel with the controlled susceptance. These are usually tuned with reactors to harmonic frequencies to absorb harmonics generated by the controlled susceptance. A Static VAr Compensator (SVC) can be designed as a thyristor-controlled reactor (TCR) or a thyristor-switched capacitor (TSC). They are normally connected to a busbar by a circuit breaker.

**Table 5** - *The Static VAr Compensators Installed in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Inductive Rating (MVAr) | Capacitive Rating (MVAr) | Number of Banks |
|---|---|---|---|
| 400 | 250 | 250 | 4 |
| | 150 | 250 | 1 |
| 220 | 22 | 22 | 1 |
| 132 | 10 | 35 | 5 |
| | 10 | 20 | 1 |

### *1.2.4.5 Series Capacitors*

South Africa has series capacitors due to the long transmission distances in its system. The series capacitors are connected to the 400 kV network. They reduce the series impedance of the interconnection and hence reduce series reactive losses, which gives a better voltage regulation. The compensation factor is defined as the percentage of line reactance compensated by the series capacitor installation and varies from 40 to 70%. Improvement of system transmission capacity and system stability limits are generally the aims in installing these elements. The choice of the MVAr rating is therefore governed by the transmission line length and the desired improvement in transmission capability. In South Africa series capacitors are kept in service at all times except when switched out for maintenance or transiently by-passed by the protective gaps across capacitors. Series capacitors are also switched in order to avoid sub-synchronous resonance.

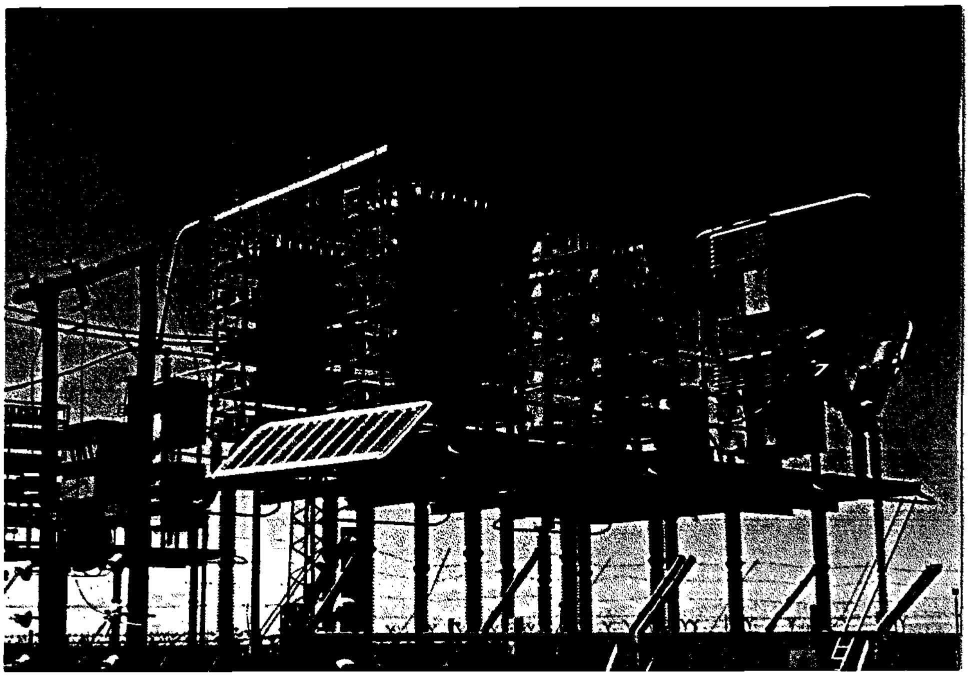

**Figure 3** - *A series capacitor installation at Nestor Substation, located in ESKOM's 400 kV connection to the Cape.*

In South Africa, series capacitors are fitted with circuit breakers to by-pass units when sustained oscillations occur.

The future development will not see too much progress in the development of shunt reactors and shunt capacitors. Also no essential improvement of synchronous compensators is in sight. Static VAr Compensators, based on power electronics will be the main subject of development in this area. Thyristors with higher power and light-triggering will be introduced.

In figure 4 a scheme is shown of a voltage and reactive power control system [1.4].

The abbreviations used are:
SC = Shunt Capacitors
SR = Shunt Reactors
AQR = Automatic Reactive Power Controller
AVR = Automatic Voltage Controller
LRT = On-load Ratio Tap-changers

To gain a better understanding of the voltage and reactive power controller, the operating characteristics are shown in figure 5. In South Africa switching of shunt capacitor banks on the 275 kV system is used for voltage control in addition to automatic voltage controller action. Network transformer tap changers are generally used for the local voltage control. In general it can be said that remote control together with local control is used in the ESKOM main transmission system. These control-modes are supervised by National Control (in Germiston) and Regional Control Centre's (Country-wide).

### *1.2.4.6 Other Means of Reactive Compensation*

In periods of low power system demand it is possible to use the following means of reactive power generation/absorption:

1) Declutched operation of generators as synchronous compensation plant.
2) Part loaded operation of generators for additional reactive power generation or absorption purposes.
3) Switching out of service transmission lines and cables, this to control the required amount of reactive absorption capacity.
4) Tap staggering of transformers operating in parallel to absorb reactive power by means of circulating current loops between transformers.
5) Load shedding.

In the previous overview a short summary is given of reactive power compensation and the involved power equipment in general as well as the situation in the ESKOM power system.

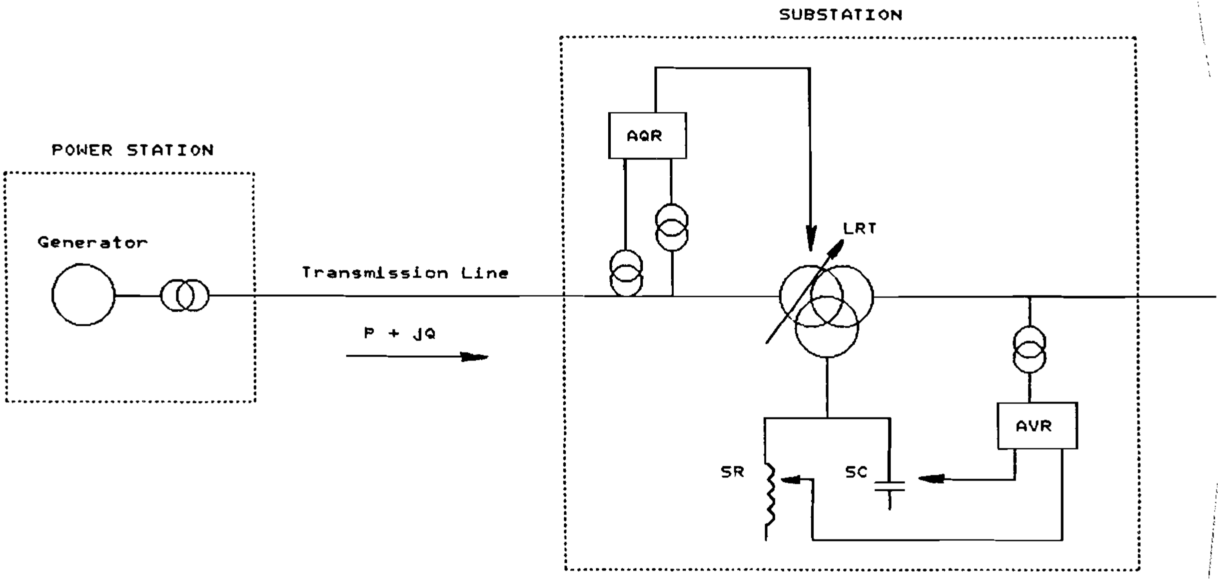

Figure 4 - *Voltage and reactive power control system [1.4].*

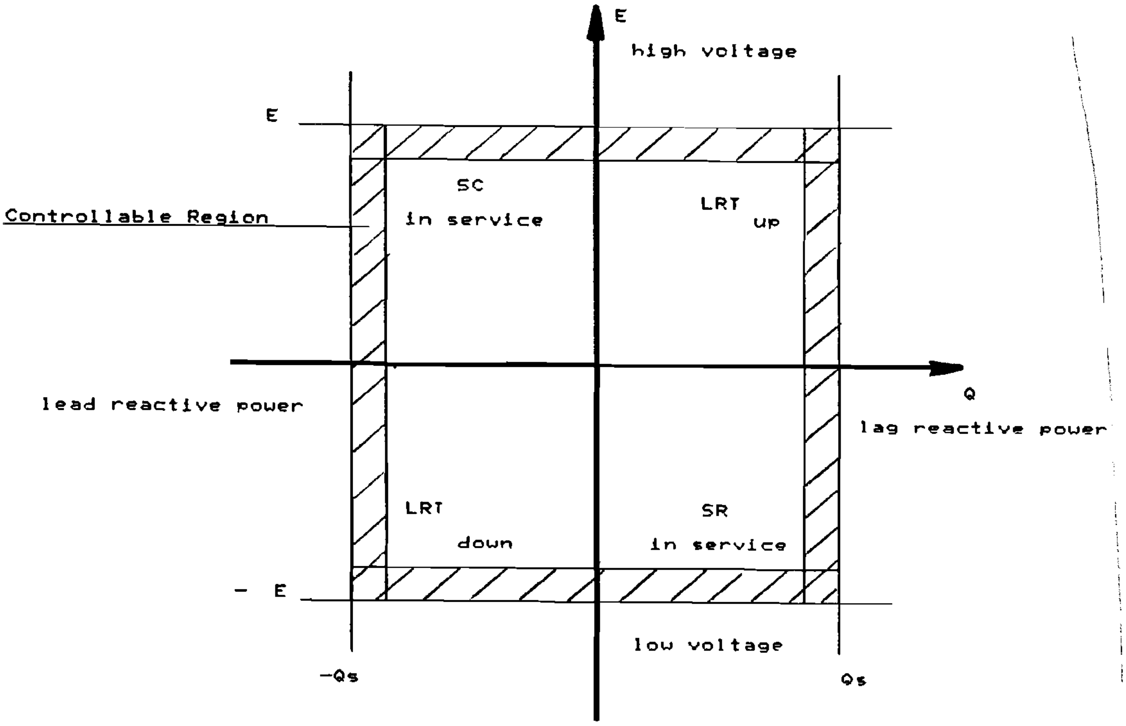

Figure 5 - *Characteristics of the voltage and reactive power controller according to figure 4 [1.4].*

### *1.2.4.7 Planned Reactive Power Equipment*

Finally, in tables 6, 7 and 8, a summary of the planned Shunt Reactor Units or Banks, Shunt Capacitor Banks and Static VAr Compensators up to the year 2000 is given.

**Table 6** - *Planned Shunt Capacitor Banks up to the year 2000 in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Rating (MVAr) | Number of Units | Total Rating (MVAr) |
|---|---|---|---|
| 400 | 300 | 1 | 300 |
| 275 | 150 | 2 | 300 |
| 132 | 12 | 2 | 24 |
| 88 | 48 | 4 | 192 |

**Table 7** - *Planned Shunt Reactor Units or Banks up to the year 2000 in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Rating (MVAr) | Number of Units | Total Rating (MVAr) |
|---|---|---|---|
| 765 | 400 | 9 | 3.600 |
| 400 | 200 | 3 | 600 |
|  | 100 | 19 | 1.900 |
|  | 50 | 3 | 150 |

**Table 8** - *Planned Static VAr Compensators up to the year 2000 in the ESKOM Power Supply Grid [1.6].*

| Voltage (kV) | Inductive Rating (MVAr) | Capacitive Rating (MVAr) | Number of Units |
|---|---|---|---|
| 400 | 100 | 300 | 1 |
| | 50 | 300 | 3 |
| 275 | 50 | 300 | 3 |

**Table 9** - *Comparison of the installed and planned shunt capacitor banks and shunt reactors.*

| | Installed | Planned |
|---|---|---|
| Shunt Capacitor Banks | 6.600 MVAr | 816 MVAr |
| Shunt Reactors | 5.800 MVAr | 6.250 MVAr |

For the shunt reactors, 3.600 MVAr is planned at 765 kV and 2.650 MVAr at 400 kV.

For the shunt capacitors this is spread over the system voltages.

The planned equipment is either serving as replacement of old units or as new equipment because of system expansion or changes in load pattern.

### *1.3 Summary*

Reactive power is produced or absorbed by all major components of a power system:

- Generators;
- Power transfer components;
- Loads **(Linear and Non-linear)**;
- Reactive power compensation devices.

Reactive power production or absorbtion by power transfer components depends mainly on operating voltage and current and can therefore hardly be changed during normal operation. Also changes in reactive power of generators and loads are limited.

Reactive power compensation devices are installed to improve:

- Reactive power balance;
- Voltage control;
- System stability including damping of power oscillations.

Reactive power compensation devices can be switched or continuously controlled.

Shunt reactors and shunt capacitors are the most applied reactive power compensation devices. Connecting or disconnecting these shunt reactive devices to or from the power system can be problematic.

Taking the large number of reactive power equipment, which is in operation and which is planned for the coming years, into consideration it is clear that possible solutions to these switching problems have to be investigated for future installations.

Also for equipment in service, which operates satisfactory, it is important to monitor the presently applied technologies in comparison with state of the art solutions. In the following chapters this will be explained, and possible solutions to the switching problems will be given.

## *1.4 References*

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# Chapter 2: Controlled Switching

## *2.1 Introduction*

Controlled switching is the operation of a switching device in such a manner that contacts are closed or opened at a predetermined point on a reference voltage or current wave.

Other expressions that are in use, and which have the same meaning as "controlled switching", are:

1. Point-on-wave switching
2. Time Staggered switching
3. Synchronous switching
4. Phase-angle-controlled switching
5. Controlled synchronous switching
6. Phase-delayed switching
7. Phase-displaced switching

In all these cases with switching is meant energizing as well as de-energizing. Up to now most of the applications are in the area of energizing capacitive elements and de-energizing shunt reactors.

Controlled switching is used to minimize stresses on the power system and its components. Also the stresses on the circuit breaker during switching operations by switching on the most favourable time-instant when switching small capacitive and inductive currents or even fault currents can be minimized with controlled switching. Applications of controlled switching can be found in the areas of energizing and de-energizing of capacitive as well as inductive power equipment.

Capacitive loads are in general the following:

1. Transmission lines under no-load conditions.
2. Compensated (long) lines.
3. Cables.
4. Capacitor Banks (Single or Back-to-Back).
5. Filter Banks.

The following loads are inductive:

1. Shunt reactors.
2. Transformers under no-load.
3. Reactor loaded transformers.

Problems with switching of small capacitive and inductive currents can be solved by applying controlled switching. However there are some restrictions in the applications. Not every circuit breaker is suited for controlled switching. Also care has to be taken that controlled switching is not chosen as an easy way out of certain problems. In general it can be said that a reduction of currents and voltage transients or harmonics when switching capacitive and inductive elements can be reached.

As mentioned it is necessary with controlled switching to switch at the most advantageous (controlled) time-instant. This means that the circuit breaker has to operate with a certain required accuracy of the switching instant for the various applications. The reliability of controlled switching also has to be looked at. The breaker operating mechanism is a determining factor with respect to the accuracy. The application of controlled switching means that control components such as sensors and electronic devices have to be implemented into the breaker itself or into a breaker or station monitoring system. These electronics are used in a hostile environment to control the switching moment. This means that appropriate shielding measures have to be taken to assure correct operation of the switching device. Field experience with controlled switching is important in evaluating the theoretically set goals with practice. In general it can be said that mechanical as well as dielectric aspects of the circuit breaker have to be considered very carefully.

Controlled switching for normal conditions reduces voltage and current transients to a minimum. In doing so also the mechanical and dielectrical stresses to power equipment are minimized. Controlled energizing of capacitors avoids the high inrush currents and the associated grid voltage disturbance. Controlled energizing of inductive loads eliminates the direct current part of the inrush current. With the application of controlled de-energizing of capacitors it is possible to avoid restrikes with short arcing times. Also when de-energizing reactors it is possible to avoid (multiple) reignitions, by controlling the arc time of the breaker. By eliminating the possibility of restrikes possible severe and dangerous overvoltages can be avoided.

The biggest problem with the application of controlled switching is the mechanical stability of the circuit breaker because the maximum tolerances for the timing are set at about ± 1 ms. If the tolerance is larger the impact that controlled switching has, vanishes rapidly. The large variations of the operating times of circuit breakers under different conditions for the operating system (temperature, control coil voltages, pressure of the insulating medium and or driving medium) were the reason that wide application of this technique is still not found. A lot of progress has been made in the development of circuit-breakers and their operating mechanisms in the last decades, this gave an impetus to the consideration of applying controlled switching in the various possible fields.

CIGRE Working Groups have been working for over 20 years on the topics of small inductive and capacitive current switching. A main cause of concern is the determination if a circuit breaker is restrike-free or not. Problems with test circuits arise in the case of a restriking breaker because the phenomena after restrikes are strongly dependent on the actual power system and substation configuration in the immediate vicinity of the circuit breaker. Therefore to test a circuit breaker in an adequate way on being restrike-free is very difficult in a laboratory. In the decades before and after the second World War many articles have been published in switching of small currents and the restrikes occurring on interruption, especially with oil-circuit breaker and airblast breakers. The application of controlled switching pushed engineers in the direction of designing special circuit breakers suited for this purpose. With the sulphur hexafluorid ($SF_6$) technology being applied the number of restrikes was reduced considerably. However the risk of restrike may rise with the present trend towards circuit-breakers with high operating voltage per breaker unit. A method to prevent restrikes is the application of controlled switching. The practical applications of controlled switching will be dealt with in chapter 4: Experimental Field Measurements.

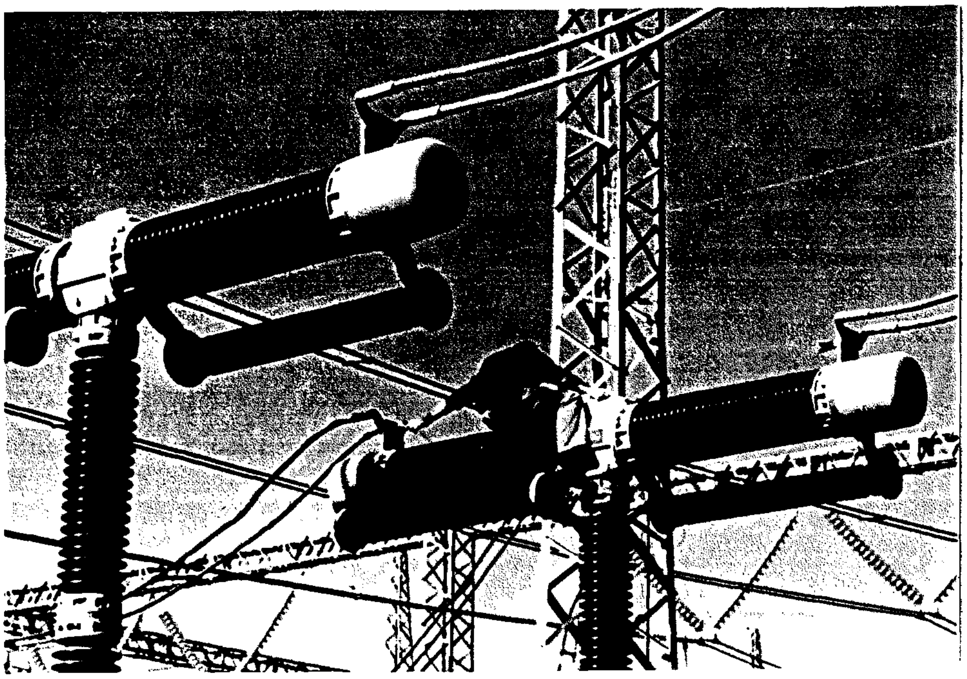

**Figure 1** - *Connecting the leads for no-load tests to the breaking chambers of the AEG S2-300 breaker at ESKOM's Apollo Substation, near Olifantsfontein.*

## 2.2 *History of Controlled Switching*

Controlled switching already has a long history. Many inventors have proposed specially designed electro-mechanical devices to obtain circuit breakers with minimum arcing time during interruption of short circuit currents. In short circuit test laboratories controlled closing is a normal feature. Sometimes also controlled opening of master-circuit breakers is used to minimize contact wear. It is necessary to control the opening and closing of the circuit breaker under test to meet the conditions as set in IEC 56 [2.1]. Also the number of random tests which would otherwise be necessary to prove a circuit breaker can be reduced considerably.

Kesselring (1967) [2.2] developed a controlled switching device to minimize the short-circuit current duration to about 10 ms. Nitta and Kiyokuni (1970) [2.3] developed a circuit breaker which employed controlled switching techniques with a compensation scheme for changes in breaker operating time due to variations in temperature and pressure. Kriechbaum (1971) [2.4] demonstrated that with the use of controlled switching contact wear during interruption in a high power testing station is greatly reduced. Beehler and McConnell (1971) [2.5] developed a new circuit breaker with high speed opening by application of an electro-dynamic drive. This breaker, the first of this kind, was used to provide primary protection for the largest synchronous condenser at that time in the USA. Berglund et al. (1973) [2.6] also designed a high speed opening breaker, also with the purpose of keeping the fault clearing time as small as possible. Fast fault clearing is important to maintain system stability margins.

The very first application for controlled switching that was found in the literature were by Hürbin (1929) [2.7] and Grünewald (1935) [2.8]. They were amongst one of the first that applied controlled switching with the energizing of capacitor banks.

Bauer (1934) [2.9] and Bornitz (1942) [2.10] also explained the application of controlled switching with the emphasis on the energizing of power capacitors. Prince et al. (1954) [2.11] published on a new design of a 115 kV Stored-Energy-Type restrike free Capacitor Switch, which was demonstrated in field tests. Williams et al. (1955) [2.12] was one of the first that published on the use of controlled opening for capacitor banks. Later applications in the field of line switching were published. Maury (1966) [2.13] published about the application of synchronous closing of 525 kV and 765 kV circuit breakers, with and without closing resistors, for unloaded transmission lines. Thorén (1970) [2.14] also published on this topic for shunt-reactor-compensated lines. Konkel et al. (1977) [2.15] demonstrated the use of a controlled closing device for controlling conventional 500 kV circuit breakers equipped with one closing resistor in each phase. He published his preliminary switching surge model studies and the results of subsequent field tests with a prototype of the control device. In Russian investigations by Beliakov (1978) [2.16] it was indicated that the use of controlled closing applications for high voltages like 750 kV, or even up to 1500 kV, for the switching of transmission lines might be a necessary future specification for the operation of breakers at these voltage levels.

In 1977, Brunke and Schockelt [2.17] published on the controlled energizing of shunt capacitors at 230 kV with vacuum breakers. In 1985, Alexander [2.18] also demonstrated the practical application of controlled switching for shunt capacitors at 69 kV and 230 kV, also with vacuum circuit breakers. From the mid-eightees up to now a considerable amount of papers has been published on the subject of controlled switching. In the 1988 CIGRE Conference Session controlled switching was described in two papers. In the 1990 CIGRE Conference Session, controlled switching was a preferential subject. Within CIGRE Study Committee 13 (Switching Equipment) a task force on Controlled Switching was established in June 1991.

At present detailed studies are not easy because there is no sufficient field experience with the performance of controlled switching systems with respect to cost, reliability and their efficiency of controlling switching surges. It is also a fact that the state of technology in this field is not yet stabilized. A lot of development work is still under progress.

As mentioned before one of the main problems is the long term reliability of the circuit breaker and of the necessary electronic equipment involved to carry out controlled switching. No appropriate testing methods or protocols for the mechanical characteristics are laid down in international specifications on circuit breakers at present. Appropriate mechanical testing methods have to be established in future. The CIGRE reliability survey on circuit breakers in service has shown that mechanical defects represent a significant contribution to the overall failure. Mechanical defects are associated with circuit breaker operating mechanisms.

### *2.3 Circuit Breaker Operating Mechanisms*

Most utilities have a lot of circuit breakers of yesterday's technology (airblast, bulk oil, minimum oil, double pressure $SF_6$, magnetic airbreak) in service. In the last two decades, modern circuit breakers using the puffer (or single pressure) and self-assisted or self-blast (also single pressure) $SF_6$ principle have been introduced.

Circuit breakers are equiped with different operating systems.
The following operating systems are applied widely:

1. Spring stored energy operating mechanism.
2. Pneumatic operating mechanism.
3. Hydraulic operating mechanism.
4. Combined systems (for example spring stored energy and pneumatic or hydraulic).

The choice for a certain operating system depends mainly on the following criteria:

1. Operating experience with a certain system, the feedback from customers to the manufacturer, but also tradition.
2. The adaptability of the operating system to a certain selected circuit breaker.
3. The manufacturers own possibilities to develop and manufacture operating system technology.
4. The energy requirements for the operating system.

Most of these criteria affect especially the breaker manufacturer, the client only wants a reliable system with the least possible maintenance, so a high availability. It is a fact that whatever operating system is chosen, that it is expected to stand still for most of its live. Shunt capacitor and shunt reactor breakers can be operated daily on weekdays, line breakers do usually not operate very often. Irrespective of the operating frequency, the system has to store a large amount of energy continuously and release it instantly on demand.

The first transmission circuit breakers were based on the bulk oil principle. Later minimum oil breakers were developed. Both types had solenoid spring, combined spring and hydraulic, or pneumatic mechanisms, depending on the sort of breaker operation. Air blast breakers were developed in the 1940's. They have compressed air as their functioning medium, and use a spring operating mechanism in conjunction with pneumatic valves or a pneumatic mechanism. With the introduction of $SF_6$ technology the performance of circuit breakers has increased enormous. For example voltage ratings which used to require up to twelve contacts in series on an airblast or minimum oil breaker can be achieved with two contacts in the $SF_6$ technology. All operating mechanisms are used to provide a controllable source of energy, but they all have their particular characteristics.

Pneumatic and hydraulic mechanisms have to be monitored continuous, because of the inherent leakage of air or hydraulic pressure. The reliable operation depends on the correct functioning of the valves and seals in the mechanisms. With a spring mechanism if the springs are charged and latched, ready for use, no further monitoring of the mechanism is required. The materials used in the mechanism and the correct functioning of the latches determines the reliability of this mechanism. Taking all three mechanisms into perspective, it can be said that the spring mechanism will be the least complex. Spring mechanisms are applied up to 420 kV and 63 kA. Most of the breakers that are being applied for controlled switching purposes have either spring or hydraulic mechanisms.

In table 1 an overview is presented of the characteristics of the three operating mechanisms. From this table it follows that pneumatic and hydraulic mechanisms are the most complicated ones. They need continuous pressure monitoring devices to ensure operating of the breaker if needed.

In appendix 1, more detail is given about the structure of the operating mechanisms as they are presented in table 1. Also details on the construction and the operation of the AEG S2-300 circuit breaker are presented.

At the 150 kV Borssele Substation (Owned by the utility Delta Nutsbedrijven) in the south of The Netherlands, an ABB circuit breaker with spring drive is used for controlled energizing of a 150 MVAr capacitor bank. This installation was commisioned in the first week of November 1993. It is the first controlled switching installation for a power utility in The Netherlands.

**Figure 2** - *The ABB (LTB 170 D1) $SF_6$ Circuit Breaker with Spring Mechanism (BLK52) at Borssele Substation, The Netherlands.*

**Table 1** - *Characteristics of the operating mechanisms.*

On the next page table 1 gives some of the important characteristics of the three most applied operating mechanisms for high voltage power circuit breakers.

Abbreviation: NA = Not Applicable.

| FUNCTION | OPERATING MECHANISM | | |
|---|---|---|---|
| | PNEUMATIC | HYDRAULIC | SPRING |
| Energy storage | Air Receiver | Pressure accumulator for nitrogen and hydraulic oil reservoir | Motor-wound Spring |
| Monitoring stored energy | Pressostat | Control Nitrogen volume | NA |
| Energy recharging | Compressor-Motor combination | Hydraulic Pump-Motor combination | Gearbox and motor |
| Monitor energy recharging | Pressostat and Motor Control via Contactor | Pressostat and Motor Control via Contactor | Mechanical changeover of Limit Switch during Winding. |
| Overload monitoring | Pressostat | Pressostat | NA |
| Energy output | Pressure via pipeworks | Pressure via pipeworks | Mechanical axis |
| Emergency Close Open operation | Other Compressor Motor combination and Manual Close and Trip Facilities | Hand Pump and Manual Mechanical Close and Trip Facilities | Mechanical Levers |
| Recharging in Emergencies | Other Compressor Motor Set | Hand Pump | Hand Crank |
| Critical Elements of the System | Compressor Plants, Monitoring Devices and Dehydrators | Oil leakages, Nitrogen leakages and Monitoring Devices | Latches |
| Damping Mechanism | By means of Additional Devices | Integrated in Operating Cylinder | By means of Additional Devices |

### *2.4 Characteristics of the Circuit Breaker*

The many different switching devices that are in use all have their own specific properties. These specific properties will to a large extent determine their behaviour during switching operations. Dielectric as well as mechanical properties, with the emphasis on controlled switching, will be discussed in the following sections.

#### *2.4.1 Dielectric Characteristics*

Before going into more detail two situations, depending on the sort of load to be switched, can be distinguished for a controlled closing operation:

1. Closing upon voltage zero.
2. Closing upon voltage peak.

Controlled opening (physical opening of the contacts), will usually be started at or around voltage maximum. The dielectric strength between the contacts is of major importance both on closing and on opening of the contacts. With a making operation the dielectric strength will determine the number and severity of the pre-ignitions. With an opening operation the dielectric strength determines if reignitions (inductive loads) or restrikes (capacitive loads) will occur.

The dielectric strength between the contacts is determined by the following factors:
1. The geometrical shape of the contacts and the electrical field shape at the switching operation.
2. The contact velocity (making or breaking).
3. The state the contacts are in.
4. The characteristics of the arc extinguishing medium.

After a certain number of switching operations, the dielectric strength will be subjected to changes, these can be due to:
1. Pollution and subsequent deterioration of the arc extinguishing medium.
2. Physical alterations of contacts and nozzles due to switching operations, eg. pre- and re-ignitions, and short-circuit interruptions will give burnoff and wear of contacts, this will affect the operating times as well.
3. Also the mechanical wear of contacts and nozzles plays a significant factor.

The dielectric strength is thus not a constant parameter, it is governed by statistical scatter. This can be scatter of, for example the mechanical components and the pollution of the arc extinguishing medium. Also statistics on the physical behaviour of the dielectric play an important role. Altogether the dielectric strength is a complex function of a lot of parameters. **Closing upon voltage zero** is the most difficult situation that can be encountered.

This is usually the case with energizing shunt capacitors and filter banks which may have an earthed or un-earthed neutral. In the case of an *earthed* neutral, the energizing should occur at or near the instant of zero phase-to-earth voltage in each phase. This is explained in appendix 2. This means for a three-phase situation, that the first pole should be closed at 0 ms or $0^0$, the second pole at 3,33 ms or $60^0$, and the third pole at 6,67 ms or $120^0$, all times with reference to the first pole. If closing at voltage-zero is possible, the current transients will be eliminated completely. However in practice only an approximation to the voltage-zero is possible. Therefore the current transients cannot be completely eliminated.

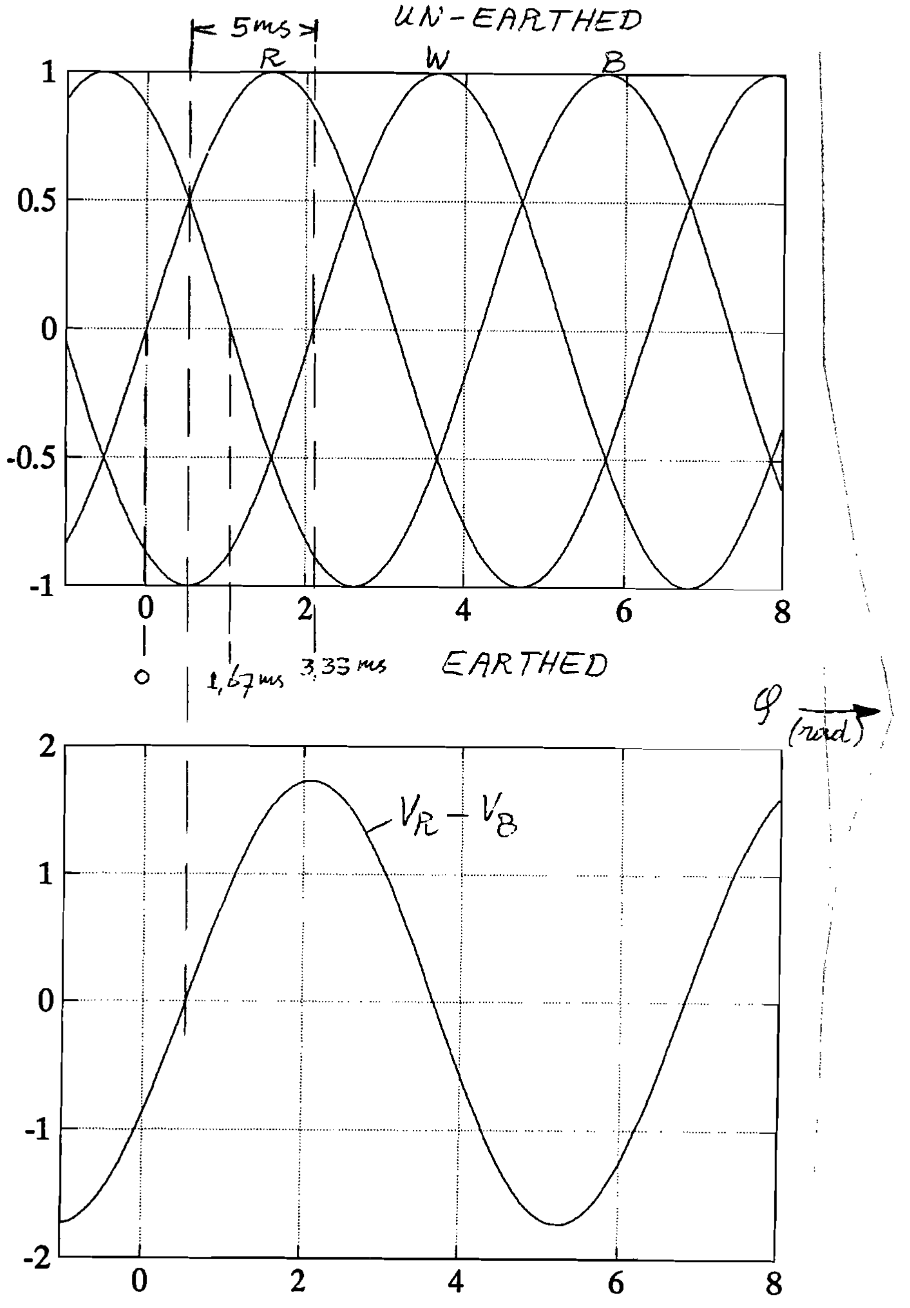

**Figure 3** - *Control points for energizing at gap voltage zero for capacitive loads (un-earthed neutral).*

In the case of an *un-earthed* neutral, the optimum time is dependent upon the pole closure sequence. Random closing is satisfactory for the first pole since no current flow is established. The second pole must close at a voltage-zero of the phase-to-phase voltage appearing across that pole. The third pole must close at a voltage zero of the 1,5 per unit (the neutral is at 0,5 pu and the source at 1 pu) voltage appearing across that pole. Another possibility is to close two poles simultaneously, this means that the voltage across each pole will be $\frac{1}{2}\sqrt{3}$ per unit (half of the sum of two (co)-sines with a phase difference of $120^0$). The third pole to close would then again experience a 1,5 per unit voltage, and will be energized 5 ms or $90^0$ later.

Note that 1 per unit (pu) is equivalent to the systems peak phase-to earth voltage.

The fact that energizing of shunt capacitors or filters must take place when the voltage across the pole is zero, can be problematic. To achieve energizing when there is zero voltage across the contact gap, the rate of fall of the withstand voltage $U_d(t)$, must be larger than the rate of change of gap voltage $U(t)$, at zero voltage.

This can be expressed in the following relation:

$$\frac{d\,U_d(t)}{dt} = k \cdot \omega \cdot U_{Peak} \cdot \frac{\sqrt{2}}{\sqrt{3}}$$

The value of **k** must be **k** > 1 to permit energizing at voltage zero without pre-arcing. So the rate of fall of the withstand voltage of the closing contacts, also known as the pre-strike characteristic, must be more steep than the rate of change of the applied gap voltage immediately before voltage zero.

Harner [2.25] stated that the rate-of decrease of the dielectric strength for an $SF_6$ breaker is assumed to be at least 100 kV/ms based on a 20 kV/mm dielectric withstand and a 5 m/s closing speed. He states that they found a value of 10 kV/mm at a pressure of 6 bar. However he also states that a value of 15 kV/mm may be more appropriate because of contact roughness. Taking this into account a rate of decrease of the dielectric strength might be only 50 kV/ms to 75 kV/ms. Lower values of the rate of decrease of the dielectric strength necessitate **higher closing speed** or a **lower system voltage.**

If the gradient of the prestrike characteristic is lower than that of the applied voltage around voltage zero prearcing takes place during the rise of the voltage or close to the crest of the sinusoidal voltage wave. Schramm [2.26], [2.27] states, if a prestrike must be avoided outside of 1 ms from the system voltage zero crossing the rate of change of the prestrike characteristic must not be lower than 95% of the maximum rate of change of the system line-to-ground voltage. Standard designs of circuit breakers have prestrike characteristics with gradients in the order of 40 kV/ms per break. This value can be found irrespective of the type of circuit breaker, and it is to a large extent also independent of the voltage rating per break. Schramm does not mention any closing speed in his discussion. The 40 kV/ms value as reported by Schramm differs considerably from the values as they were stated by Harner.

It can be concluded from the previous that for un-earthed neutrals depending on the sequence of pole closure, in at least the pole that is stressed with 1,5 pu (phase-to-earth) some prearcing might occur. Schramm concludes that controlled energizing is only possible without pre-striking with standard breakers rated up to 145 kV per break, in which the stated limits are not exceeded. Harner also says that voltages above 145 kV are not possible to handle for single-gap breakers. Multiple gap breakers have to be used in that case.

Various researchers [2.25] - [2.30] have investigated the allowable closing time window around the voltage zero. This time window determines the advantage of controlled switching over other methods of reducing transients on energizing. It can be concluded that a time window of ± 1 ms is almost generally accepted and that smaller windows are possible if the breaker characteristics allow this.

Berneryd [2.28] and Alvinsson [2.29] have a different philosophy. For a capacitor bank with isolated neutral, the first pole closes against the sources phase-to-ground voltage. The second pole against phase-to-phase voltage, and the third pole against 1,5 times (1,5 pu) the phase to ground voltage. At random switching (uncontrolled), the second pole can close by pre-arcing at the peak-value of the phase-to-ground voltage or at 1,73 pu. This is the worst case. It is ideal to close the first two poles at a phase-to-phase voltage zero and the third pole 5 ms later. However those are the theoretically optimum points, it requires that the contacts touch when the voltage becomes zero but also that the dielectric strength holds while closing. As will be clarified in the next section, every breakers operating times are subjected to a certain spread, and also the dielectric withstand will have a tolerance. Schramm and Harner base their discussion on a breaker with no pre-arcing at all. Berneryd and Alvinsson take a certain amount of pre-arcing into consideration in their theory. However they strictly stay within the ± 1 ms time window. It is a fact that the larger the time-window, the more severe the transients will be.

**Table 2** - *Values of the gradient du/dt, at voltage zero of three phase-to-ground voltages, for the power system and the circuit breaker [Schramm - 2.26].*

| Power System | | | Breakers Pre-arcing Characteristics<br>40 kV/ms per break | |
|---|---|---|---|---|
| Rated Voltage kV | Frequency Hz | $\frac{dU_d(t)}{dt}$ kV/ms | Breaks per Pole | $\frac{du}{dt}$ kV/ms |
| 145 | 50 | 37,2 | 1 | 40 |
| 420 | 50 | 107,8 | 2 | 80 |

In figure 4, the pre-arcing probability distribution can be improved by setting the nominal closing instant a little later then the gap voltage zero. For normal closing speeds (order of say 4 to 5 m/s) the requirement as to allow no pre-arcing at all sets a low upper limit to the system voltage. The upper limit can be raised considerably if some pre-arcing is allowed, this is illustrated in figure 5. The nominal instant of contact touch is chosen in such a way that in the preceding half cycle pre-arcing is avoided for the shortest anticipated closing time and the lowest anticipated withstand strength.

The maximum pre-arcing voltage in figure 4 is 0,60 pu (72,5 kV power system), while in figure 5 it is 0,85 pu (170 kV power system). It depends on the user how much pre-arcing voltage will be considered as acceptable. Normally a high pre-arcing voltage is not allowed because of the disturbances on the system. It is the object to prevent transients and not to cause them, so careful consideration must be given to a proper choice of the circuit breaker and its operating mechanism.

Berneryd demonstrates in his work some statistical distribution functions (Gaussian, rectangular and triangular) of the gap breakdown voltage, with the time-instant $t_d$ as a parameter. $t_d$ is the time-instant after the gap voltage zero, as it is indicated in figure 4. The variation in closing time $T_1$ is expressed as $\Delta T$. The closing time has a Gaussian probability distribution function, with a deviation $\sigma$ = 0,5 ms. He determined the 10% and 50% probabilities for exceeding the breakdown voltage, with the rate of fall of the withstand voltage **k** as a parameter. Berneryd concluded that this **k-factor** must be larger than **1,5** for satisfactory functioning.

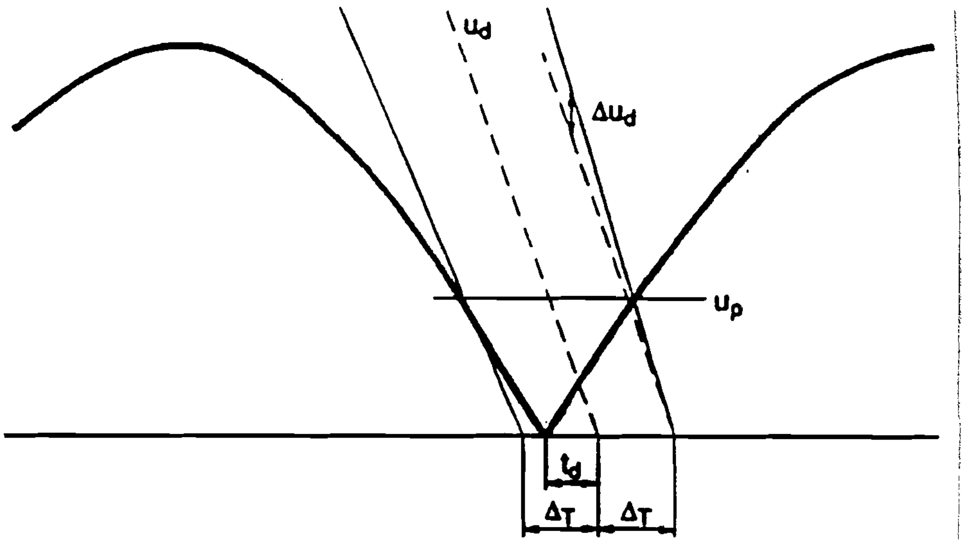

**Figure 4** - *Voltage withstand of the breaker gap decreases faster than that the gap voltage approaches zero.*

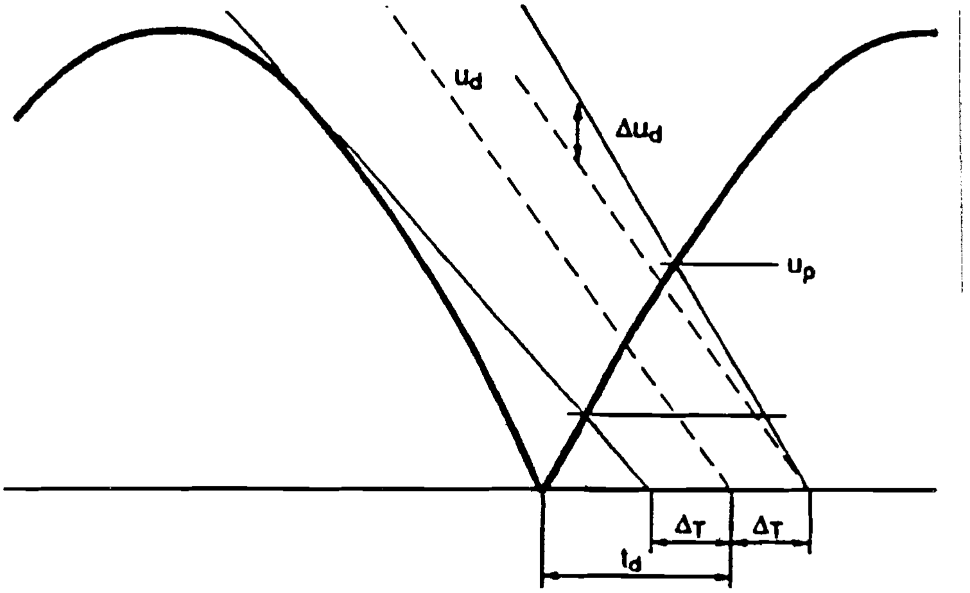

**Figure 5** - *Gap voltage approaches zero faster than the voltage withstand strength of the gap.*

| | |
|---|---|
| Power system data: | Figure 4: **72,5 kV**, 50 Hz<br>Figure 5: **170 kV**, 50 Hz |
| Breaker closing data: | 55 ± 11 kV/ms<br>Window ± 1 ms around voltage zero. |

Note that figure 4 and 5 refer to the same type of breaker.

The concern on the dielectric withstand is usually not of concern to the customer in the stage of purchasing the installation. For example, the utility Delta Nutsbedrijven, in the south of The Netherlands ordered a controlled switching installation for a 100 MVAr capacitor bank. They have set the maximum acceptable limit for for the transient overvoltage at 1,3 per unit. The manufacturer (in this case ABB) has to deliver the installation within this specification. During field tests on commisioning of the controlled switching installation, this requirement was checked, and the operation was found to be satisfactory. The field tests on commisioning of this installation will be discussed in chapter 4.

Concerning the time spread, the following values are reported by Berneryd:

1. $\Delta T = \pm 1$ ms for spring operated circuit breakers without self-adjustment.

2. $\Delta T = \pm 0,5$ ms at frequent operations and with a self-adjusting control device.

Some $SF_6$ circuit breakers can only be applied in a limited range of rated voltages. It is of course possible to use circuit breakers with a steeper rate of fall of withstand voltage during closing.

This steeper rate of fall of the withstand voltage can be achieved by means of:

1. Higher $SF_6$ pressure [2.31].
   The disadvantage of this measure is, that the breaker can only be used in areas with certain minimum ambient temperatures, otherwise heaters have to be used to maintain a certain minimum temperature. This makes the circuit breaker complicated and expensive.

2. Higher speed of closing
   A higher speed means that special requirements have to be set on the operating mechanism, this can also be negative from a financial point of view. A contact speed as low as 4 m/s is reported to be sufficient for energizing at gap voltage zero. From formula (1) and the previous explanation, it can be concluded that the requirements for a 60 Hz power system are 20% higher.

3. Contacts of special design (field controlled). This method however has its practical limitations.

Generally **energizing at gap voltage peak** is an easier task to achieve than at gap voltage zero. Due to the sinusoidal wave shape the requirements for closing accuracy are less stringent than for closing at voltage zero. Typical SF6 breakers of standard design can be applied for closing.

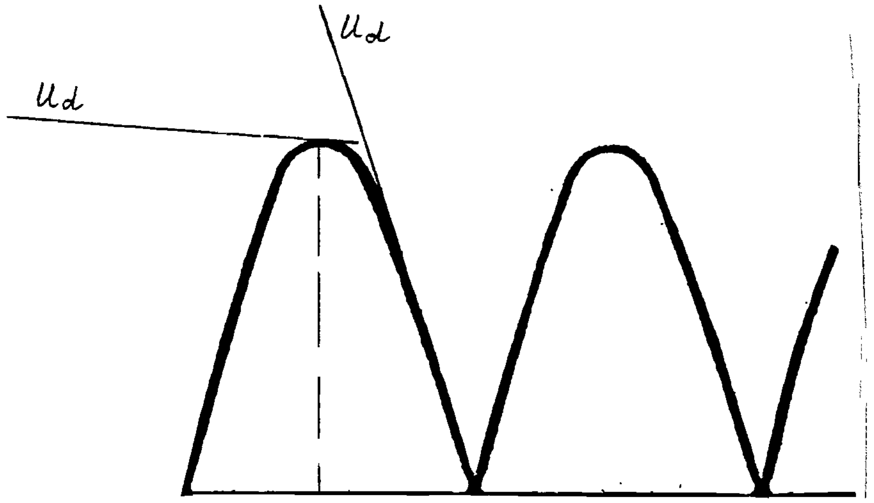

**Figure 6** - *Pre-arcing characteristics for energizing at gap voltage zero and at gap voltage peak.*

Critical conditions for reignitions occur at small arcing times. Only dielectric conditions determine if there will be reignitions. In order to avoid reignitions the dielectric withstand characteristic of the breaker has to be higher than the actual recovery voltage at all time-instants. Controlling the arcing time by means of controlled opening can eliminate the occurence of reignitions or restrikes. For opening control to eliminate reignitions for shunt reactors or restrikes with capacitors, or to minimize contact erosion for fault switching, the control accuracy is nominal, and no high requirements have to be set to the timing. A time window of up to ± 2 ms around peak current is reported as being sufficient.

### *2.4.2 Mechanical Characteristics*

Controlled switching requires that the poles can be independently controlled. Two basic design concepts are possible:

1. Three-pole operated circuit breaker with single operating mechanism. This kind of mechanism is only offered by ABB.

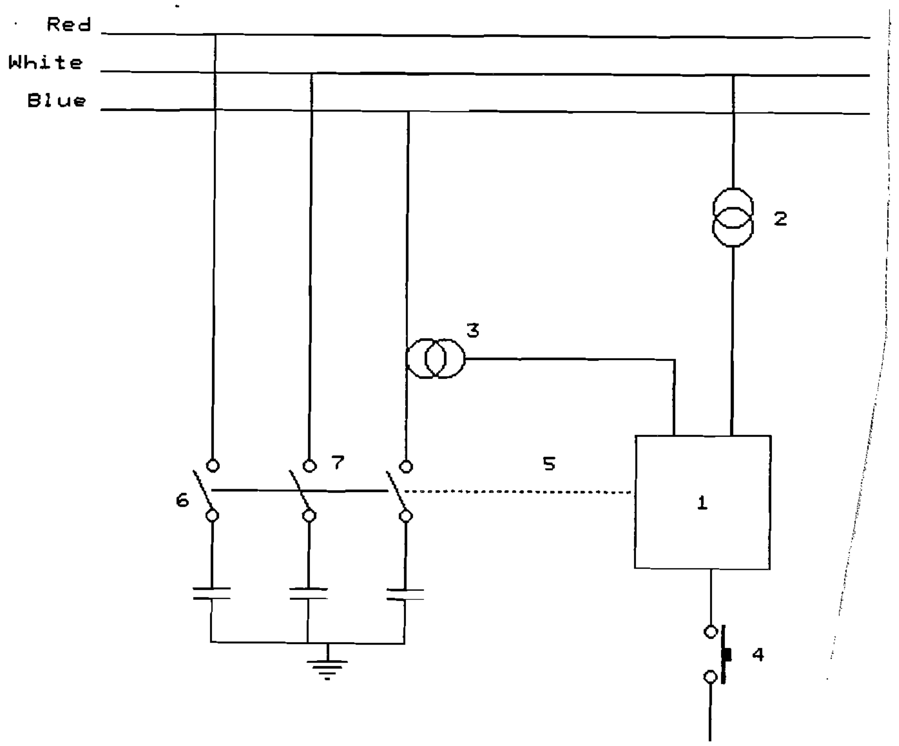

**Figure 7** - *Three-pole operated breaker with single operating mechanism and interphase drive train for time-staggering.*

Legenda on figure 7:

1. Controlled switching unit.
2. Voltage Transformer, for reference voltage zero detection.
3. Current Transformer, for detection of (initial) current flow and thus adaptive control of operating time.
4. Push Button to carry out a Controlled Switching event.
5. Time Controlled Impulse to activate operating mechanism.
6. Circuit-Breaker that has to be controlled.
7. Time lag between phases by mechanical means.

2. Single-pole operated circuit breaker with one operating mechanism per pole. This kind of mechanism is used in general for controlled switching.

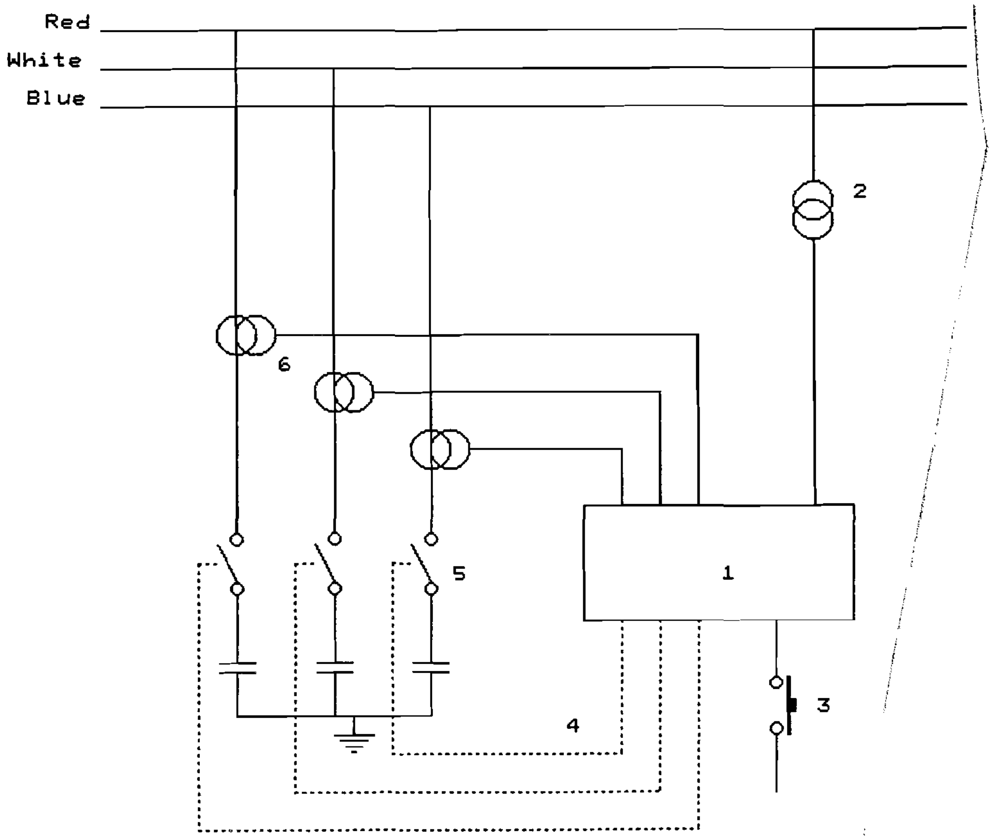

**Figure 8** - *Single-pole operated breaker with one operating mechanism per pole.*

Legenda on figure 8:

1. Controlled switching unit.
2. Voltage Transformer, for reference voltage zero detection.
3. Push Button to carry out a Controlled Switching event.
4. Time Controlled Impulse to activate operating mechanism.
5. Circuit-Breaker that has to be controlled.
6. Current Transformers for adaptive control.

The use of three separate operating mechanisms is the most obvious solution to carry out controlled switching. A three pole operated circuit breaker with a single operating mechanism is also possible. Both systems have their specific properties. With three-pole operated circuit breakers only one operating mechanism is necessary. The appropriate time delay between the poles is accomplished by mechanical means in the interphase drive train.

The mechanical staggering is introduced by different dimensions of certain components in the mechanical linkage. If these differences are restricted to a few standard dimensions and thus standard time staggerings, then this is an economically feasible solution. These different dimensions of certain components do not affect the reliability of the breaker. As there are only a few standard time staggerings available, only certain controlled switching duties are possible. The possibility for fine-tuning of the controlled time-instant are limited.

Rees [2.32] investigated the use of controlled switching in three pole enclosed GIS circuit breakers by means of mechanical linkage systems between the poles. Due to the small distances between the poles this would lead to complicated linkage systems with disadvantages concerning mechanical reliability. However ABB [2.33] has applied mechanical staggering in a 130 kV GIS for energizing of converter transformers for the Gotland HVDC-Link in Sweden.

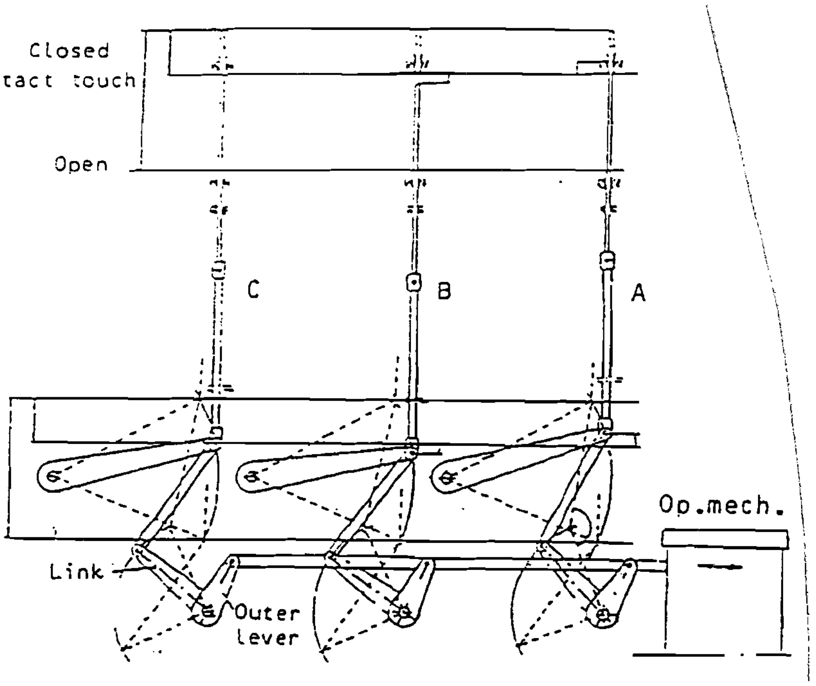

**Figure 9** - *Three-pole operating mechanism (ABB) with mechanically staggered contacts [2.33].*

Single-pole operated circuit breakers need three operating mechanisms. The extra mechanisms put an extra financial burden on the switching installation. Also the reliability of the installation is affected in a negative way. With a single-pole mechanism there is more freedom to control the time-instant then with a mechanically staggered mechanism. Using three single-pole mechanisms also implicates that a pole-discrepancy relay must be used, whereas this is not strictly needed with a single-pole mechanism. With a single-pole mechanism there is a large flexibility for the adjustment of the time lag between poles. It is also possible to apply controlled switching to already installed circuit breakers. However one should be aware of the mechanical properties of the breaker.

The type of breaker operating mechanism determines the specifications for the time control system. With a single pole operated breaker, three separate timed control signals are needed. For a three pole operated breaker one control signal is enough.

In general it can be said that the mechanical characteristics that influence the operating times must be consistent and reliable. The trend for state of the art breakers is that they are designed with a reduced number of components. This means a higher reliability. Also reduction of weight, moving masses, mechanical stresses on components and drive energy requirements play an important role. Modern circuit breakers use either spring or hydraulic operating mechanisms, or a combination of spring and hydraulic. Pneumatic drives are used to a lesser extent. They are prone to larger operating time variations (due to limited air receiver pressure, especially if successive operations are necessary) than spring operated breakers. The required energy for a self-blast breaker is approximately 20% of that required for a conventional puffer breaker. It is possible to use a smaller, simpler and cheaper operating mechanism with a self-blast breaker. This means that this kind of breaker would be a good candidate for controlled switching purposes.

To exploit the advantages of controlled switching, a time spread of ± 1 ms at maximum is required. Two major factors influence this tolerance:

1. Spread in dielectric withstand as discussed.

2. Spread in mechanical operating times.

The operating times are determined by the operating mechanism itself, but also by ambient conditions upon this mechanism. Further the time in between successive breaker operations (standing time) and the frequency of operation plays an important role.

In general the following parameters can have an influence on the operating times of a circuit breaker:

1. Ambient temperature.
2. Condition and characteristics of arc extinguishing medium.
3. Stored energy (air or hydraulic pressure, spring tension).
4. Control voltages.
5. Number of previous operations
6. Aging effects (lubrication may deteriorate, mechanical parts will wear, corrosion may occur, springs and seals may change their properties, etc.).
7. Intervals between operations (infrequent operations give an uncontrolled time spread).
8. Contact burning (Pre-arcing).
9. Seasonal ambient and environmental effects on the mechanical system (Sea-environment, humidity, arctic and desert climate).
10. Contact bounce and contact rebound.

Important is also the measuring of the closing time on commissioning of the breaker. Present day operating time measuring devices need a dedicated person to operate this equipment. The procedure and the protocol must be well known and used by everbody. If this is not the case, then serious errors (measuring on other control coil, measuring on the auxilliary contacts instead of the main contacts, etc.) are possible. This measurement is especially important if a fast iteration to the control point on the reference signal is wanted.

The influence of these individual parameters is highly dependent upon the design of the breaker. Parameters with probably the largest influence on operating time are:

1. Ambient temperature.
2. Stored energy level.
3. Control voltage.

Aging effects and number of operations may have significant effect, however very little information on this topic is available, because of the little field experience. The same is valid for the intervals between operations (standing time).

Field experience with no-load testing of circuit breakers has shown that the very first shot (= switching operation) is very often missed (= not recorded with the measuring equipment) due to a variety of reasons. Most of them are directly related to the personnel (and the state of their equipment) responsible for carrying out these tests. This very first "magical" shot is a very important one because usually it gives an indication of the operating times after a certain standing time.

A long period without operation for the breaker is the most problematical area as to

what can be anticipated:
- Mechanical parts can wear.
- Quality of lubrication may deteriorate.
- Corrosion will occur.
- Springs and seals may change their properties.

Since the CIGRE 1988 Conference in Paris, more attention is focussed on the mechanical stability of circuit breakers with respect to controlled switching. Despite this, not many specific reports have been published on this topic. In all the CIGRE Conference papers and Discussion Contributions (Berneryd [2.28], Moraw [2.34], Alvinsson [2.35], Neumann [2.36], Degen [2.37]) only **indications** are given of the influence of different parameters on the operating time spread. It is very difficult to compare the different published values because a lot of important information (parameter ranges, exact time intervals, etc.), necessary to make comparisons, is not mentioned in the publications.

One paper that gives some extensive information on the variation of operating time under the influence of different parameters is by Pastors and Kießling [2.38]. They investigated a Siemens circuit breaker with a hydraulic drive.

They separated the influence of the different parameters on the operating time, by varying one parameter and keeping the others constant. Their findings can be expressed in the following approximative equation:

$$t_{Close}(T,\ U,\ P) = K_1\, e^{-K_2(100+T)} + \frac{K_3}{U_{Control}} + \frac{K_4}{P_{Hydraulic}} + K_5\, T + K_6$$

The oil viscosity is exponentially dependent with temperature, therefore also the operating time has an exponential temperature dependent factor. This is expressed in the first part of the above expression together with the factors $K_1$ and $K_2$. The resistance of the control coils for operating the breaker increases with temperature. The coil current decreases therefore with increasing temperature. This can be compared with a decreased control coil voltage. Temperature showed a linear relation to the closing time, with a multiplication constant $K_5$. They measured a hyperbolical curve for the dependence of operating time on the control coil voltage as well as the hydraulic oil pressure. The different thermal coefficients of expansion for the porcelain-insulators and the internal insulating rods change the operating time in a linear way. The thermal time constants of the porcelain and the rods were not taken into account.

As it is clear from the above equation, the linearised formula is only valid for the closing operation of the breaker. For an opening operation the resultant hydraulic pressure is dependent on some factors like initial pressure $SF_6$, ambient temperature, and the temperature increase of the breaker unit due to the normal current flow before the opening sequence was initiated. Altogether this is a very complicated mechanism, and thus it is difficult to give a general equation for the dependence of the operating time of a breaker on different parameters. Detailed research is still necessary.

The influence of standing time was also investigated. It was found that a standing time of 60 days in between successive breaker operation did not affect the operating time of the breaker. Also the often mentioned possible problem of "sticky" latches in the drive hydraulic system in relation to the standing time were looked at. The hydraulic system has an inherent leakage, because of this the pressure will always vary between a lower and an upper value. This continuous varying pressure prevents this "sticky" effect according to Pastors and Kießling. Pastors and Kießling claim that breakers with hydraulic drives are suitable for use in a controlled switching installation. However more work must be carried out in the area of application of the hydraulic drive with other breaker types. Also the effect of the neglected parameters in this project (thermal expansion coefficients and time constants) must be investigated.

The CIGRE Task Force on Controlled Switching has gathered information for different types of drives for $SF_6$ breakers. Table 3 [2.49] summarizes their findings. It indicates that the timing is highly dependent upon the type and design of the specific circuit breaker in question. A summation of all tolerances would lead to the conclusion that it is not possible to use present day breakers for controlled switching purposes. The allowed accuracy of ± 1 ms is exceeded to a large extent. Therefore an adaptive control system is necessary for accurate time control. The values in the table are for each independent pole of a three pole breaker, and therefore require separate opening mechanisms for each pole. The simultaneity between poles will be greater if it is assumed that both positive and negative values of accuracy are possible.

Table 3 - Influence of various parameters of $SF_6$ Circuit Breakers on the operating time tolerance with pneumatic, hydraulic and spring operating mechanisms.

| Parameters | Pneumatic Mechanism |  | Hydraulic Mechanism |  | Spring Mechanism |  |
|---|---|---|---|---|---|---|
|  | Close | Open | Close | Open | Close | Open |
| Temperature | ±1,5 ms | ±1 ms | 70 us/oC | 30 us/oC | 70 us/oC | 30 us/oC |
| Control Voltage | ± 1 ms | ± 1 ms | ± 1,5 ms | ± 0,5 ms | ± 0,5 ms | ±0,5 ms |
| Stored Energy | Not Available | Not Available | -3 to +2,5 ms | ± 0,5 ms | -3 to +2,5 ms | ±0,5 ms |
| Number of Operations | + 1 ms | + 1,5 ms | ± 2,5 ms | ± 1 ms | + 2,5 ms | +1,5 ms |
| Infrequent Operation over 10 years life | Not Available | Not Available | ± 10 ms | Not Available | ± 10 ms | Not Available |

| | |
|---|---|
| Temperature: | The temperature range is from -40 to +40 oC. For the pneumatic mechanism from -25 to +55 oC with the use of a heating device. Without heating device a 10 ms variation is possible at the lowest temperature for open and close. |
| Control Voltage: | The control voltage range is -15% to +10% around the nominal voltage. |
| Stored Energy: | The stored energy varies from -5% to +5% around the nominal value. |
| Number of Operations: | For the pneumatic drive over a total of 10.000 operations. For the hydraulic and spring drive over a total of 1.000 operations. |
| Infrequent Operation: | More than 6 months at 20 oC or more than several hours at - 50 oC. |

Another effect that is encountered when closing and opening contacts is the contact bouncing or rebound effect. This effect has been found to be present at various occasions with different breakers. In appendix 3 a graph-recording is given of a no-load test on a Delle PK6 airblast breaker. On this recording which was made with a Ultra Violet Paper Recorder, it can be clearly seen that the bounce and rebound effects are present. Also during the no-load tests on the ABB $SF_6$-breaker at Borssele Substation these effects were measured, both on closing and opening. No-load tests that were done at KEMA on ABB HPL breakers also showed this effect. The maximum duration of this effect was about 2 ms, this is long in comparison with a half-cycle time duration. In table 4 some time results from no-load tests at Borssele, of this bouncing effect are given.

**Table 4** - *Timing results showing the contact bouncing effects of a closing operation as measured during no-load field tests at Borssele Substation.*

| | Red Phase | White Phase | Blue Phase |
|---|---|---|---|
| Bounce Events | 33,8 ms First Close | 34,2 ms First Close | 31,7 ms First Close |
| | 34,2 ms Bounce Open | 34,8 ms Bounce Open | 32,5 ms First Bounce Open |
| | 34,7 ms Final Close | 35,5 ms Final Close | 33,0 ms Second Bounce Close |
| | Closed | Closed | 33,1 ms Second Bounce Open |
| | Closed | Closed | 33,4 ms Final Close |
| Average Closing Time | 33,8 ms | 34,0 ms | 31,8 ms |
| Bounce Time | 0,9 ms | 1,3 ms | 1,7 ms |

For the Red Phase contact the time duration between first contact touch and final contact closing is equal to 0,9 ms. For the White Phase contact this is 1,3 ms, and for the blue phase contact this is 1,7 ms.

A similar bouncing phenomenon was discovered on the opening of the breaker, the results are given in table 5. In table 6 the bounce and rebound times together with the average closing times are summarized.

On opening no rebound was measured on the blue phase for this occasion, also on all the other openings no rebounds were detected on the blue phase.

**Table 5** - *Timing results showing the contact rebound effects of an opening operation as measured during no-load field tests at Borssele Substation.*

| | Red Phase | White Phase | Blue Phase |
|---|---|---|---|
| Rebound Events | 23,6 ms<br>First Open | 22,7 ms<br>First Open | 25,1 ms<br>Breaker Open |
| | 23,8 ms<br>Rebound Close | 22,9 ms<br>Rebound Close | Open |
| | 24,3 ms<br>Final Open | 23,5 ms<br>Final Open | Open |
| Average Opening Time | 23,9 ms | 23,3 ms | 24,5 ms |
| Rebound Time | 0,7 ms | 0,8 ms | No Rebound |

The opening time is calculated from the first contact open. There are almost no publications on the contact bouncing effect. Closing of electrical contacts is almost invariably accompanied by some bouncing, which can last a few milliseconds. The bounce effect affects the erosion of the contacts in a negative way. Barkan [2.39] published a study on this effect, however his study was limited to low voltage - low current circuits, and practical effects as have been measured are not treated in his work. It is also possible to think of the contact bouncing in combination with prestriking. This effect has been reported by Brunke [2.17]. A similar effect as Brunke described, has been measured at Apollo (ESKOM Grid) on an AEG S2 breaker. During no-load tests at Eiger Substation, also on an AEG S2-300, contact bounce times of about 0,5 ms on closing (closing time 102 ms) have been measured. At Apollo multiple prestrikes have been measured, in a duration of more than 5 ms. ***It is very well possible that excessive rebound effects at the end of an opening stroke can possibly cause restriking.*** The bounce and rebound effect are primarily determined by mechanical design parameters.

The forces on the contact fingers and the contact finger-plug geometry are dimensioned in such a way that the radial forces are maximized and the axial forces minimized. On top of this criteria related to proper field distribution have to be taken into account. The circuit breaker operating velocities are very high and thus some bouncing can be expected. The no-load test equipment which was used in these tests did not had a filter network. With such a filter network it would be possible to define bouncing in a consistent way. The no-load tests were carried out with low voltage and low current, which are much smaller then the rated values. In general it can be said that some bouncing is allowed, however as long as it does not affect the circuit breakers switching performance.

Kirchesch etal [2.40] reported some interesting results on the influence of the temperature on the mechanical performance of a circuit breaker. No-load opening and closing operations were done in a climate chamber, changing the temperature from -40 $^0$C to +70 $^0$C. The three-phase breaker was equiped with a spring mechanism below the central pole. The opening velocity increased significantly with increasing temperature, the closing velocity changed only very little.

In figure 10 the measured tripping times are plotted against temperature. The operating times $t_0$ between the beginning of the tripping pulse and the contact separation or the contact touch consists of two parts. These two parts also follow from the principle diagrams for the discussed operating mechanisms.

$$t_{Operating} = t_{Tripping} + t_{Travel}$$

The first part is the tripping time $t_{Tripping}$ until the latch becomes removed and the motion really starts. The second part is the travel time $t_{Travel}$. The travel time can be calculated when the contact stroke and the velocity are known.

The tripping times from figure 10 are then obtained by using the following equation:

$$t_{Tripping} = t_{Operating} - t_{Travel}$$

On opening, the opening springs have to be released only, and the temperature dependance is far below the scattering of the values. However it becomes significant in the closing case in which the action of the operating mechanism takes place.

Kirchesch attributes the measured behaviour to the increase of the viscosity of the lubrication media. The current through the open and close coil increases with decreasing temperature due to the decreasing resistance, but this seems to have no influence on the operating times.

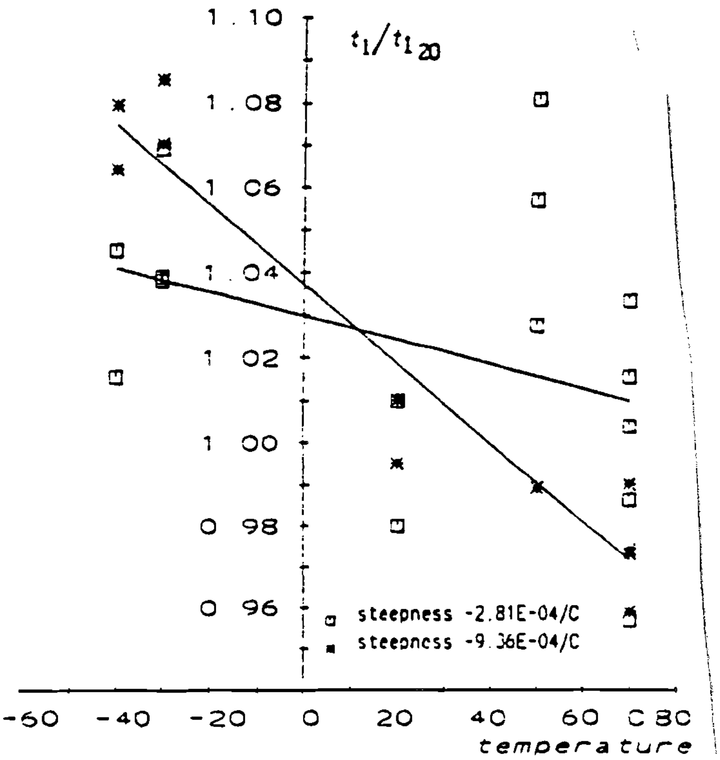

**Figure 10** - *Circuit breaker operating times as a function of temperature as reported by Kirchesch [2.40].*
** = Closing, □ = Opening.*

Kirchesch also carried out some electrical endurance tests with a rated normal current of 2 kA. In order to obtain the same electrical stress for all three poles, the tripping pulses for the more than 2000 CO-operations were varied accordingly. The main stress during normal current interruptions turned out to be erosion of the arcing contacts. The erosion of the nozzle was found to be negligible. The duration of the **opening time decreased** (in total more than 10%) and that of the **closing time increased** (in total about 10%) by the number of switching operations. The change was according to a linear function. These changes are significant when related to the maximum allowed operating time tolerances for controlled switching.

### *No-load Measurements*

With no-load tests in South Africa and in The Netherlands, the influence of control voltage, stored energy and $SF_6$-pressure was investigated. The results can be found in appendix 3.

### *2.4.3 Reliability of Circuit-Breakers*

CIGRE Working Group 13.06 conducted two international enquiries on the reliability of high voltage circuit-breakers. In the **first international enquiry** [2.43] for circuit-breakers, information on circuit-breaker failures and defects in service were processed for the four year period 1974 to 1977. These breakers were installed on systems having voltages equal to or above 63 kV and belonging to 102 utilities from 22 countries. The first enquiry concerned 77.892 circuit-breaker-years of all technologies. The **second international enquiry** covered single pressure $SF_6$ circuit breakers with a rated voltage of 72,5 kV. Breakers operating at voltages of 63 kV and above were also included. This enquiry concerned a total of 70.708 circuit breaker years, and was carried out from 1988 through 1991. Janssen [2.44] - [2.46] has published some preliminary results of the second international enquiry. In 1994 a final report will be published with an overview of the final results, a summary of results is presented in table 7. The percentages of the total number of major and minor failures are also given in brackets.

**Table 6** - *Comparison of the final data obtained from the first and second international enquiries on circuit-breaker failures and defects in service (failure rates per 100 circuit-breaker-years) [2.44]-[2.46].*

| Responsible Subassembly | Major Failure Rate | | Minor Failure Rate | |
|---|---|---|---|---|
| | First Enquiry | Second Enquiry | First Enquiry | Second Enquiry |
| Components at Service Voltage | 0,76 @<br>(48%) | 0,14<br>(21%) | 0,92<br>(26%) | 1,44<br>(31%) |
| Electrical Control and Auxilliary Circuits | 0,30<br>(19%) | 0,19<br>(29%) | 0,57<br>(16%) | 0,92<br>(20%) |
| Operating Mechanism | 0,52<br>(33%) | 0,29<br>(43%) | 2,06<br>(58%) | 2,05<br>(44%) |
| Others | | 0,05<br>(7%) | | 0,25<br>(5%) |
| Total Failure Rate | 1,58<br>(100%) | 0,67<br>(100%) | 3,55<br>(100%) | 4,66<br>(100%) |

@ = including 20% for operating elements at service voltage, such as valves.

A **major failure** means a complete failure of the circuit breaker which causes the lack of one or more of its fundamental functions. Any failure which does not cause a major failure is **minor failure**. The **main components** at service voltage are the interrupting unit, auxilliary interrupters, pre-insertion impedances, grading impedances, and the main insulation to earth. The main **sub assemblies** for the electrical control and auxilliary circuits are the open and close circuits, auxilliary switches, contactors, heaters, and the gas density monitor. The major parts of the **operating mechanism** are compressors, pumps, energy storage, control elements, actuators, damping devices, and the mechanical transmission.

The results show a large decrease (improvement of reliability) of the major failure rate (50%), whereas the minor failure rate shows an increase. The components of the operating mechanism are still the largest contributor to the failure rate, and thus the reliability of breakers. Also the parts that are exposed to the arc are, the components at service voltage, are a large contributor to the failure rate. The drive and control mechanism of a circuit breaker have a significant effect on the operating time accuracy. This was already illustrated in table 3. With a feedback system it is possible to compensate changes, however only to a certain extent, in the operating time. The trend in breaker design is to make simplified designs with a fewer number of parts. This has resulted in the use of single gap breakers at higher system voltages, which however increases the risk of restrike. The most important component to check in a circuit breaker to monitor its condition, is the contact travel. The contact travel provides information about the operating speed, and also governs the pressure rise in the puffer cylinder. This means that the operating times have to be monitored. Many articles on continuous condition monitoring of circuit breakers use a measurement of the operating times. This can be directly coupled to the possible controlled switching task.

In the last years the link between continuous condition monitoring devices and controlled switching technology has grown closer. In a controlled switching application, it is necessary to check the operating time of the breaker but also the timing performance of the controlled switching device. Circuit breaker control functions can be easily realized with micro-processors. The hardware can be standardized and only by some software-changes the required controls for different types of switchgear can be realized. This means that there are some interesting possibilities for the implementation of controlled switching within condition monitoring devices. The implementation of controlled switching will not impose extra maintenance on the circuit breaker. This is important because in the results of the first enquiry it is stated that half of all failures are due to design, manufacture but also incorrect erection and maintenance procedures contribute to this. Unfortunately within ROTEK (ESKOM's Repair and Maintenance Facility) or ESKOM past data on circuit breaker failures in service, is not readily available. It would be very interesting to learn how the ESKOM statistics compare with the CIGRE results. It is also important when it is considered to implement condition monitoring and controlled switching. Some utilities are still very reluctant on the application of diagnostics whereas others can't wait to implement it as soon as possible. The state of technology for diagnostic techniques is still developing. It is sensible to wait until the technology in this field is more or less stabilized. By that time it might also be possible to have a good overview on the breaker failures in the ESKOM grid. In figure 11 [2.27] the reliability of circuit breakers compared with instrument transformers and aircraft electronics over the years is given. The Mean Time Between Failures for circuit breakers has increased significantly over the years. The MTBF for instrument transformers and electronics is much less than that of the circuit breakers. The MTBF of a controlled switching installation will be determined by the control device, and will thus be less than that of the circuit breaker alone. This may be compensated to some extent by the increase in reliability of the loads to be switched because these are subjected to reduced stresses.

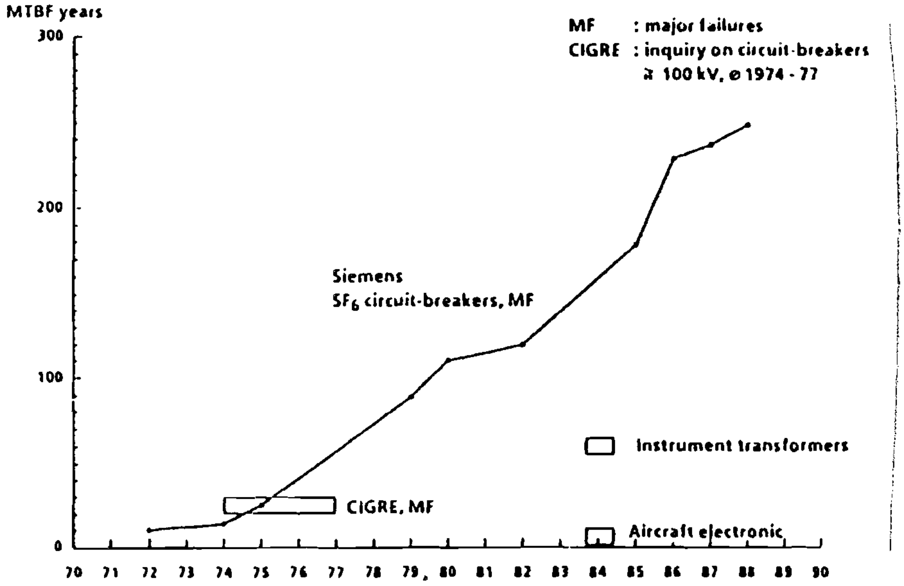

**Figure 11** - *The reliability of Siemens Circuit Breakers compared with instrument transformers and aircraft electronics as a function of time [2.27].*

### *2.5 Implementation of a Controlled Switching Device*

In figures 13 and 14 block diagrams are given for controlled switching schemes. For most cases the block diagram of figure 14, a single pole operated circuit breaker with one operating mechanism per pole, is applicable. Seen from the viewpoint of electronic circuitry, a controlled switching unit can basicly consist of three functional units:

1. The **input stage**, consisting of input lowpass filter network, galvanic separation, zero crossing detector.

2. **Intermediate stage**, consisting of logic circuitry, electronic timers or phase shift networks.

3. **Output stage**, consisting of a galvanic separation network and an output impulse control source.

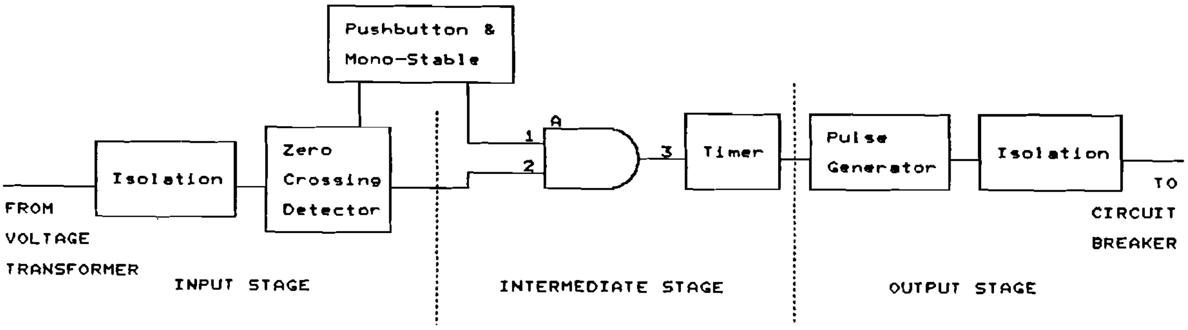

**Figure 12** - *Principle diagram of a controlled switching device for one phase.*

A controlled switching unit can be realized with commercially available electronics. Controlled switching units such as they are supplied by switchgear manufacturers have some specials, like on-board microprocessors and some extra monitoring (feedback) circuitry. For field tests at Apollo Substation in South Africa, a controlled switching device was developed based on the above mentioned three stages. The device was used for controlled energizing as well as controlled de-energizing of a 150 MVAr - 275 kV Capacitor Bank unit.

### *2.5.1 Controls and Instrumentation*

The set-up for a controlled switching device, like in figure 12, has been used by many scientists throughout the years [2.17], [2.18], [2.27], [2.28]. Sprecher Energie has patented their controlled switching device [2.47], also their design is in principle equivalent with that of figure 12. For the cases of transmission line switching two voltage measurements, one on the load-side of the breaker and one on the supply side are needed. Voltage measurement, on the supply side of the breaker, is sufficient for other purposes provided no trapped charge is present. The timing for the other phases is derived from the the phase-angle relation between them and the monitoring phase. In the most general scheme only one voltage transformer is used for reference voltage (110V or 110V/$\sqrt{3}$ winding) monitoring purposes. Some commercial devices use a current feedback from current transformers, for adaptive control. With the monitoring of the phase currents it is possible to calculate the real operating time of the circuit breaker because the close coil current time initiating instant is known and also the start of current flow is detected. Only small variations in operating time can be compensated for by adaptive control.

Voltage and current transformers have inherent amplitude and phase errors. The amplitude error is not important when only one voltage transformer is used. However when using two voltage transformers, one on each side of the circuit breaker terminals, it is of importance, because it will give a time error in the detection of a gap voltage zero. The phase-angle error of a voltage transformer is not a problem with the use of typical instrument transformers.

Depending on the application of the controlled switching device, it is also possible to use current zero detection instead of voltage zero detection. For example with controlled opening of shunt reactors this is used.

The voltage and current transformers provide the input for the controlled switching device. It is generally well known that within Substations, the use of electronics can be problematic. Appropriate measures must be taken to rule out any possibility for disturbances during controlled switching. The input stage of controlled switching devices usually have a separation transformer, also lowpass-filter networks are used.

For the application at Apollo, use was made of an optic fiber between the voltage transformer and the device. This fiber was also used to monitor the busbar voltage for that phase. The device itself was located in a shielded room on a Mercedes Truck, located next to the capacitor bank under investigation. An on-board power-supply, in the form of a diesel-generator-set, on the Truck was used. This to rule out any possible disturbances which might come through the Substations mains. During other measurements disturbances were coupled in through the Substations mains. This gave problems with the measuring equipment, especially problems with the triggering of the measuring system were encountered.

The output stage of the controlled switching device consisted of three opto-couplers and three fast intermediate relays. From the relays the close or trip coil of each phase was actuated with a time controlled impulse with a maximum duration of about 50 ms. The control pulse setting can be done with a step less than 0.2 ms. The coupling between the relays in the truck and coils in the circuit breaker cubicle were made with multicore shielded cable.

In the applied device a digital timer was used to establish a controlled timing sequence. As mentioned before, electronics are very sensitive to disturbances. This problem is already known for many years. In early designs for controlled switching devices, this characteristic has been recognized and dealt with in an appropriate manner.

In the "old" days, Williams [2.12] used a synchronous switching device for synchronous tripping of a test breaker in a General Electric Switchgear Development Laboratory. He developed a controlled opening device (for interrupting capacitive currents) in order to be able to test a breaker over the complete range of contact-parting angles. He used a phase-shifting Selsyn. The Selsyn triggered an electronic circuit that tripped the breaker at any predetermined point on the voltage wave. For our design a selsyn was kept as a spare in case interference problems would be to persistent to cope with.

Many different names are in use for the phase-shifting element: Selsyn (of Swedish manufacture), Magslip (of English manufacture), Tramo (of Dutch manufacture) and Synchro (of American manufacture). Selsyns (from self synchronous) [2.48] are used as transducer-element in for example radar-equipment, it is used extensively in all kinds of military equipment. As indicated every industry uses its own name. These devices were developed originally as remote-position repeaters. The selsyn is similar in construction to an electrical machine. It has a stator, a rotor, and a small air gap between the two in the magnetic path. The stator has three windings symmetrically disposed. The rotor is essentialy a single coil. If the rotor is supplied from an alternating current source, transformer action is induced in the stator windings.

The three rms voltages on the stator terminals are:

$$E_a = E_1 \cdot \cos(\theta_1)$$

$$E_b = E_1 \cdot \cos(\theta_1 - 120°)$$

$$E_c = E_1 \cdot \cos(\theta_2 - 240°)$$

The angle $\theta_1$ is the angle between the rotor and the stator. These single-phase voltages of different magnitude do not form a three phase system. The step in angle can be set in steps of one degree (equal to 0,056 ms), this gives sufficient control accuracy. A time-step of ± 1 ms is equal to ± $18^0$. The phase-shifted signal can be picked up from the selsyn stator and fed to the base of a transistor which will be driven into saturation, the collector of the transistor will control the output stage. This can be for example a differentiator and a thyristor. The block-voltage transistor output is differentiated, this gives positive and negative pulses, these can be used to control the thyristor. With very few components a low-cost controlled switching device can be made in this way. One must be aware that a intermediate transformer is necessary to adapt the output of the voltage transformer (110 V or 100V) to the selsyn voltage which is usually about 50 Volt.

An other method is to use a transformer with a split secondary winding, as in figure 13. Between the outer connections a variable resistor and a capacitor are used as a phase-shifting network. The phase-shift controlled output is taken from the central tappings in the network. Using Kirchhoffs law, gives for the upper loop:

$$-E + i \cdot R + V_o = 0$$

and for the lower loop:

$$-E - V_o + i \cdot X = 0$$

Combining these two equations gives:

$$\frac{V_o}{E} = \frac{1 - j \cdot \omega \cdot \tau}{1 + j \cdot \omega \cdot \tau}$$

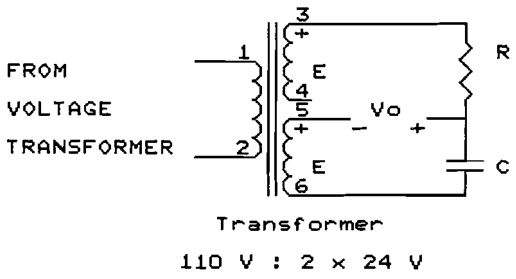

**Figure 13** - *Phase-shift network for controlled switching purposes.*

E and $V_0$ are vectors, $\tau$ equals the product of R and C and is the time-constant of the network. The absolute value of the quotient equals one.
For the phase-shift, the following equation is valid:

$$\varphi = -2 \cdot \arctan(\omega \cdot \tau)$$

Hence it is possible to vary the phase-angle between zero and $180^0$. By using a commutator it is possible that also the $180^0$ to $360^0$ area can be covered. Also with this input stage a sufficient control accuracy can be obtained, also with very few components and at low cost.

### 2.5.2 *Review of Applications*

Most of the controlled switching devices have been installed in Austria (39), Sweden (77), Switzerland (114) and the USA (68) [2.49]. It is however believed that more installations can be found worldwide, because for example in Japan only 11 installations are reported. Out of the 163 units for transformer switching, 100 units are used for 16⅔ Hertz single-phase railway transformers. Controlled de-energizing of capacitive loads is used for two 400 kV transmission lines. Controlled de-energizing of shunt reactors (53 units reported) is used to prevent reignition overvoltages and as such to prevent the reactor (inter-) winding insulation. 112 units are used for controlled closing of capacitive loads.

In tables 8 and 9 an overview is presented of controlled close and open switching operations. Table 8 gives an overview of the various important factors on closing, whereas table 9 gives similar information for the opening sequence.

*Shunt Capacitor / Filter Bank Switching* - On energizing of a capacitor bank, very often prestrikes across the contact gap occur, as breakdown occurs usually around the peak of the voltage. High inrush transient currents, in the order of about 10 pu can be expected with frequencies around 1 kHz, depending on the source configuration, are normal. The voltage experiences a large dip when not energized at voltage zero, as the capacitor which is being energized, behaves as a short-circuit. With back-to-back bank-switching much higher values for the transients are to be expected. These differences are discussed in chapter 3: Conventional Methods versus Controlled Switching. It is desirable to energize at gap voltage zero. This imposes different settings for the timing for the cases of un-earthed and earthed banks. An accuracy of ± 1 ms is required to give sufficient damping of transients on capacitor energizing. Normally a capacitor bank is energized with no trapped charge on the capacitors. The trapped charge is drained by either discharge resistors which are in parallel with the capacitors or by magnetic voltage transformers which might be present because of metering and protection purposes. Controlled de-energizing of capacitors is possible. $SF_6$-breakers are by a lot of people assumed to be restrike-free. However there is no proof that this is the case for every breaker. It is necessary to control the arcing-time on opening in such a way that the contacts are separated enough when the arc extinguishes. $SF_6$-breakers are however capable of interrupting capacitive currents with very short arcing times, these can be in the order of up to a millisecond. Critical conditions for reignitions occur at very small arcing times. At these very short arcing times, the dielectric conditions determine if there will be reignitions. A time of about 5 ms before current zero is reported as being sufficient.

*Transmission Line Switching* - Maury [2.13] and Konkel et al. [2.15] reported on this topic, both described the energizing of 500 kV and 765 kV transmission lines with controlled closing and pre-insertion resistors on lines with trapped charge. Especially the trapped charge is responsible for very high overvoltages. Also in this case the optimum time is gap voltage zero. It is necessary to use voltage measuring facilities on the supply side as well as the line side of the breaker. A closing accuracy of ± 1 ms is required. For de-energizing the same arguments are valid as for the case of shunt capacitor bank switching.

*Transformer Switching* - The inrush currents which occurs with the energizing of transformers are about 10 to 15 times the peak value of the rated current. The harmonic oscillations resulting from the energizing of large transformers can lead to asymmetries in the voltage as well as problems in the local power system.

In Austria [2.33] a lot of attention has been focussed on the controlled energizing of large transformers used at a HVDC station, because the voltage distorsion caused by inrush currents caused commutation failures which in turn lead to plant trippings. Also in Sweden [2.34] controlled energizing of transformers at an HVDC station is used. De-energizing a transformer is not a problem, because of the high damping by the losses of the transformer. If a reignition would occur, high overvoltages can be expected. The general attitude towards controlled switching of transformers is, that more investigation is necessary in the near future.

The control point for closing is dependent on the degree of remanence remaining before closing. For controlled closing three cases [2.28] have to be distinguished:

1. The magnitude of the remanent flux is small:
   The inrush current will be negligible if the transformer is energized at voltage peak.

2. The polarity of the remanent flux is known:
   Controlled closing at the voltage peak with a polarity which decreases the remanent flux will give a substantial inrush transient reduction.

3. The polarity of the remanent flux is not known:
   Controlled closing at the voltage peak with the correct voltage polarity. Energization at a voltage peak with the incorrect polarity, still gives a reduction of about 50% in the inrush transient.

A reduction of the remanent flux seems possible by placing capacitors in parallel to one of the transformer windings. After interruption of the unloaded transformer, a damped current oscillation will reduce the remanent flux considerably, if the capacitors have the correct dimensions. They should be dimensioned in such a way that the current flow in the capacitor is of the same order of magnitude as the steady state magnetizing current.

Berneryd [2.28] and Andersen [2.50] state that it is possible to connect a fraction of shunt capacitor plant permanently to power transformers when controlled closing is used. Berneryd states an accuracy of ± 1 to 2 ms. An accuracy smaller than this will give even better results. The optimum controlled switching times are dependent on the core construction, type of winding, connection and treatment of the neutral point of the transformer [2.34].

***Shunt Reactor Switching*** - Especially the controlled interruption of small inductive currents is a very usefull method to prevent excessive overvoltages due to reignitions. It is possible to eliminate all reignitions by appropriate control of the contact parting time. In literature, control times vary from about 5 to 10 ms before current zero, with an accuracy of about ± 1 to 2 ms. Controlled closing to minimize inrush currents must be done at gap voltage peak. The maximum current inrush for reactors is two per unit (not dangerous), whereas for capacitor banks this inrush current is of much higher order. Therefore controlled closing of shunt reactors is of less importance. The optimum controlled switching times are dependent on the power system and shunt reactor earthing connections.

| TABLE 7<br>CLOSING | TRANSFORMER | SHUNT REACTOR | TRANSMISSION LINES | SHUNT CAPACITOR |
|---|---|---|---|---|
| CONVENTIONAL UTILITY PRACTICE | Closing Resistor | Direct on system or permanently connected | Closing Resistor | Series impedance: pre-insertion or permanently |
| REDUCTION OF TRANSIENTS | Voltage surges: Minimized<br>Current surges: Depends on remanence | Minimized inrush current surges, reduction of DC-inrush | Minimized overvoltages | Minimized inrush currents, no voltage disturbance. |
| CONTROL POINTS | Depends on remanence, core construction, type of winding, connection and treatment of neutral-point. | At voltage peak, 1,67 ms (1st phase), 5,0 ms (2nd phase), 8,33 ms (3rd phase) after voltage zero | At gap voltage zero 0 ms (1st phase), 3,33 ms (2nd phase), 6,67 ms (3rd phase) | At gap voltage zero, depends on treatment of the neutral-point. |
| REQUIRED TIME WINDOW | ± 1 to 2 ms | ± 1 to 2 ms | ± 1 ms | ± 1 ms |
| MONITORED SYSTEM PARAMETER | Source Side Voltage | Source Side Voltage | Source Side Voltage and Line Side Voltage | Source Side Voltage |
| APPLICATION OF ADAPTIVE CONTROLS | Adaptive control for short term repeatability under nominal conditions is used. Further operating time variations due to control voltage, stored energy and ambient temperature can also be compensated for. | | | |
| CONSEQUENCE OF SYSTEM MALFUNCTION | High inrush currents, asymmetries in system voltage | High inrush currents with large DC-part. | Very large Overvoltages | Very High inrush currents, large voltage disturbances. |
| BACK-UP IF SYSTEM FAILES TO OPERATE | Normally none | Normally none | Surge Arrester | Surge Arrester |

| **TABLE 8**<br>OPENING | SHUNT REACTOR | TRANSMISSION LINE | SHUNT CAPACITOR |
|---|---|---|---|
| CONVENTIONAL UTILITY PRACTICE | Opening Resistors and Surge Arrester | Surge Arrester | |
| REDUCTION OF TRANSIENTS | No reignition and minimized chopping overvoltages | No Restrikes | |
| CONTROL POINTS | 5 ms before current zero | | |
| REQUIRED TIME WINDOW | ± 1 to 2 ms | | |
| MONITORED SYSTEM PARAMETER | Source Voltage and Current | | |
| APPLICATION OF ADAPTIVE CONTROLS | Adaptive control for short term repeatability under nominal conditions is used. Further operating time variations due to control voltage, stored energy and ambient temperature can also be compensated for. | | |
| CONSEQUENCE OF SYSTEM MALFUNCTION | High reignition probability | Higher restrike probability | |
| BACK-UP IF SYSTEM FAILES TO OPERATE | Opening Resistor if available | Usually no back-up | |

## *2.6 Summary*

Controlled switching already has a long history. The poor mechanical stability of the circuit breakers throughout the years was the main reason that this switching technology has not been applied widely. In the last years controlled switching has gained considerable interest again because of the improved mechanical stability of present day breakers. Based on the number of successful applications of controlled switching and the apparant high reliability of SF6 breakers it would appear that present day breakers can be used with little or no modification for one or more controlled switching applications. To a certain extent, low velocity and poor pole simultaneity can be compensated for by a suitable choice of the timing command. Dielectric and mechanical characteristics of the circuit breaker determine the suitability of a breaker for a particular controlled switching task. The dielectric withstand depends highly upon the spread in withstand and spread in operating times.

Many no-load tests have been carried out in the laboratory and in the field. During these tests many factors that influence the operating times were investigated. Temperature, control voltage and stored energy are three parameters that can influence the operating times to a large extent. For controlled switching installations use of adaptive control to compensate for these influences, is highly recommended.

A combination of controlled switching with condition monitoring devices has been suggested. However information on circuit breaker failures should be available first, in this way the appropriate techniques can be applied. It would be interesting to see how the CIGRE statistics compare with ESKOM's statistics. It is recommended that such information is gathered, the ideal place to do this is at ROTEK. By the time that this information is available, the technology in the field of controlled switching should be more or less stabilized, and a well considered decision can be made.

Different possible secondary circuits have been suggested to implement controlled switching for field test purposes. It is recommended that with future field tests controlled switching must be used. In this way all the possible conditions for closing and opening can be measured in an adequate manner. This is especially recommended when commissioning tests are done for future substations. These new breakers will be stable enough, because usually spring drives are used. From our no-load tests it can be concluded that these are very stable, especially the latest generation LTB-breakers from ABB.

This novel switching technology has a promising future, it must however be mentioned that **general application is not recommendable at the moment.** The reason for this is that the controlled switching technology is still developing. Only circuit breakers that are sufficiently stable and fast enough can cope with this duty. In the following chapters some applications of controlled switching as they were used in field tests in South Africa and the Netherlands, will be discussed.

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# Chapter 3

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# Conventional Practice versus Controlled Switching

## *3.1 Introduction*

*Capacitive Current Switching* - In practice the following cases are important when switching of capacitive currents is considered:

1. Lines under no-load conditions.
2. Series and Shunt Compensated lines.
3. Cables.
4. Capacitor banks (Single and Back-to-Back).
5. Filter banks (Single and Back-to-Back).

The lengths of cables and lines in new installations are increasing. Utilities are applying capacitor banks on many different voltage levels for voltage control. Capacitor banks are sometimes partly designed as filters to get rid of high harmonics [3.1]. In principle the switching of capacitive currents is not a big problem. The currents are usually less then about 1 kA. The transient recovery voltage goes slowly up to about 2 per unit. In the system no overvoltages are generated and the de-energized bank has a trapped charge of about 1 per unit just after de-energizing has taken place. However this is only the case when the circuit breaker is restrike free at all possible arcing times.

After a restrike a high frequency transient current flows, the character of this current is determined by the voltage difference and the impedances on the source and the load side of the breaker. If the arc extinguishes on a certain moment of the transient current [3.18], [3.19] the possibility of an overvoltage exists.

On energizing there will usually be pre-arcing which can give an intermittent but also a continuous transient current. In the case of lines and cables the initial current is limited by the surge impedance. With capacitor banks the line-impedance will limit any transient currents. Sometimes extra damping reactors are applied to limit transient currents also when energizing capacitor banks in a back-to-back situation.

The inrush current for a capacitor bank can be many times larger (up to about 10 to 100 pu) than the steady state current. Whereas the inrush current for a shunt reactor is maximum twice the steady state current (or exactly $2\sqrt{2}$).

There are some differences between line switching and shunt capacitor bank switching. Firstly the stationary voltage is not the same in both cases, because in line switching, the increase in voltage caused by the Ferranti effect is present. The Ferranti effect is the voltage increase at the end of the line caused by the distributed nature of the line-inductance and line-capacitance. This is different from the voltage increase caused by the shunt capacitor bank. Secondly, line-dropping under no-load conditions is accompanied by surge waves, these are not present when shunt capacitors are interrupted. Thirdly the damping influences are different, they are stronger in the case of the transmission line. The three phases in the capacitor bank are relatively stronger coupled than transmission lines. With a transmission line there will be more coupling or cross-talk between phases than in a capacitor bank. Also the voltage stress of the circuit-breaker when interrupting capacitor banks is different from that caused by unloaded transmission lines.

The behaviour of an unloaded series compensated transmission line with respect to the switching conditions and the recovery voltage, will not differ significantly from a non-compensated line. This is however not the case for the by-pass breaker, which can be subjected to significant stresses. The behaviour of a shunt compensated line will have a big impact on the recovery voltage. After de-energization, a non harmonic oscillation will start. The oscillation circuit consists in this case of the transmission line and the shunt reactors inductance. The nonharmonic oscillating frequency [3.82], [3.83], [3.84], [3.85] will usually be of lower value than the power frequency.

The correct functioning of converter stations, is closely linked to the generation of its harmonics. To keep the harmonics out of the network, shunt filters are used at converter stations. These shunt filters have a low impedance for a certain harmonic, this is obtained by resonant tuning of these filters. The harmonic content of the current may be large compared with the power frequency current itself. The superposition of the harmonic currents can produce additional current zeros in the total current which has to be switched by the circuit-breaker. The recovery voltage will differ from the (1 - cosine)-shape because of the presence of the harmonic components. In general it can be said that switching of filter banks will not cause any specific problems [3.43]. Switching of filter circuits means in general switching of heavily distorted currents. The currents can have multiple zero-crossings per half period and a strongly distorted recovery voltage.

The object of IEC tests for capacitive current switching is to investigate if breakers are restrike free under different arcing time durations. There is still a lot of discussion on the method that must be adopted to test breakers on being restrike-free.

*Inductive Current Switching* - With inductive loads in high voltage networks, one has to think of the following:

1. Shunt reactors.
2. Shunt reactor loaded transformers.
3. Transformers under no-load.

Shunt reactors more or less suddenly appeared in large numbers when long transmission lines for the high voltages started to be built some thirty to fourty years ago. Characteristic parameters of an overhead line are its shunt capacitance (due to the electrostatic field from line to earth) and series inductance (due to the magnetic field around the conductors). The line can be "stiffenned" by a suitable choice of a series capacitance and a shunt inductance, which gives a smaller voltage difference, in amplitude and phase, between the line ends.

In South Africa both shunt reactors and series capacitors are in use. Three ways of connecting shunt reactors are distinguished, namely line reactors, busbar reactors and tertiary connected reactors. In the 1950's and the 1960's the interconnected power systems all over the world started to expand, this required a considerable amount of permanently switched-in reactive power. The factors that previously restrained the adoption of shunt reactors were amongst others fears about the overvoltages arising on the disconnection of the shunt reactor, and also doubts about the reliability of such new-fangled ideas. Throughout the years many scientists have done a lot of work in trying to clarify the phenomena and find solutions for the problems that occur on the de-energizing of small inductive currents.

Not only under type test conditions must a breaker be restrike free but this must also apply for the many years which the breaker must perform its duties in the field. This however can not be guaranteed under the present standards. CIGRE Study Committee 13 - Working Group 04 is involved in a discussion on the complete range of switching of capacitive currents. It will make proposals on the improvement of IEC Standards in future.

*Experimental Field Measurements* - The controlled switching technology as it is described in the previous chapter, has been appplied in various case studies in the South African and Dutch transmission networks. Controlled closing and opening of shunt capacitor banks as well as controlled opening tests on a tertiary connected shunt reactor have been carried out. Field test trials have been carried out on the following sites:

1. *Stikland Substation*, near Stellenbosch, Cape Province, South Africa.
   Three parallel shunt capacitor banks of 72 MVAr each at 132 kV.
   The new technology of fuseless capacitor units from ABB (USA) is used in this station. The neutrals of these capacitor banks are earthed through low-voltage

capacitors. At Stikland only random energizing and de-energizing switching tests have been carried out. Single bank as well as back-to-back switching was investigated.

2. *Apollo Converter Station*, near Johannesburg, Transvaal, South Africa.
   Two separate field tests were carried out at this station:
   A) A 200 MVAr filter bank (5th, 7th, 11th, 13th and high pass filter arms) externally fused capacitors, at 275 kV.
   B) A 2 x 150 MVAr shunt capacitor bank, internally fused, double star, un-earthed neutral at 275 kV.

   Random as well as controlled energizing and de-energizing switching tests were carried out on the shunt capacitor bank. The filter bank was only switched at random.

3. *Doetinchem Substation*, PGEM, The Netherlands.
   A 50 MVAr tertiary switched shunt reactor at 50 kV. This tertiary reactor is connected to the transformer that is responsible for the coupling of the Dutch 150 kV and 380 kV National Grids. Controlled de-energizing tests have been carried out.

4. *Borssele Substation*, Utility Delta Nutsbedrijven, The Netherlands.
   A 100 MVAr shunt capacitor bank, internally fused, double star, un-earthed neutral at 150 kV. The first controlled closing installation at a Dutch utility was installed in October 1993. On commissioning field tests were carried out. Also equipment was installed to facilitate the need for long term (approximately 5 months) measuring and monitoring of the voltage signals on every controlled energizing.

At Eskom's 765 kV Beta Substation random switching tests on shunt reactors (400 MVAr as a three phase bank) have been carried out by Eskom and Messrs Toshiba. These tests will be discussed in chapter 4. Also controlled de-energizing tests for capacitive as well as inductive currents carried out at KEMA's High Power De Zoeten Research laboratories will be discussed. During these field trials the controlled switching technology has been studied in all its practical aspects.

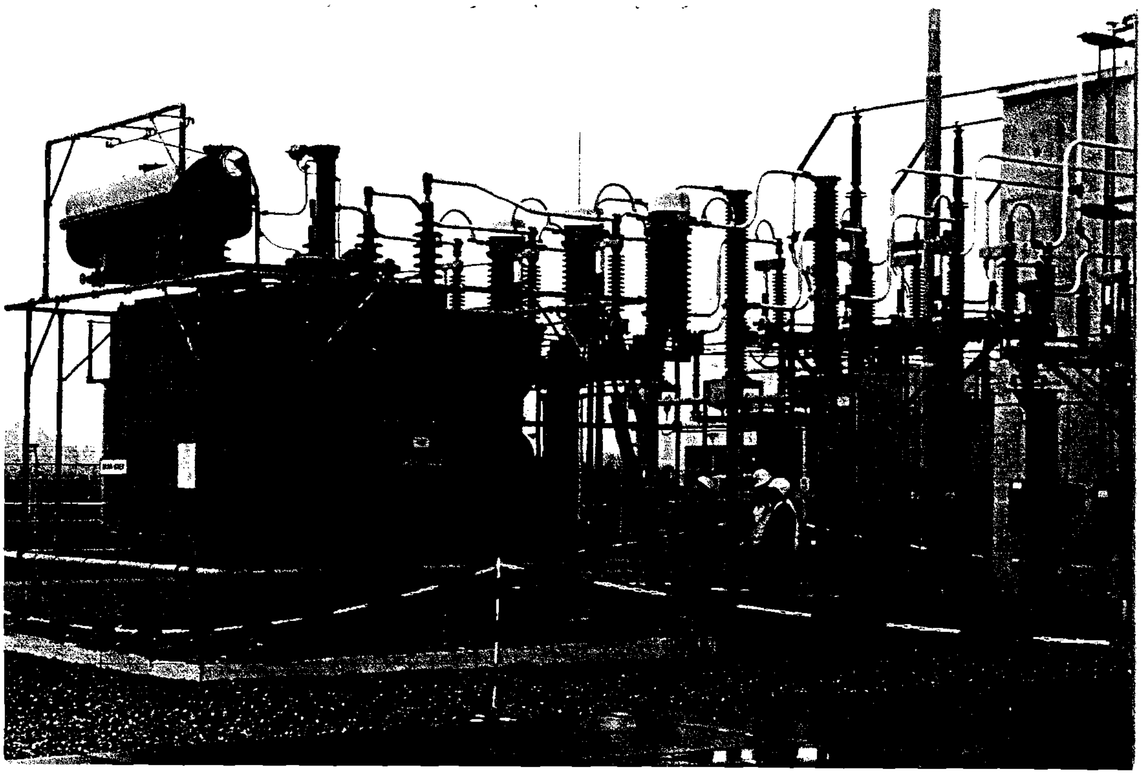


**Figure 1** - *A 50 MVAr tertiary switched shunt reactor at 50 kV. This tertiary reactor is located at Doetinchem Substation, The Netherlands.*

For the past 30 years all of Eskom's shunt capacitor banks have been built using internally or externally fused capacitor units. The advantages and disadvantages have been debated over this period, but no definite conclusion was reached. The new technology of fuseless capacitor units [3.4] was recently introduced into the Eskom system at Merapi and Stikland Substations. The adoption of fuseless capacitor banks in the Eskom higher voltage system would have a tremendous impact on the resolution of several problems associated with the conventional fused capacitor application. Moreover, the fuseless capacitor technology is cheaper and enhances the shunt capacitor reliability. In appendix 4 more background on the substation layouts [3.17], and the fundamental construction and features of shunt capacitor banks [3.2] -[3.11] and shunt reactors [3.12] - [3.16] are given.

## *3.2 Shunt Capacitor Bank Switching*

### *3.2.1 Review of Literature*

Since the beginning of this century, many researchers have published on their experience of switching phenomena with shunt capacitor banks. An excellent overview (from 1931 up to 1969) of the most important articles published in the USA is given in reference [3.18]. Morant is presently working on an overview in cooperation with CIGRE Working Group 13-04 [3.19]. A lot of the early (German, Austrian or Swiss) literature can be found in the bibliographies of [2.9] and [2.10].

Based on the experience of the utility, their power system computer simulations and the manufacturers recommendations, the power equipment specifications and an associated operating protocol are developed. In the many papers which have been devoted to the concerns associated with shunt capacitor applications, a lot of practical experience is summarized. The most important concerns related to shunt capacitor bank switching are:

1. ***High frequency inrush currents*** on energizing, but also ***high frequency outrush currents***, in the case of back-to-back switching or in the case of system faults such as phase-to-phase short-circuits. Stresses on the power system, the circuit breaker and the power equipment in the immediate vicinity of the switched breaker must be studied carefully. For example overvoltages on the current transformer secondary connections have to be considered. The burdens have to be able to withstand these overvoltages. Related references are [3.20], - [3.28], [3.30], [3.32], [3.34] - [3.36], [3.42] - [3.45].

2. Overvoltages on energizing of a shunt capacitor bank. Two kinds of overvoltages have to be distinguished, namely the ***transient overvoltages*** and the ***sustained overvoltages***. The sustained overvoltages can be due to a high value of the local steady state system voltage (usually not more than 10% of the per unit value). Also overvoltages caused by resonances which are triggered by energizing of the capacitor bank have to be considered.
   The transient overvoltages depend on:
   ***Source Characteristics*** - The ratio of the source inductive reactance and the source resistance (X/R ratio) and the length of the transmission lines connected to the busbar are important. The general trend is that the transient overvoltages become higher when the source gets weaker.
   ***Parallel Shunt Capacitor Banks*** - Any parallel shunt bank operates as a source, and thus creates a stiffer source on the concerned busbar. This means that the transient overvoltage is reduced for back-to-back energizing, however because the source is stiffer the inrush currents are more severe now than in the case of single bank switching. Multiple frequency transients will occur in this case.

*Permanent or Temporary Impedances* - Pre-insertion impedance installed in the circuit breakers, permanently installed series impedance circuits can act as current limiting devices or spread the transients of smaller magnitude out over time. Also the point-on-wave that the circuit breaker is closed is an important factor in determining the severity of the transient. Related references are [3.23] - [3.28], [3.30], [3.32], [3.35] - [3.41], [3.44], [3.45] and [3.46] - [3.55].

3. Overvoltages related to the de-energizing of capacitive loads, especially if a breakers shows *restriking* behaviour, or more specific concerns on the circuit-breakers transient recovery voltages. Directly related to this are the *surge arrester duties* (if present). Surge arresters are applied for overvoltage protection. In the case of multiple restrikes the surge arresters can be overloaded with as result, if a *back-up breaker* fails to clear quick enough, their subsequent destruction. Related references are [3.20], [3.21], [3.29].

4. *Voltage magnification phenomena at remote capacitor locations* represent another source of problems. Under certain conditions of the power system very high (magnified) overvoltages can occur at these remote capacitor locations caused by the switched capacitor bank. A A A related reference is [3.37], [3.41].

5. *High phase-to-phase overvoltages at the remote end of long lines terminated with transformers* can also be caused by shunt capacitor bank switching. Travelling waves can cause transients of about twice the maximum system voltage on two phases. If the polarity differs this means that a phase-to-phase transient of about four times (exactly 2'3) the maximum phase-to-earth voltage can be present which can be dangerous for the integrity of the transformers insulation. Related references are [3.32] - [3.35].

Most of the published papers on capacitive current switching fall under one of these points, and are based upon two different kinds of investigations. Some information results from field testing of actual systems and from laboratory testing of power components. Another source of information are the experiments with Transient Network Analyzers (TNA) and the studies with computer programs such as ATP (Alternative Transients Program - Personal Computer Version of EMTP) or EMTP (Electromagnetic Transients Program).

Capacitive switching surge data obtained during field tests are usually a by-product of circuit-breaker field tests in which the performance of the circuit-breaker is of primary concern. As a consequence of the field test, the obtained data is directly related to the specific local systems and the specific local circuit parameters.

The only general information available investigating switching surges over a wide range of system parameters and circumstances are obtained by studies on systems in miniature such as the TNA or with EMTP. However the major drawbacks are that the circuit-breakers specific properties are not taken into account in a correct way in the used computer-software-models or in the miniature substitutes. In these model-studies idealized circuit-breaker models are normally used which can give completely different results. However despite these drawbacks some graphs that were produced with ATP-programs [3.86], [3.87], [3.88], [3,89] will be used to illustrate the coming discussions.

From the foregoing it may be clear that there is a need for several methods to damp or reduce transients on shunt capacitor bank switching. These methods will now be briefly discussed.

### *3.2.1.1 Inrush and Outrush Current-Limiting Series Damping Network*

Three different designs for such a damping network are generally in use.

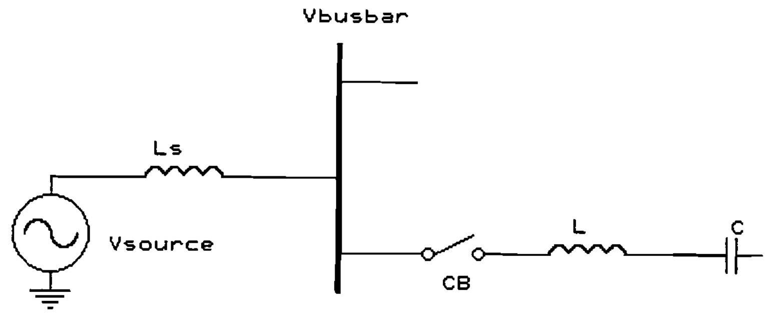


**Figure 2** - *Damping network consisting of a current-limiting reactor only.*

To decrease the maximum value of the inrush or outrush currents but also the frequency of these currents, a series connected air-reactor is used in each phase. This can be the case for single or back-to-back switching of capacitor banks, but also switching in the case of inter-phase faults in the vicinity of the bank, or when the shunt capacitor bank circuit breaker restrikes. In this principle diagram the reactor is drawn as a concentrated element. Within some utilities this reactor is in reality split into multiple reactor-elements of lower inductance and also connected in series with the shunt capacitor units. This is done in order to protect the shunt capacitor bank (it avoids destruction of the capacitors due to high outrush current) in the case of a short circuit between the reactor and the shunt capacitor bank.

Especially the case of nearby faults in the network is a complex problem, and if circuit breakers must be able to operate satisfactory under such a duty, appropriate testing in a High Power Laboratory is necessary. The transient recovery voltage of the circuit breaker has a (1 - cosine)-shape due to the capacitor bank. This TRV has a low rate of rise which will cause an early attempt to interrupt the current at short arcing time. In short, the capacitor bank causes the TRV to have a reduced rate of rise, to have an increased peak value, and that the time to reach this peak value is longer. The dielectric withstand capability of the contact gap will probably not be sufficient enough and the result is a reignition. If the breaker reignites a superposition of the power frequency current and a high-frequency transient, which can have a considerable magnitude, component will flow. Due to the high magnitude of this transient current additional current zeroes will be present in the current which gives the breaker an opportunity to interrupt.

The impact of the high frequency transient can be decreased by a suitably chosen series reactor.
This reactor must meet the following characteristics:

1. It must control the maximum values of the inrush and outrush currents within the limits that are dictated by the circuit breakers specifications.
2. Negligible losses in steady-state operation.
3. The damping device should have a high reliability, ie its construction must be as simple as possible.
4. It shouldn't have a significant influence on the steady state system.

The ANSI standards [3.28] require that special duty (definite purpose) breakers must withstand transient current with a peak value of 20 kA and a frequency of 4250 Hz. Based on this requirement, some of the reactor and resistor values which are used in the Eskom system are tabulated in table 1. To damp the oscillating transients usually a parallel resistor is added. Laboratory tests at KEMA [3.36] have shown that the effect of the damping resistor depends on the extinguishing medium of the breaker. In these tests a markable difference between an $SF_6$ breaker and a minimum-oil breaker was noticed, and revealed an overvoltage reduction for the $SF_6$-breaker but not for the minimum-oil breaker.

**Table 1** - *Standardized values for the reactor and the parallel resistor in a series damping network for Eskom's shunt capacitor banks.*

| System Voltage (kV) | Capacitor Rating (MVAr) | Reactor ($\mu$H) | Resistor ($\Omega$) |
|---|---|---|---|
| 88 | 2 x 24 | 500 | 10 |
| 132 | 2 x 36 | 600 | 10 |
| 275 | 2 x 75 | 800 | 20 |

Practice has shown [3.29], [3.35], [3.36] that even when the circuit-breaker application does not require the breakers to switch capacitors, they may still be exposed to capacitive switching duties during system faults in the vicinity of a capacitor bank. So this reactor is not only important for the capacitor bank breaker but also for other (general purpose) breakers (if they restrike) located close to the capacitor bank. The

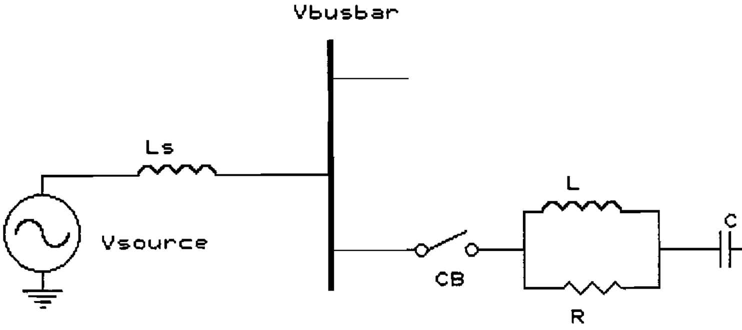


**Figure 3** - *Damping network consisting of a parallel resistor - reactor circuit.*

laboratory tests also showed that breakers with different extinguishing media have reignitions after the interruption of fault-currents. As mentioned before this is due to the current interruption at short arcing times when the dielectric withstand is not high enough yet. Interruption at a high frequency current zero occurred with some of the tested breakers whereby overvoltages were produced, whereas other tested breakers waited for a power frequency current zero extinction and thus increased the arcing time.

In the second solution this resistor is permanently in service, so continuously dissipating energy. In order to prevent this energy loss the MOV is used to bring the resistor in the circuit during transient conditions.

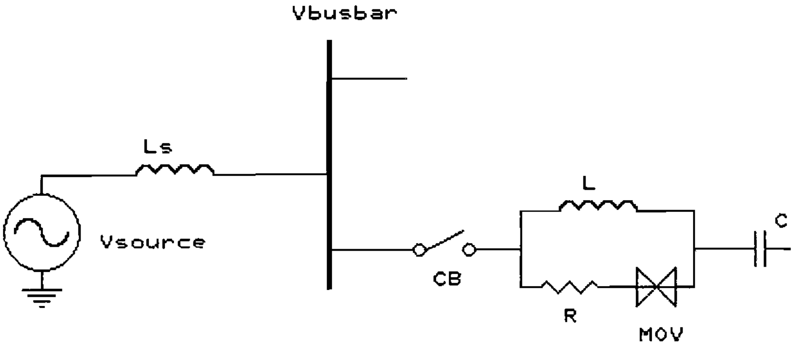


**Figure 4** - *Damping network with an extra surge arrester, to prevent steady state resistor loss, in series with resistor.*

The third possible design is a damping circuit which consists of a reactor in parallel with a resistor which is in series with a Metal Oxide Varistor (MOV or Zinc Oxide Arrester). This MOV "switches" on the resistor only during inrush or outrush transients. This design is relatively new, and not many papers have been published on this design yet [3.42], [3.44], [3.45]. The utility EdF in France has several of these designs in use. So far the operational experience is satisfactory.The application of a zinc oxide surge arrester depends on economics. It is possible that a full BIL (Basic Insulation Level) damping network (Reactor with Parallel Resistor) is more economic and also a simpler solution. It also depends of course on the type of problem that has to be dealt with. This damping network can provide protection on limiting the magnitude of inrush and outrush currents, it can prevent loss of breaking capability for general purpose breakers, but also provides damping in the case of a circuit-breaker restrike. The design of this damping circuit mainly focusses on stresses due to energizing transients because the branch parallel to the reactor only operates when transient currents pass through the reactor. The reactor is used to decrease the magnitude of the transient current. The resistor is provided to damp the transients as quick as possible.

The MOV must behave as an open switch during the steady state conditions and as a closed switch during transient conditions. This means that the protective level must be as low as possible (as close as possible to the maximum steady state voltage), so that the MOV remains conductive as long as possible during transients, and such that sufficient damping is reached during the conducting state of the MOV. When choosing the maximum continuous operating voltage for the MOV, also harmonics have to be taken into account.

This new damping circuit is a permanently inserted passive system which operates automatically, so a high degree of reliability can be expected. Presently EdF is gathering field experience with this type of damping circuit. If this turns out to be satisfactory, all the high voltage shunt capacitor banks may be equipped with this damping device.

Relatively high component values are used: a reactor of 5 mH in parallel with a 60 Ω resistor which is in series with a 4 kV MOV. This design is used for the 30 MVAr shunt capacitor banks in the 72,5 kV and 100 kV networks. In the USA [3.42] some utilities are also considering this damping circuit, but apparantly this idea is still developing.

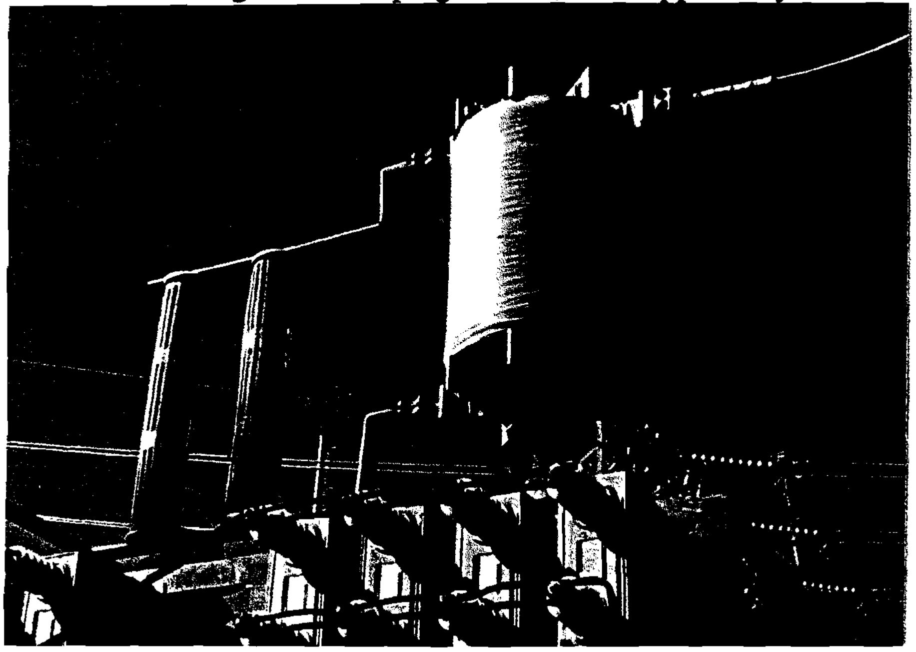


**Figure 5** - *The damping network (R = 10 Ω - L = 600 μH) on a 72 MVAr - 132 kV shunt capacitor bank at Eskom's Leander Substation, near Welkom, South Africa.*

### *3.2.1.2 Pre-Insertion or Closing Resistors or Inductors*

With the resistor in the switching device, two different inrush transients must be considered, see also figure 2. The first transient when the resistor is inserted, then we have a RLC series circuit as a resulting circuit. The purpose of the resistor is to limit the inrush current. The second transient occurs when the resistor is bypassed and the circuit changes into a primarily LC series circuit with a much smaller resistive series element. The magnitude of the inrush current at this stage depends on the time-instant of bypassing or shorting of the resistor and also the value of the resistance. The larger the resistance value, the larger the voltage-change which occurs when the resistor is by-passed. In the principle diagram of figure 6, only one closing or pre-insertion resistor is used. It is very well possible to use more then one resistor, this can result in a further reduction of transients, however the transients are spread out over a longer time-interval. Choosing the correct value of the resistance value is very important for a gradual energizing operation. If the resistor is large, the first transient will be small whereas the second transient may still have significantly large values, and thus the aim of using a closing resistor is not reached.

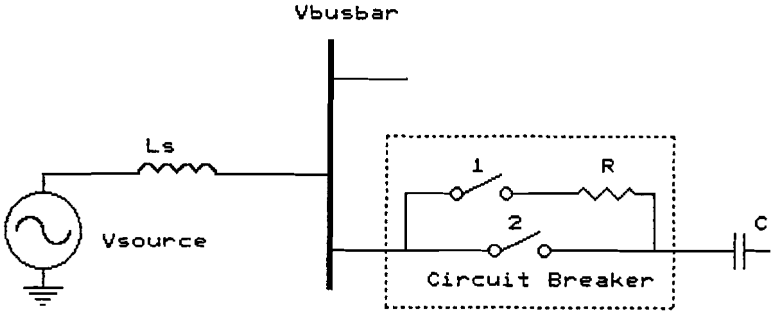


**Figure 6** - *Principle diagram of Circuit-Breaker with Closing Resistors.*

When a closing resistor is used, the busbar voltage will not collapse to zero. The reduction in the busbar voltage collapse results in a reduced step-voltage-wave which will be injected on energizing into the system. If the closing resistance value is chosen in such a way that the RLC series circuit shows a nearly critically damped transient oscillation behaviour, the busbar voltage will have very little overshoot and the will damp the transients within say less than a quarter of a period of the 50 Hz current. The change in busbar voltage will still be abrupt on energizing but reduced to a level such that it has less impact on the system.

Pre-insertion or closing resistors typically absorb a large amount of energy on capacitor bank energization. The energy capability of the resistor can lay down limits on the frequency of switching operations but also limit the size of the shunt capacitor bank rating. The use of pre-insertion impedance makes the mechanical construction of the circuit breaker much more complicated, this also has its impact on the reliability of the switching device and the overall installation.

Instead of a resistor also an inductor can be used as a pre-insertion or closing impedance. The extent to which the busbar voltage collapses is also significantly reduced because of the high surge-impedance of the inductor. The voltage will not collapse abruptly, but initially in an exponential way, in this case because the pre-insertion inductor surge-impedance will have a very high value compared with the surge impedance of the connected infeeding transmission lines. The presence of transients on the system voltage will be of longer duration as the damping will be much less in this case. The travelling wave that is injected into the system in this case will have less impact because on energizing the initial busbar voltage will not collapse abruptly.

In the case of a closing resistor a step function wave will be injected into the system, whereas in the case of a closing inductor a rampe function wave will be injected. The step function wave that will be injected with direct energization of a shunt capacitor bank will of course be of larger magnitude. Energizing through a closing inductor will produce a lower rate of change of the busbar voltage. This will have less impact [3.33] on the initial turns of a transformer winding.

Also circuit breakers with opening resistors are used, the principle diagram is the same as for closing resistors.

### *3.2.1.3 Controlled Closing*

Controlled closing has been discussed and recommended by several researchers [3.46] - [3.55] as a very effective means of energizing a capacitor bank. As reported in the second chapter of this report, there are two major requirements upon the circuit-breaker in this case. The mechanical stability and inherent operating time of the circuit breaker must be sufficient and very consistent, an accuracy of ± 1 ms is absolutely required. Also the rate of fall of the dielectric strength must be sufficient and in such a way that energizing within this ± 1 ms time-window is possible. This means with or without pre-arcing but absolutely within this time-window. The ideal time-instants for energizing of shunt capacitor banks with earthed and un-earthed neutral are fundamentally different, see chapter 2. This can also be said of the overvoltages that can occur on energizing these banks in an un-controlled way, or because of timing errors in the closing instant. The influence of system load on the damping of transients when energizing takes place within this ± 1 ms is also significant, this has been proven with field tests at Borssele Substation [3.55].

If a switching device adheres to these two fundamental requirements, controlled closing is the ideal means of energizing because local but also remote transients will be virtually eliminated.

In the papers on controlled switching the following topics are discussed:

1. The required time-window on circuit breaker closing and opening, and the effect

of time-spread around the optimum control points, for the different possible loads, as well as the effect of the neutral treatment of the different possible loads.

2. Field test results showing the voltage and current wave forms for practical situations.
3. Computer simulation results showing these wave forms for the model of the power system.
4. Block diagrams of control circuits for controlled switching.
5. Comparisons of controlled switching with other means of transient reduction.
6. Circuit breaker requirements, such as closing speed and no-load test results under various conditions.
7. Adaptivity algorithms and adaptive control methods and the various parameters that influence the operating time accuracy.
8. Economical and reliability aspects.
9. Future applications and perspectives.

All these points have been or will be discussed in chapters 2 and 3. The damping of the network can have a significant effect in the case of controlled closing. This network-damping effect was not treated in any of the published papers. During field tests at Borssele Substation the impact of this effect became clear. It will be discussed in a later section.

#### *3.2.1.4 Other Methods*

*Controlled Opening* - Controlling the arcing time of a breaker makes it possible to prevent circuit breaker restrikes. Only a few controlled opening installations are used at present for transmission line opening. A lot of research is still being carried out at the moment.

*Surge Arresters* - The function of a surge arrester is to protect the insulation of other power equipment connected to the same busbar as the arrester, without putting itself at risk (energy demands on the arrester). This is done by limiting the overvoltage to the arresters clipping level. The arrester begins to conduct when the system voltage approaches the arresters protective level. The voltage which causes the arrester to operate can be an overvoltage due to an energizing procedure of a capacitor bank. Also overvoltages which occur on restriking of the circuit breaker will operate the arrester. The arrester is used as a second line of defence in this case. Care must be taken when determining the arresters energy demands especially in the case of restriking. If multiple restrikes occur, the voltage may possibly resonate upwards. When restriking occurs in one circuit breaker pole, and the capacitor banks neutral is un-earthed, then there will be a significant neutral-voltage. The other two poles are often subjected to a very high voltage difference across their poles and are forced to restrike. In general arresters can only be used up to a certain limit because they are not capable of dissipating the capacitive power of the bank. High current surges are possible, expecially in the case of back-to-back banks.

***Varistor aided Switching*** - This solution was presented during the 1992 Cigre Conference [3.42], allthough the idea has already been suggested some decades ago. The construction of the breaker is similar to a breaker with a closing or opening resistor. Instead of the linear resistor, a non-linear resistor or ZnO Varistor is used. The current-voltage characteristic of the varistor is such, that interruption of the varistor current occurs naturally in the $SF_6$, without blasting. The transient voltages are limited to 1 per unit with varistor aided switching.

### *3.2.2 ESKOM Experience*

Within ESKOM some 150 MVAr shunt capacitor banks at 275 kV have given problems, which are due to a certain extent to the principle of adopting the same configuration for all capacitor ratings as it has been dictated by ESKOM's standardisation philosophy. The un-earthed double star configuration adopted by ESKOM has proven to be reliable for banks up to voltages of 132 kV because the equipment used can easily be manufactured with the required capabilities in relation to the transients and fault conditions.

This can not be said for the 275 kV un-earthed shunt capacitor banks. The following events [3.2] have been recorded:

1. The contacts of circuit breakers are subject to contact-erosion due to the inrush currents, especialy during the back-to-back energizing of shunt capacitor banks. Also voltage surges can be induced in the station control and protective circuitry. Interference with communication systems in the area is also possible. Current transformers are stressed and the time clearing characteristics of the unit protection fuses change with successive energizations.

2. Circuit-breaker restrikes on de-energizing of capacitor-banks. Due to neutral voltage excursion flashovers to earth of the bank neutrals occur during a restrike. On some occasions the restrikes also caused severe damage to the unbalance protection current transformers and to the neutral itself.

3. Explosions of internally fused capacitor units.

4. Tripping of circuit breakers in remote capacitor banks due to the voltage magnification phenomena at that remote busbar.

5. Severe phase-to-phase overvoltages at remote substations, due to the voltage-surges on capacitor bank energizing. This caused transformer insulation damage which might have been the start of insulation failures. Surge arresters at the remote busbar do not offer protection for phase-to-phase surges. The phase-to-phase overvoltages are dependent on the size of the shunt capacitor bank being switched, source characteristics, length of lines between the switched capacitor and the remote busbar.

Another problem related to the capacitor banks is, that the older banks have PCB-insulating oil in the capacitor cans. This makes special procedures necessary for the removal and destruction of faulty cans. The main cause of the mentioned problems are the current and the voltage transients which occur on bank energizations or with restriking on de-energization.

Elaborate studies in the USA have lead to the conclusion that shunt capacitor banks at voltages higher than 230 kV have improved performance if the bank neutral is earthed. According to Westinghouse, shunt capacitor banks in the USA and Canada of such high voltage and also large size are usually commissioned with the neutral earthed. The ability to control the transients more effectively and the use of a less expensive protection scheme, which is also less affected by transients, in shunt capacitor banks with earthed neutral played a determining role in the American decision to adopt this kind of neutral treatment. The connection of the bank neutral to the earth grid requires special connections and must be of the lowest possible impedance. In some cases this might turn the cost factor in favour of the un-earthed neutral configuration.

Based on these experiences, in the following section some equations for current and frequency will be derived for single as well as back-to-back energizing of shunt capacitor banks with simplified diagrams. It is very easy to determine the behaviour for (idealized) three-phase circuits with the help of computer simulation software such as the Alternative Transients Program. Therefore only one-phase representations of circuits to explain the phenomena will be used.

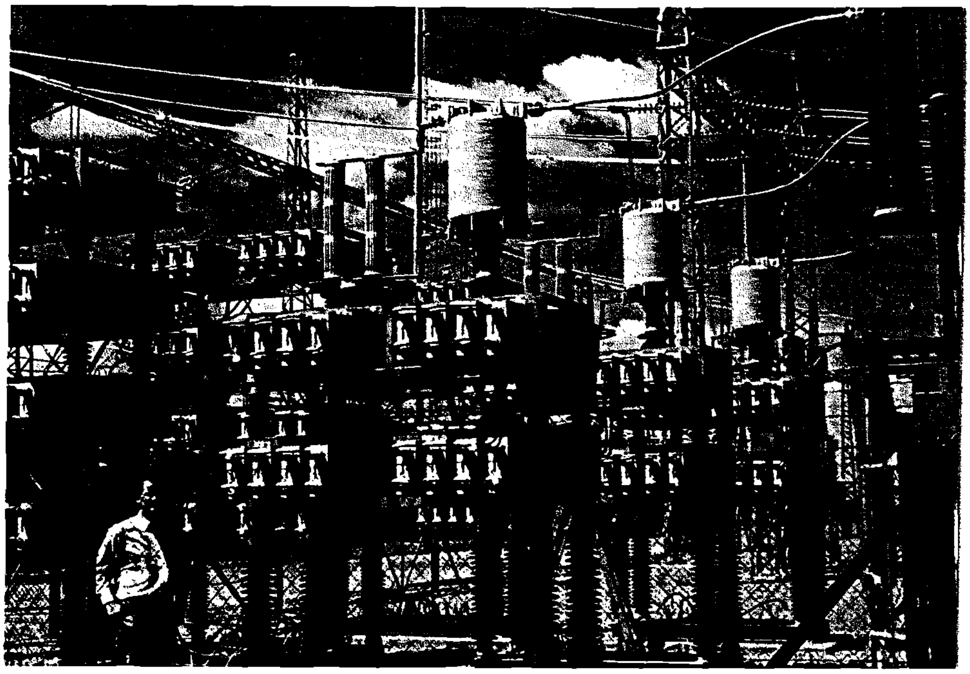


**Figure 7** - *A 72 MVAr - 132 kV Shunt Capacitor Bank at Eskom's Leander Substation, near Welkom, South Africa.*

### *3.2.3 Capacitor Banks Switching Phenomena*

Energizing and de-energizing one phase of an earthed shunt capacitor bank, or two phases of an un-earthed shunt capacitor bank may be represented by a single phase circuit diagram. When this diagram is analysed with respect to voltages and currents, it can be concluded that higher order linear differential equations will rule the behaviour of the circuit during transient and steady state conditions. Analyzing them can be difficult. It is definitely impractical every time when a capacitor switching problem is encountered to analyze these equations all by hand, therefore some practical equations will be derived. Also computer programs, such as EMTP or ATP, have been developed to study three-phase situations quickly and in detail. To get a grip on the phenomena which can be encountered on capacitor bank switching, a single-phase circuit-diagram will be used.

The phenomena that occur when switching capacitive currents are already known for a very long time. Despite this knowledge, there is still a wide believ that the high inrush and outrush currents and also severe voltage distorsions that occur during energizations are the severest transients that one has to take into account. However this is absolutely not the case when the possibility of a circuit-breaker restrike is considered. Especially for oil circuit breakers many papers have been published on single and multiple restriking phenomena [3.18], [3.19]. For the modern $SF_6$ circuit breakers a restrike occurs very seldom.

From basic circuit theory it is well known fact, that the transient current can be a large multiple of the steady state current. The duration of the transients are determined by the time-constant of the circuit. In the circuits that are interesting for the investigation, the resistance R is usually of very small value. So this means that the transients decay very fast, however their magnitude can reach significant values. On the instant of energizing, the capacitor behaves as a short-circuit and the current is determined by the voltage to resistance ratio. This equation also makes clear that in circuits with very low inductance the inrush currents can become very large. Values between 10 to 100 times the steady state current are possible in practice. However in real systems, a series inductance component will always be present. This can be the inherent inductance of the power circuit, but it can also be an added component. Usually the magnitude of the inductive reactance is of much higher value than the magnitude of the resistance, and therefore they usually influence the transient phenomena in a determining manner. To determine the ***severity of the transients***, usually the following criteria are used:

1. The maximum value and frequency of inrush and outrush currents.

2. The maximum value of overvoltages at the switched busbar.

3. The magnitude and the slope of the very steep voltage dip because this determines

the overvoltage at remote busbar locations in other substations.

4. The duration or rate of decay of the transients.

These criteria are only valid for the case of single and back-to-back energizing of capacitor banks. The current transients are more severe during back-to-back energizing while the voltage transients are more severe during single bank energizing. It can also be said that back-to-back switching gives a big kick to the circuit breaker and that single bank switching gives a big kick to the power system. The magnitudes of the transients are determined by the point-on-wave on which the circuit is energized. These magnitudes are in proportion to the magnitude of the busbar voltage at the moment of energization.

*Energizing in Gap Voltage Zero* - The voltage equals zero but the current is in its maximum. The total inrush current in this case can only become about double the steady state current value, and this will only occur after about half a cycle of the natural frequency. The transient is a cosine and its decay is exponential. The total capacitor voltage will only become slightly larger (a few percent) than 1 pu (the steady state voltage) in case the ratio of the natural frequency ν of the oscillatory circuit to the frequency ω of the power system, is large. The transient decays exponentially with a sine function.

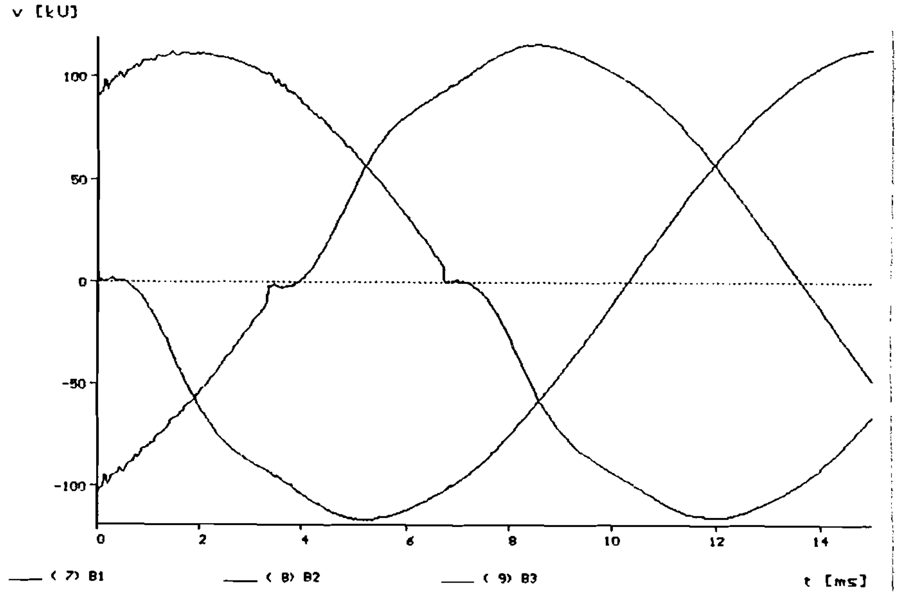


**Figure 8** - *Busbar voltages calculated with ATP at Stikland Substation on energizing of a single bank near gap voltage zero in each phase.*

*Energizing in Gap Voltage Maximum* - This is the worst case and also the most usuall case in practice. The transient voltage can become maximum twice the steady state value if the circuit has a high natural frequency. On energizing the busbar voltage will have a very steep voltage dip, which can dip down to the zero-voltage line. The slope of this dip can be dangerous in that it can generate high overvoltages at remote busbars. At the moment of circuit closing the completely uncharged bank represents a short circuit to the system and the inrush current is only limited by the impedance of the circuit supplying the bank. Energizing a capacitor thus has the character of closing the circuit-breaker on a short circuit. In conclusion it can be said that the closing point-on-wave and the natural frequency are very important. The highest inrush currents will occur when energizing takes place in gap voltage maximum. The ideal point-on-wave for energization is thus at gap voltage zero.

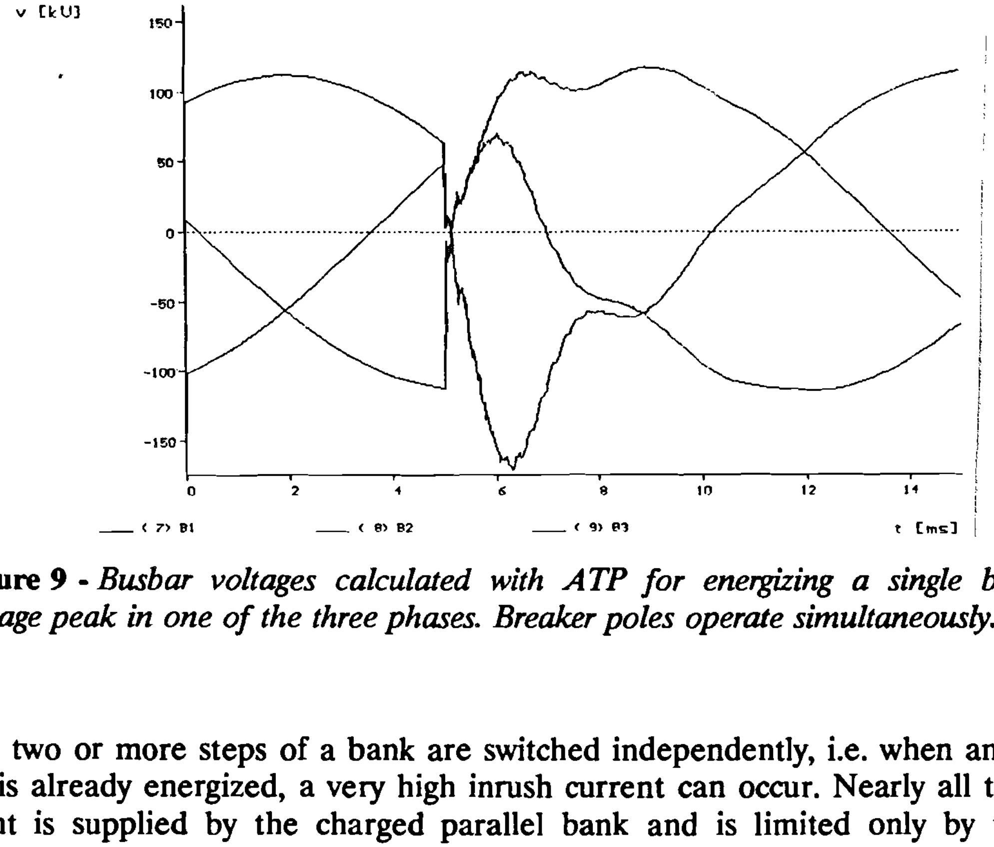


**Figure 9** - *Busbar voltages calculated with ATP for energizing a single bank at voltage peak in one of the three phases. Breaker poles operate simultaneously.*

When two or more steps of a bank are switched independently, i.e. when an adjacent bank is already energized, a very high inrush current can occur. Nearly all the inrush current is supplied by the charged parallel bank and is limited only by the small inductance in and between the banks.

To calculate the inrush current for a single as well as for a back-to-back situation, the following equation is generally in use:

$$i_{Inrush\ Maximum} = u_{Maximum} \sqrt{\frac{C_{Total}}{L}}$$

In this equation $C_{Total}$ equals the total capacitances. In these calculations resistance is neglected, so the calculated current will be slightly high and therefore on the safe side. These inrush currents are high but normally below the momentary current rating

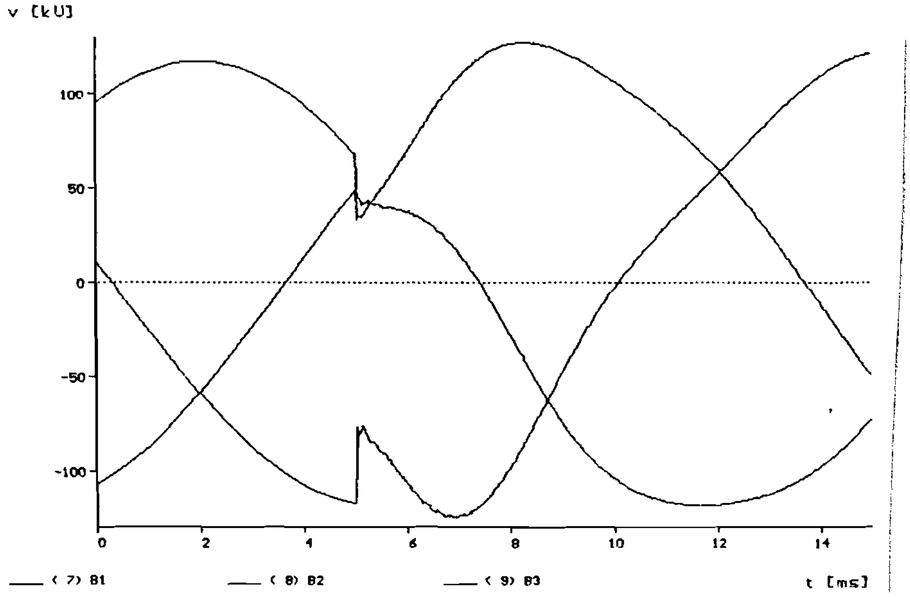
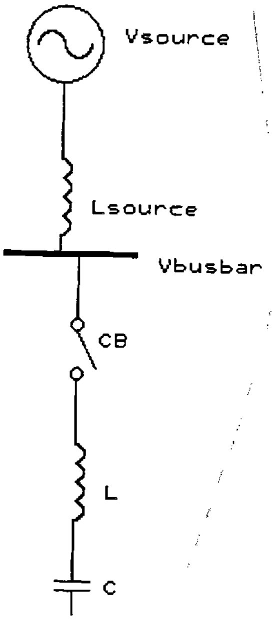


**Figure 10** - *Busbar voltages calculated with ATP for energizing in a back-to-back situation at voltage peak in one of the three phases. Breaker poles operate simultaneously, and two banks of 72 MVAr are already energized.*

of the circuit breaker. The circuit breakers are build to withstand the contact burning and mechanical stresses produced by an occasional closing of the breaker against a short circuit. However frequent closing operations with high inrush currents can cause rapid contact deterioration. The mechanical shock and stresses produced by the extremely high rate of rise of current is also a very severe problem. So as it may be clear, it is often necessary or at least desirable to limit the shunt capacitor bank inrush current. One means for providing this function is the installation of an inrush-current limiting reactor in each phase, or one of the other previously discussed damping networks or of course controlled switching !

In IEC 56 [2.1], [3.27] the following simplified circuits are used to calculate inrush currents and frequencies.

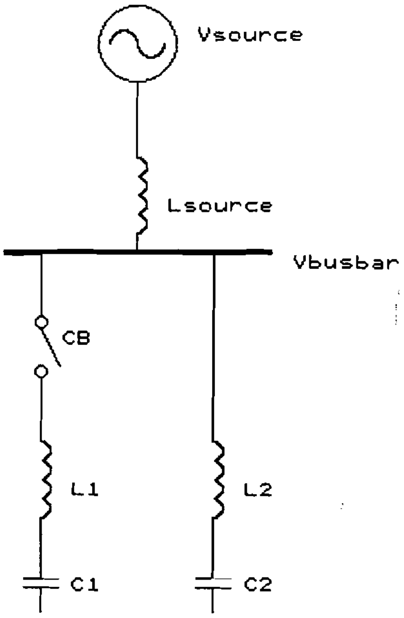
**Single-Bank Switching:**



$$i_{Inrush\,Maximum} = U_{Peak}\sqrt{\frac{2}{3}\,\frac{C}{L_0 + L}} \approx U_{Peak}\sqrt{\frac{2}{3}\,\frac{C}{L_0}}$$

$$f = \frac{1}{2\cdot\pi\cdot\sqrt{C\,(L_0 + L)}} \approx \frac{1}{2\cdot\pi\cdot\sqrt{C L_0}}$$

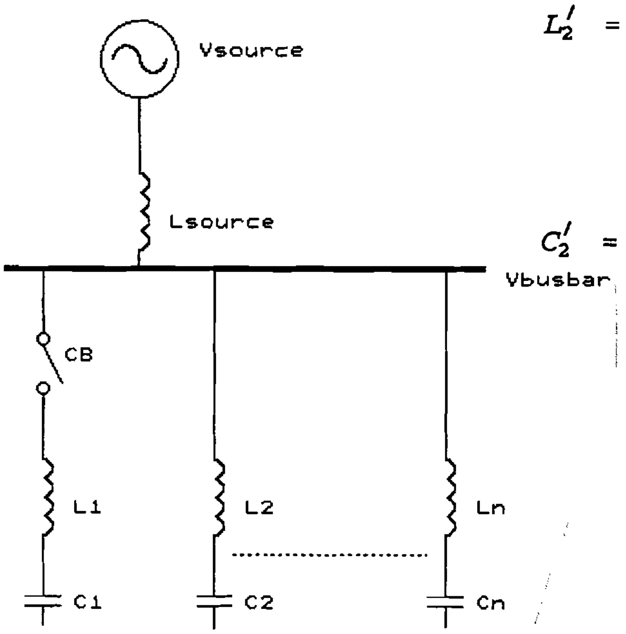
**Two Banks Back-to-Back Switching:**



$$I_{Inrush\,Maximum} = U_{Peak}\sqrt{\frac{2}{3}\cdot\frac{C_1\,C_2}{C_1 + C_2}\cdot\frac{1}{L_1 + L_2}}$$

$$f = \frac{1}{2\cdot\pi\cdot\sqrt{\frac{C_1\,C_2}{C_1 + C_2}\,(L_1 + L_2)}}$$

## N Banks Back-to-Back:



$$L_2' = \frac{1}{\frac{1}{L_2} + \frac{1}{L_3} + \ldots\ldots \frac{1}{L_x}}$$

$$C_2' = C_2 + C_3 + \ldots\ldots C_x$$

Legenda on the equations and figures:
f = Inrush frequency
$L_0$ = Network inductance
L, $L_1$, $L_2$,...$L_n$ = Inductances in series with capacitor banks
C, $C_1$, $C_2$,...$C_n$ = Bank capacitances
With a number of n equal banks of capacitance C and inductance L, we have:

$$I_{Inrush\ Maximum} = U_{Peak} \sqrt{\frac{2}{3}\left(\frac{x-1}{x}\right)^2 \frac{C}{L}}$$

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{LC}}$$

This method of reduction gives results which agree to within ± 5 % of test values with a transient network analyzer. In [3.20] calculations are made with the same simplified diagrams but also for diagrams which do not neglect the influence of the source. Flöth derived and solved fourth order differential equations, and studied the circuits for different values of inductance and capacitance. In the case of back-to-back switching one has to make a distinction between two superimposed frequencies, which frequency is superior to the other one depends on the distribution of inductances and capacitances in the circuit. Flöth concluded that there is a significant discrepancy between the "exact" and the simplified circuits and thus that it is recommended to use a correction on this simplified approach if more accuracy is needed. He confirmed his theory with field test trials. In the present issue of IEC 56 however the simplified approach is used. Lumping together the capacitances and the series inductances, and thus a simplification obviously has proven to be satisfactory for practical use.

Using these single line diagrams it is also very easy to calculate the maximum frequency of the inrush current. If we use the assumption that the inrush current must be one hundred times smaller than the continuous RMS value of the current:

$$I_{Inrush\ Peak} \leq 100 \cdot I_{RMS}$$

For any combination of bank-to-bank switched capacitors, the equivalent diagram can be reduced to an equivalent of two banks.

If we use:

$$\begin{aligned} C_1 &= C \\ C_2 &= x \cdot C, \quad x \geq 1 \\ L &= L_1 = L_2 \end{aligned}$$

then all possibilities are covered. For the inrush current and frequency we have for this case the following equations:

$$I_{Inrush\ Maximum} = u \sqrt{\frac{2}{3}} \sqrt{\frac{x}{x+1}} \sqrt{\frac{C}{2L}}$$

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{2}} \sqrt{\frac{x+1}{x}} \sqrt{\frac{1}{LC}}$$

For the steady state current we have:

$$I_{RMS} = \frac{u}{\sqrt{3}} \cdot 2\pi f_p \cdot C$$

We assumed that:

$$I_{Inrush\ Maximum} \leq 100 \cdot I_{RMS}$$

If we substitute the earlier deducted equations:

$$\frac{u}{\sqrt{3}} \cdot \sqrt{\frac{x}{x+1}} \cdot \sqrt{\frac{C}{L}} \leq 100 \cdot \frac{u}{\sqrt{3}} \cdot 2\pi f_p \cdot C$$

$$\sqrt{\frac{1}{L\,C}} \leq \sqrt{\frac{x+1}{x}} \cdot 2\,\pi\, f_p \cdot 100$$

Substituting the equation for the natural frequency yields:

$$f \leq \frac{100}{\sqrt{2}}\,\frac{x+1}{x}\,f_p$$

The ratio-part for x in this formula is at maximum for x = 1.
This gives:

$$f \leq 100 \cdot \sqrt{2} \cdot f_p$$

This means that for a power frequency of 50 Hz the natural frequency will be lower than 7 kHz. If we use the assumption that the inrush must be smaller then, say twenty times the steady state current, then we have, f ≤ 1,4 kHz.

So far we have only studied single-phase circuits. In practice a lot of shunt capacitor banks are three-phase units. If the neutral is earthed, then each phase can be treated as before, so as three separate single-phase circuits. However if the neutral is un-earthed, then the situation is different. The voltage stresses across the circuit-breaker are dependant on the neutral treatment of the source and that of the capacitor bank. Many researchers have published on the neutral treatment and its impact on the recovery voltages and the neutral voltage. Situations which will alter these maximum values are:

1. *Pole simultaneity* - If the pole non-simultaneity [3.23] is greater than a quarter of a cycle, (or 5 ms) the maximum voltage is higher than 2,5 per unit for an un-earthed shunt capacitor bank. The recovery voltage due to the influence of pole non-simultaneity of the first pole to clear when de-energizing an un-earthed bank can be higher than 4 per unit. The non-simultaneity can be due to a stuck breaker-pole but also due to the changing mechanical settings with time of the breaker. The sequence in which the phases are interrupted and the degree of pole non-simultaneity are important factors in determining recovery voltage.

2. *Nearby faults* - In general when there are nearby faults, this means an increased stress compared with the healthy situation, on the circuit-breaker poles.

3. *Circuit-breaker restrikes* - Restriking can greatly increase the recovery voltage values over those imposed on the breaker if no restriking takes place. Values that are a multiple of the per unit voltage are possible and can have a destructive effect on the equipment, if the breaker fails to clear. The neutral voltage for an un-earthed bank can be much higher than the normal 0,5 pu value due to restri-

king or non-simultaneity. This can cause the neutral to flash over to earth which is usually the beginning of the end of the installation with the restriking breaker. In a restrike-free breaker, the recovery of the dielectric strength must exceed the recovery voltage at all times. Design factors of the breaker rule the possibility of a restrike. Adequate opening speed and the presence of flow of extinguishing medium are some of these factors.

4. *Neutral treatment* - Apart from the two possibilities of a (directly) earthed neutral and a floating or un-earthed neutral there is a third possibility. Earthing of the capacitor bank neutral through low voltage capacitors. The maximum voltages on the neutral in this case are then well below 1 kV. This method has been described in appendix 4 and is used on the new fuseless technology capacitor banks in the Eskom power system. This method of earthing is practically the same as the case of a directly earthed neutral.

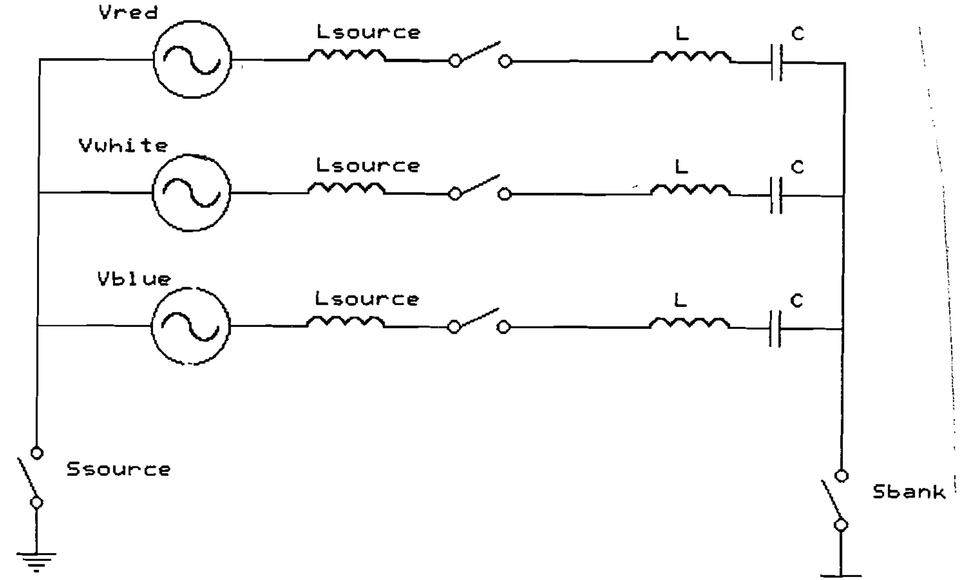


**Figure 14** - *Principle schematic diagram of a three pole shunt capacitor bank installation.*

Legenda on table 2:

- 1 per unit equals the peak value of the steady state phase voltage.
- The Red Phase is assumed to be interrupted first.
- E = Earthed and U = Un-earthed.

**Table 2** - *An overview of the voltage stresses in the case that the poles operate simultaneous and that the breaker behaves restrike-free.*

| Neutral Treatment | Time Period between Extinction of Phase Red and the Phase | | Maximum Breaker Recovery Voltage Stresses of the Phase (Per Unit) | | | Maximum Neutral Point Voltages (Per Unit) | |
|---|---|---|---|---|---|---|---|
| | White (ms) | Blue (ms) | Red | White | Blue | Source | Shunt Capacitor Bank |
| Source E<br>Bank E | 3,33 | 6,67 | 2 | 2 | 2 | 0 | 0 |
| Source E<br>Bank U | 5 | 5 | 2,5 | 1 + ½√3 | 1 + ½√3 | 0 | +½ |
| Source U<br>Bank E | 5 | 5 | 2,5 | 1 + ½√3 | 1 + ½√3 | -½ | 0 |
| Source U<br>Bank U | 5 | 5 | 2,5 | 1 + ½√3 | 1 + ½√3 | -½ to 0 | 0 to +½ |

### *3.2.3.1 Discharging a Shunt Capacitor Bank*

When a capacitor bank is de-energized, there is a trapped charge. This charge has to be drained as fast as possible for various reasons, such as personnel safety, to prevent extreme inrush phenomena, but also to make it available for operation again. When there are no provisions made to drain this trapped charge, it will take very long until the capacitor voltage has dropped to a safe level. Various methods to discharge a capacitor banks trapped charge after de-energization are in use:

1. Discharging through a resistive element is the most applied method. Parallel to a capacitor a discharge resistor is connected. This resistor has to drain the trapped charge usually within 5 to 10 minutes after a succesfull de-energization has taken place. So its resistive value must be dimensioned to meet this requirement. A disadvantage is, that this resistor also dissipates energy when the bank is in operation.

The following equations characterize the discharging voltage and current:

$$u_C = U_{Trapped} \cdot e^{\frac{-t}{RC}}$$

$$i_C = \frac{U_{Trapped}}{R} \cdot e^{\frac{-t}{RC}}$$

Within Eskom a lot of capacitor bank control circuits are equipped with timers, they block any close-signal to the breaker for about five to ten minutes after de-energization, this to make certain that there is negligible trapped charge on the following close-operation. For lower voltages it is also possible that auxiliary switches are used to switch a discharge shunt resistor bank to drain trapped charges, this is an expensive method. The given discharge-equations are valid for a parallel RC circuit. In practice however again one has to take the inductance in the circuit into consideration. This inductance is however of such small value that there is no significant difference and the given equations are still valid. The value of the discharge resistance is in the order of Mega Ohms.

2. Discharging through an inductive circuit is also applied in a lot of cases. The discharge phenomena in this case are usually governed by the saturation characteristic of the discharging inductive circuit, and they result in nonharmonic oscillations. There are several possibilities for inductive discharge circuits:

   2.1. Magnetic Voltage Transformers (MVT) parallel to the switched capacitor bank or transmission line. The trapped charge is drained very fast, usually within 300 ms, with this method.

   2.2. Magnetic Voltage Transformers that form an integral part with the capacitor bank and are dimensioned to smaller values then the line to earth voltage. They are a part of the capacitor banks protection circuit. The filter bank at Apollo was equipped with such protective voltage transformers, and on top of that also a magnetic voltage transformer parallel to the bank was present.

   2.3. Line or busbar connected shunt reactors parallel to the switched transmission line. Draining of the charge goes usually according to a weakly damped oscillation. The draining can be accelerated by inserting a damping resistor between the neutral of the reactors and earth.

   2.4. A transformer-winding parallel to the capacitor bank is another possible.

   2.5. In the lower voltage ranges some utilities use an extra reactor and an extra breaker. These extra reactors are switched in parallel with the capacitor bank and form a parallel resonant circuit. This also drains the charge very rapidly, allthough it is an expensive method.

By using magnetic voltage transformers, the discharging goes so fast compared with discharging through ohmic resistors, that the shunt resistance can be ignored in the general equivalent circuit. The energy which is stored in the capacitance is dissipated in the primary windings of the MVT. As mentioned the discharging process goes according to a nonharmonic oscillation. An accurate calculation of the discharging process requires an accurate knowledge of the non-linear flux-current relationship of the MVT. This characteristic is usually only known by the manufacturer.

The DC trapped voltage, will create a linearly increasing flux in the core of the magnetic voltage transformer. This will cause the core to saturate within some ms. This results in a low magnetizing inductance which in turn allows the capacitor bank to start discharging through the primary winding of the MVT.

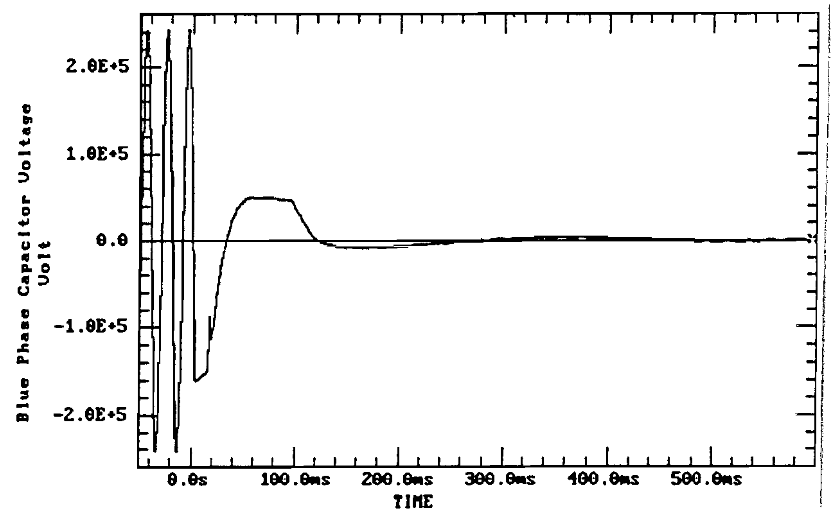


**Figure 15** - *Measured voltage at Apollo, during a discharging operation of the filter bank.*

The energy which is stored in the shunt capacitor banks or filter banks trapped charge, is now dissipated in the resistance of the primary winding of the MVT. Detailed information can be found in several papers [3.82], [3.83], [3.84], [3.85] that have been published on using magnetic voltage transformers to drain trapped charge.

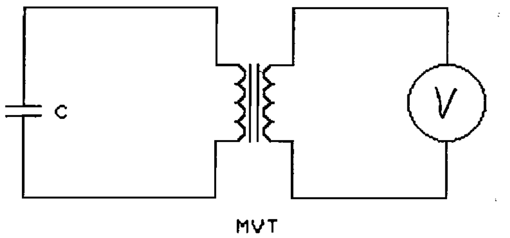


**Figure 16** - *Equivalent circuit of capacitor bank with an inductive draining element.*

## *3.3 Shunt Reactor De-Energizing*

### *3.3.1 Introduction*

The phenomena and problems that occur on the interruption of small inductive currents have been published in many papers in the last decades. CIGRE Working Group 13.02 has published the results of many comprehensive studies in some summarizing papers, of which [3.56], [3.57] and [3.58] give the most practical information for our discussion. A successful interruption results in a decaying **load side oscillation** in which the trapped energy oscillates between the load side inductance and the total load side capacitance with its inherent damping. Especially the overvoltages that can occur on de-energizing shunt reactors, got a lot of attention because they can damage the insulation of the shunt reactor windings [3.59], [3.60].

Interruption of small inductive currents is associated with overvoltages of two kinds. **Chopping overvoltages** are generated due to the current being chopped before or after the power frequency current zero, they resemble the **switching impulse stress** (250/2500 μs). **Reignition transients** occur due to the high breaker recovery voltage, they resemble the **lightning impulse stresses** (1,2/50 μs). The magnitudes of these overvoltages and their rates of change submit the shunt reactor windings to different types of risks. Current chopping overvoltages especially stress the insulation to ground and have a dominant (load-side) frequency in the range of 1 to 15 kHz. Reignition transients particularly stress the turn-to-turn-insulation and can have different dominant oscillation modes. These oscillation modes are, the **first parallel oscillation** (1 to 10 MHz), the **second parallel oscillation** (50 kHz to 1 MHz) and the **main circuit oscillation** (2 to 20 kHz). The first parallel oscillation generally only affects the immediate vicinity of the breaker and does not affect the shunt reactor windings. The main circuit oscillation is quit moderate in comparison to the second parallel oscillation and thus not regarded as dangerous for the insulation integrity of the shunt reactor. The same can be said on the load side oscillation. However, the **second parallel oscillations** that follow reignitions are important, because of the high rate of change of the voltages, when the insulation integrity is considered.

Like shunt capacitor banks, shunt reactors are usually switched daily. The associated switching transients can give a severe and repetitive daily beating to the shunt reactors insulation. Therefore since the emerged application of shunt reactors in the 1950's and the 1960's, different solutions to reduce the impact of these stresses to acceptable values, have been invented and applied.

At the moment there is an upward trend in the circuit breaker interrupting capabilities. This trend results in a decreased number of breaks per pole, and thus in a higher recovery voltage per break. This increases the risk for a reignition. One has to distinguish between ***single*** and ***multiple reignitions***. If a single reignition occurs, the current will be interrupted in the next power frequency current zero. However if a high frequency current caused by a reignition is interrupted, another reignition is possible, etc. These multiple reignitions can result in a ***voltage escalation***. Kempen [3.62] (KEMA High Power Laboratories) has measured a general trend in that the probability of restrikes increases with higher currents.

In the last decade, but especially since the 1990 CIGRE Conference Session, various papers have been published on controlling the arcing time of the circuit breaker on opening. ***Using controlled opening makes it possible to eliminate reignitions in modern circuit breakers.*** Controlled opening can only be applied with circuit breakers that have ***minimum arcing time*** which must be ***sufficiently less than a half power frequency cycle.*** Of course also the mechanical stability and the operating speed must have sufficient accuracy. By a consistent controlling of the contact parting, it is possible to control the arcing time above a certain (dangerous) minimum, and to get a current extinction at or near (with a small current chop of a few Ampere) the first occurring current zero.

Sarkinen et al. [3.63] were amongst the first to publish on controlled interruption of small inductive currents. In the last decade more papers have been devoted to the topics of controlled opening and its related aspects. IEC is presently attempting to prepare an application guide on shunt reactor switching [3.59] in which this technology is also mentioned.

### *3.3.2 Power System Characteristics*

Reignition phenomena are affected by the entire system structure, from the power-supply side of the circuit breaker, to the load-side.

***Shunt Reactor Characteristics*** - The transient phenomena that occur on a de-energization are very complicated. Therefore most of the fundamental work is based on single phase laboratory circuits. Practical situations always yield three-phase configurations. As it has already been mentioned in appendix 4, the characteristics of reactors depend to a great extent on the core design. The capacitance values are dependent on the design and construction of the shunt reactor. Due to the interaction between phases in three-phase shunt reactor interruption, the transients and the recovery voltages are affected by equipment characteristics. The type of the core and the winding connections have significant influence.

***Local System and Station Characteristics*** - The power system and the substations characteristics are also of significant influence on the phenomena during the switching of shunt reactors. Especially the power systems source capacitance is important. It is usually much bigger than the load side capacitance. In chapter 1 it was already mentioned that there are three kinds of shunt reactors connections (line, busbar, tertiary) to the power system, of which the busbar reactor is globally the most applied. Important station characteristics thus are the inductances and the associated capacitances of the connecting lines. Also any other equipment ( CVT's, MVT's, CT's, MOV's, bushings, surge arresters) that is connected between the breaker and the reactor has to be considered. For a line, 1 $\mu$H/m and 10 pF/m are used in practice. From this it follows that the inductance of a long section of line is still small in comparison to the shunt reactors inductance, however this inductance does influence the reignition process. The same reasoning is valid for the capacitance.

*Circuit Breaker Characteristics* - In [3.56], [3.57], [3.64], [3.65] *chopping phenomena* are elaborately treated. For a breaker with n gaps per pole, we can write:

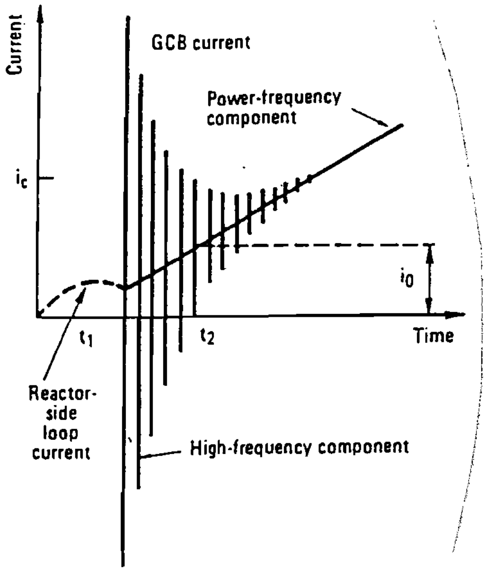
$$i_{ch} = \kappa\sqrt{n C_t}$$

$\kappa$ is the circuit breakers chopping number, it is a characteristic of the breaker. For $SF_6$ puffer breakers, $\kappa$ ranges from 4 x $10^4$ to 17 x $10^4$. The level of current chopping can be dependent on the arcing time. For $SF_6$ puffer breakers it increases with increased blast and is therefore maximum at maximum arcing time. $C_t$ is the total parallel capacitance with the breaker and depends on the reactor type and rating and on the connection arrangement. Another characteristic of the circuit breaker is the rise of dielectric strength between the breaker contacts after interruption.

It is a fact that almost all breakers will *reignite* at small contact distance and thus with short arcing times. The *reignition time-window* can be very narrow but also relatively wide. This is dependent upon different circuit breaker characteristics, such as the interrupting medium, the operating speed, etc. and thus in general on the rate of build up of dielectric withstand after an interruption. The ability of a breaker to interrupt in a current zero, depends on the frequency and the damping of the reignition current oscillation. Several scientists have discussed their findings on reignitions and subsequent high-frequency arc-extinction [3.66], [3.67], [3.68], [3.69], [3.70]. In the paper by Okabe et al. [3.71], these findings are summarized:

1. High-frequency current interruption can only occur when the high-frequency current component has attenuated and its peak touches the current zero line. This results in a strongly reduced di/dt and du/dt [3.68].
2. For high-frequency current interruption to occur, there exists a limit for instantaneous values of power frequency current on which the high-frequency current is superimposed [3.67].
3. This upper limit value decreases as the frequency of high-frequency current increases [3.67]. In figure 18 the measurement results are shown for high-frequency current interruption in a puffer-type gas circuit breaker

In figure 17 the current waveform is shown on the occurrence of a reignition. At time $t_1$ a reignition occurs, and a high-frequency current component and a power frequency current component flow in the breaker. The power frequency current flows from the power supply to the reactor, and the high-frequency current is fed by the energy in the circuits capacitances. The inherent resistance in the circuit damps the high-frequency current component, but the power-frequency current increases to its maximum amplitude as it is determined by the system voltage and the reactor inductance.



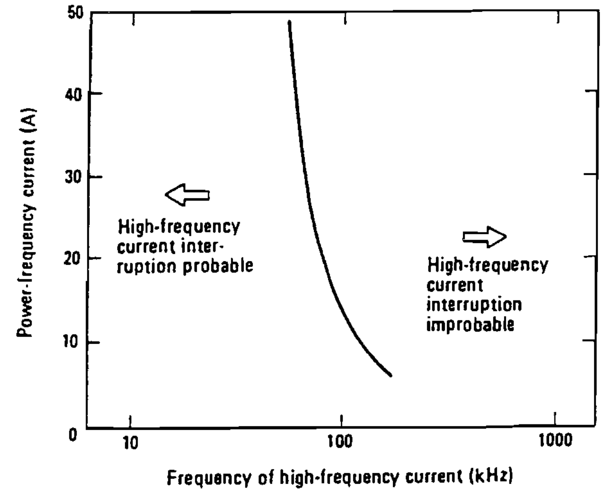


**Figure 17** - *Current associated with reignition [3.71].*

**Figure 18** - *Frequency dependence [3.71] of limit for occurrence of high-frequency current interruption.*

At time $t_2$, the amplitude of the damped high-frequency current component becomes equal to the power-frequency current component. This is the point where the peak of current touches the power frequency current zero line with a di/dt = 0 (point 1). If at time t2 the instantaneous value $i_0$ of the power-frequency current is smaller than a limit $i_c$ (point 2), then a high-frequency current interruption can occur.

Knowledge of the high-frequency current interrupting capabilities of a breaker is important in determining the circuit breakers behaviour in the field. The high frequency current interrupting behaviour affects the risk to get multiple reignitions and voltage escalation. The probability that a circuit-breaker produces repetitive or multiple reignitions after the interruption of small inductive currents thus depends especially on the di/dt interrupting capability [3.70] at short arcing times: the lower this capability is, the lower the tendency for multiple reignitions. For high-frequency currents with frequencies over 100 kHz, high frequency arc extinctions are unlikely to occur [3.69].

### *3.3.3 Switching Overvoltages and Transients*

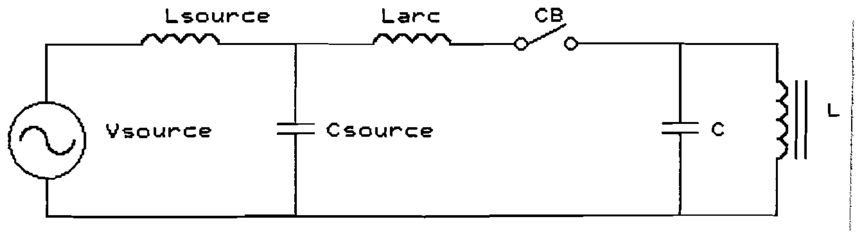


**Figure 19** - *Single phase equivalent circuit.*

At Doetinchem a 50 kV - 50 MVAr three-phase solidly grounded (three legged) reactor was field tested. Messrs Toshiba carried out field tests at Eskoms Beta Substation on a 400 MVAr - 765 kV bank consisting of three single phase (gapped core) units. For both stations the equivalent diagram in the above figure is applicable.

*Chopping overvoltages* - The overvoltage caused by current chopping can be difficult to distinguish when the interruption is followed by a reignition. Reignitions take place at small contact separations so this can be shortly after a chopping has taken place.

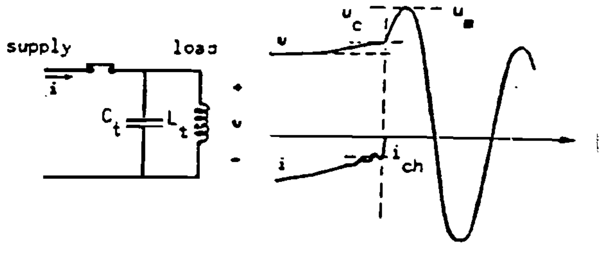


**Figure 20** - *Overvoltages at Current Chopping.*

The overvoltage that occurs on interruption of a small inductive current without reignition, is determined by the chopped current, the load-side capacitance C and the load-side inductance L. When damping is neglected, from the chopping instant to the appearance of the suppression peak $U_m$, the following energy relation applies:

$$\frac{1}{2} C U_m^2 = \frac{1}{2} C U_c^2 + \frac{1}{2} L i_{ch}^2$$

The magnitude (in per unit) of the chopping overvoltage [3.56] is defined as:

$$k_a = \frac{u_m}{u_0} \qquad k_c = \frac{u_c}{u_0}$$

Legenda:

$u_m$ = Suppression peak voltage.
$u_c$ = Value of the load-side voltage at the instant of chopping.
$u_0$ = Peak value of the phase-to-ground power frequency voltage.

The second expression gives the ratio of the load-side voltage and the peak value of the power frequency voltage. In practice the assumption is made that the chopping occurs at a moment that the supply voltage is close to its maximum and that the arc voltage can be neglected. In this case the value of $k_c$ is virtually equal to one. However this is only the case for not too small breaking current values. The following expression is then valid:

$$k_a = \sqrt{1 + \left(\frac{i_{ch}}{u_0}\right)^2 \cdot \frac{L}{C_L}}$$

Legenda:
$i_{ch}$ = Chopped current.
$u_0$ = Peak value of the power frequency voltage.
L = Shunt Reactor inductance.
$C_L$ = Load side capacitance.

Hence, for a certain installation, the overvoltage only depends on the chopped current. This expression can be re-arranged and then we get:

$$k_a = \sqrt{1 + \frac{3\,n\,\lambda^2}{2\,\omega\,Q}}$$

Legenda:
Q = Three-phase reactor rating.
$\omega$ = $2 \cdot \pi \cdot f$ = Angular power frequency.
$\lambda$ = Chopping number.
n = Number of gaps per pole.

From the last expression it follows that the chopping overvoltage only depends on the chopping number and the reactive power of the shunt reactor. The stress on the shunt reactor is determined by the maximum peak to ground voltage (this is normally the suppression peak) and the oscillation frequency. The overvoltage is **evenly distributed** along the winding, because of the relatively low oscillation frequency. This results in **low turn-to-turn voltages.**

Especially the older circuit breaker types, such as airblast breakers, caused high chopping currents which resulted in very high overvoltages. The modern (puffer and self-blast) $SF_6$ circuit breakers have significantly reduced chopping currents, because of the more favorable arc characteristic. The problem of current chopping seems to be not of high interest nowadays, this is supported by the decreasing number of series gaps per pole and also new arc quenching principles (self-blast). The discussion of overvoltages has shifted in the direction of reignition transients and high frequency interrupting capability of circuit breakers.

*Reignition transients* - In the following figure the maximum attainable overvoltages (without damping) on a reignition at the peak of the recovery voltage are given. Two cases are distinguished, a circuit breaker without current chopping and a circuit breaker with current chopping.

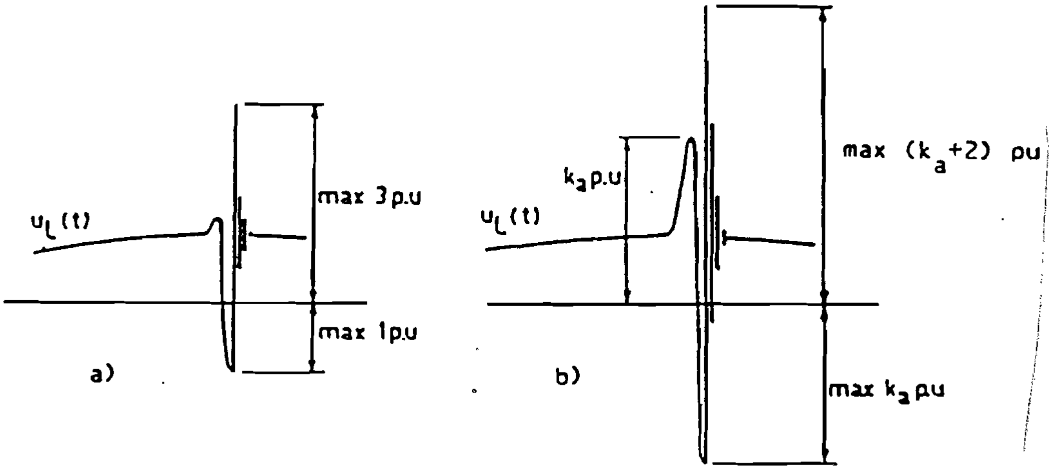


**Figure 21** - *Maximum reignition overvoltages: (a) without (negligible) current chopping, and (b) with high current chopping.*

The maximum value of the (single) reignition overvoltage to ground (in per unit) is expressed as:

$$k_p = 1 + \beta\,(1 + k_a)$$

Legenda:
$k_a$ = Magnitude of the chopping overvoltage (pu).
$\beta$ = Equivalent damping factor, normally its value is in the order of about 0,5 [3.59], [3.57] and [3.58].

The value of $k_p$ thus depends on the damping factor and the damping in the circuit.The peak-to-peak reignition transient voltage (in per unit) is expressed as:

$$k_s = (1 + \beta)\,(1 + k_a)$$

For an ideal circuit breaker, the chopping number is zero and there will be no suppression peak overvoltage and thus $k_a$ equals one. The modern $SF_6$ circuit breakers have a very low chopping level and thus a small suppression peak. Reignition overvoltages however can still reach 2 pu to ground and 3 pu peak-to-peak (for $\beta$ = 0,5).

At a reignition a **steep voltage transient** with a **very high rate of change** is created. The front time of this transient has a duration of maximum a few micro-seconds. The reignition voltage breakdown in the circuit breaker is virtually instantaneous. Thus the front time is only determined by the second parallel oscillation frequency. This frequency depends on the capacitances of the supply side and the load side networks connected to the circuit breaker pole terminals. This voltage transient is normally **not evenly distributed** along the winding of the shunt reactor, but **stresses** especially the **entrance turns with very high turn-to-turn overvoltages. The peak-to-peak value of the reignition transients can be dangerous, even in the case that a surge arrester is applied as an overvoltage limiter.**

### *3.3.4 Methods to Limit Switching Overvoltages*

Several methods are used in practice to limit switching overvoltages [3.58], [3.59], [3.60], [3.61], a short overview:

*Surge Arresters* - Surge arresters are widely applied for the protection of shunt reactors. Two types of surge arresters are generally used, non-linear resistor type arresters with series gaps and metal oxide varistors also known as ZnO-arresters. If the breaker chops at a sufficient high current level, the suppression peak will exceed the arresters characteristic, and the arrester will conduct current (or clip the overvoltage) as long as the arrester characteristic is exceeded by the overvoltage. The possibility of a reignition is thus reduced since the recovery peak is less than its prospective value.

*Opening Resistors* - Opening resistors in parallel with the main interrupting chambers are another possibility. If the main interrupter chops the current, a commutation to the resistor circuit takes place. So no current interruption has occured yet and the overvoltages will depend on the value of the resistor. The resistor auxiliary switch eventually interrupts the current. This gives a softer interruption with lower chopping currents. A breaker equipped with opening resistors will have a smaller $k_a$ in comparison with a breaker without opening resistors. A reignition may occur in either interrupting chambers, the damping effect of the resistance however will reduce the impact of them. Opening resistors can be found on the older (airblast) circuit breakers. With the modern $SF_6$ breakers (puffer and self-blast) opening resistors are found to be unnecessary because of the lower current chopping levels.

*Metal Oxide Arresters across the Circuit Breaker* - These arresters [3.72], [3.73], [3.74] are installed in parallel with each circuit breaker chamber in the same manner as a grading capacitor. They limit the voltage across the chamber according to the voltage-current characteristic of the arrester and as such they limit the rate-of-change of the reignition overvoltages. An important parameter in this case is the rating for maximum continuous system overvoltages. Also the mechanical capability of the varistor has to be considered.

*Parallel Capacitors* - The frequency of the reignition transients may be limited by installing a capacitor of a few nanofarads in parallel with the shunt reactor. In this way it is possible to ensure that the rate of change of the reignition transients does not exceed the equipments specified maximum limits. It is also possible to use a resistor in series with the capacitors. The task of the resistor is to give a more than critical damping to the reignition transient, in such a way that the transient becomes aperiodic. Hence because of this aperiodicity a current-zero after reignition is delayed. It is possible to connect the C or RC either between phase-to- ground or phase-to-phase. This method is however primarily used at medium voltages with vacuum switching devices.

### *3.3.4.1 Controlled Opening*

By applying controlled opening it is possible to eliminate reignitions in modern circuit breakers [3.59], [3.60], [3.61], [3.50], [3.71], [3.75], [3.76]. Controlled opening can only be applied with circuit breakers that have **minimum arcing time** which must be **sufficiently less than a half power frequency cycle**. By a consistent controlling of the contact parting, it is possible to control the arcing time above a certain (dangerous) minimum, so to stay outside the **reignition-time-window**, and to get a current extinction at the first occurring current zero. A contact opening in the interval from say 90 to about 150 electrical degrees before a current zero should be sufficient. Practice and various literature [3.60], [3.69], [3.70], [3.71], [3.77] sources show that the reignition-time-window is ± up to a about a few milli seconds before current zero. This window of arcing times with reignitions may be small, but still gives a certain probability to create the dangerous reignition transients. The controlled switching device has already been discussed in the second chapter. It must be noted that the required timing accuracy in this case is moderate compared with the case of energizing a shunt capacitor bank.

The following example is based on figure 22. The average opening time of a circuit breaker is in the order of about 20 to say maximum 40 ms. Lets assume that we have a circuit breaker with an average opening time of 24 ms and a timespread of ± 1 ms around the average. Lets also assume that the current wave is used as the monitoring reference signal. An opening order is given at t1. Lets assume that the intermediate

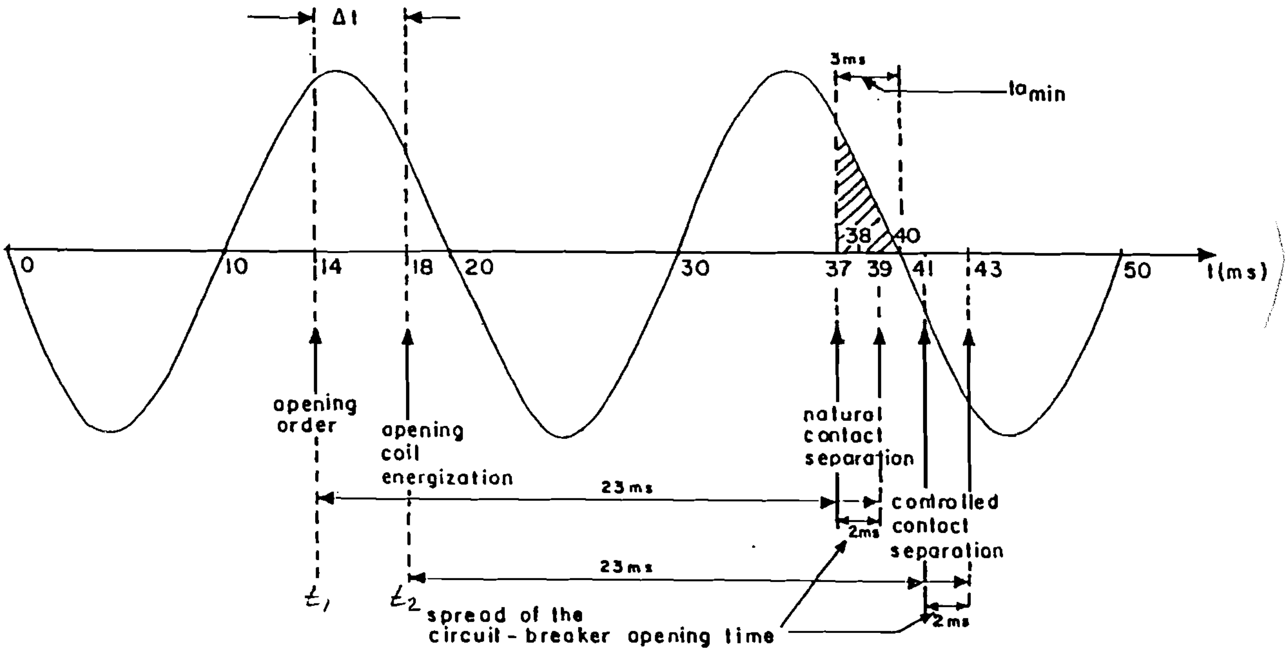


**Figure 22** - *Current wave and contact opening times in relation to the reignition-time-window [3.60].*

circuitry causes such a delay that the opening coil is energized at t2, then the separation of the contacts would occur at time (t2 + 24 ms) ± 1 ms. This means that contact separation occurs between 1 and 3 ms before a current zero. This can be completely or partly within the reignition-time-window. If we assume a maximum window of approximately 3 ms before current zero, then we have to introduce a time delay to stay out of the window. A delay of about 3 ms, would give a contact separation at (t2 + 3 ms + 24 ms) ± 1 ms. This is between 6 and 8 ms before a current zero. This should be sufficient to avoid a reignition.

Nakanishi et al. [3.76] determined the probability of reignition as a function of the arcing time. A shunt reactor interruption test was conducted in a laboratory for a 150 MVAr - 275 kV (1,6 H) shunt reactor. The TRV frequency was 1,1 kHz, which is typical in the Japanese cable systems.

In figure 23 the results of more than 1000 times of testing are presented. It can be concluded for this case, that if the arcing time is above 0,45 cycle, no reignition will occur. So if the arcing time is controlled between 0,45 to 0,5 cycle, reignition can be prevented. The controlled opening scheme is actually applied to some 300 kV GIS units in Japan.

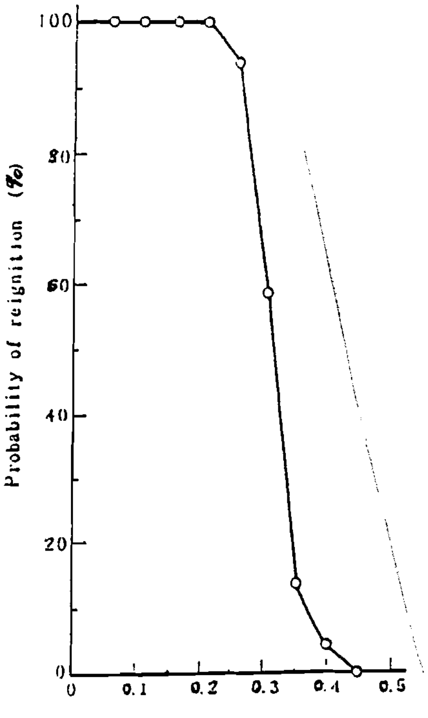


**Figure 23** - *Probability of reignition for a gas circuit breaker [3.76].*

At Tokyo Electric Power Company controlled opening [3.78] is used. They have combined the controlled opening device with a reignition detector. When a reignition occurs, the arcing time becomes longer than the designed arcing time. In the case of a malfunction of the controlled opening system, ie if a reignition occurs or a failure in the breaker the reignition detector gives an indication.

In the basic diagram of the TEPCo controlled opening system, the voltage wave is used as a reference for the controlled opening system. The tripping signals are given to each pole of the breaker with a 120 electrical degrees phase difference. The tripping signal from protection relays is given directly to the circuit breakers trip coils. Any tripping time delay may result into significant damage to the involved power equipment. TEPCo controls the arcing time at 0,4 cycle before current zero. This arcing time has been determined by considering the minimum arcing time of the breaker under the natural frequency for the applied substation. The whole TEPCo system is micro-processor controlled.

Alvinsson [3.50] also investigated controlled opening with shunt reactors. He as well used an arcing time of about 8 ms in his field test trials.

With the help of a reignition detector and a feedback to the controlled opening electronic circuitry, such as it is used at TEPCo, it is possible to control the occurrence of reignitions. However the system that TEPCo has used is quit complex, and it is based on a lot of vulnerable electronics.

Another (cheaper) possibility would be to use a reignition counter (or restrike counter for capacitive loads) and a simple straightforward controlled opening system (so only a zero-crossing detector, a time delay unit, and an output stage) without feedback from the reignition counter and also without an adaptive control for the compensation of the circuit breakers operating time spread. This can be justified by considering the relatively small time spread on opening compared with that on closing. Also the reignition-time-window is usually relatively small (a few milli seconds before current zero) compared with a half power frequency cycle. This gives a relatively wide **controlled arcing time window** of about 3 to 4 ms.

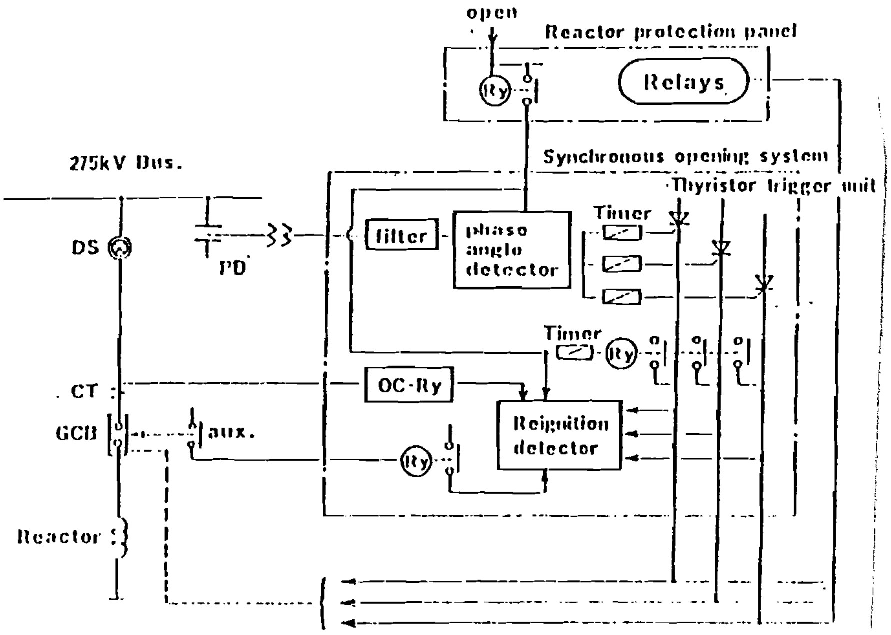


**Figure 24** - *Tokyo Electric Power Company controlled opening system for shunt reactor de-energizing [3.78].*

Reignition counters have not only been used in Japan, also in the Republic of South Africa, within ESKOM, these devices have been investigated [3.79], [3.80] to detect restriking poles on capacitor bank circuit breakers.

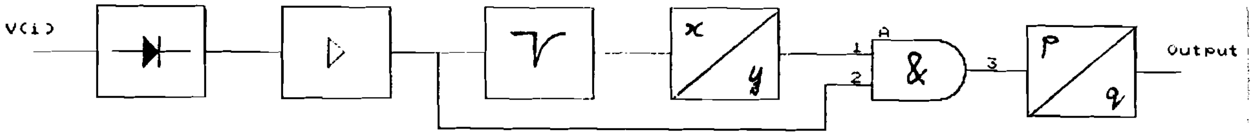


**Figure 25** - *Restrike detector principle diagram [3.79].*

The input signal is obtained from a current transformer secondary winding and converted into a voltage signal. This signal is rectified and amplified to give a steady state DC voltage while the current is present. This DC voltage feeds a delayed drop-off circuit which output is the input of an AND-gate. When the current is interrupted the DC voltage falls to zero. Normally the situation would stay like this, however if a restrike occurs things will change. When the DC voltage falls to zero, a pulse with a certain duration is initiated and applied to the AND-gate's other input. If a restrike occurs during this pulse-duration, then the AND-gate has two logical "one" signals as an input and the output will give a logical "one" signal as well. This output signal can then initiate a counting device, give an alarm, or feed a control loop of a controlled opening system. It is possible to design an active restrike detector (an extra DC power supply is necessary) or a passive configuration with storage capacitors and fast relays.

The same principle of controlled opening can also be used for the interruption of small capacitive currents [3.43], [3.77], [3.81].

### *3.4 Summary*

For shunt capacitor bank energizing, a series damping network or a pre-insertion impedance is the most widely applied practice. The impact on the reduction of transients is determined by a suitable choice of the parameters in the damping network or pre-insertion impedance. Also for shunt reactor de-energizing various methods, of which surge arresters and opening resistors are the most common, have been used to reduce the impact of transients.

One would tend to say that controlled switching is a way to forget the switching problems. However in theory this might be true, but in practice the major drawback is the mechanical stability of the circuit breaker.

For shunt capacitor bank energizing it is possible to virtually eliminate or reduce to a minimum, the impact of the inrush phenomena. For single bank energizing the impact on the power system itself is the major concern. The inrush currents are usually easy to handle, but the busbar voltage suffers from a very steep voltage dip. In the case of back-to-back energizing the impact on the circuit breaker is of major concern. Very high inrush currents of about 10 up to 100 pu can flow, this can be a problem for the circuit breaker contacts. The busbar voltage is supported by the parallel bank(s) and therefore does not have such a large voltage dip as in the case of single bank switching. It is recommendable for each new shunt capacitor bank application to consider the combination of a series damping network and controlled closing. Such a combined energizing scheme covers the solution to different switching problems that can possibly occur. A difference between critical and non-critical locations can be the base for this decision. Timing requirements are stringent and in the case of malfunctioning of the controlled closing device the series damping network is always present.

Restrikes on de-energizing of capacitive loads can be prevented by controlled opening however this method is practically not applied yet. Controlled de-energizing controls the arcing time and makes it possible to prevent restrikes. Earthing of capacitor bank neutral, direct or through low voltage capacitors should be considered especially for the higher system voltages because of the reduction of the circuit breaker stresses in this case.

It is possible to eliminate reignitions in modern circuit breakers by controlled opening in the case of de-energizing shunt reactors. A simple controlled opening unit is possible because timing requirements are less stringent than for controlled closing. For the higher system voltages it is definately recommended to use controlled opening possibly in combination with a reignition detector. If a reignition still occurs, the detector can feed a timing control loop which makes that on a next switching no restrike takes place.

## *3.5 References*

### *Characteristics of Shunt Capacitor Banks*

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# Chapter 4

## Experimental Field Measurements

### *4.1 Introduction*

Field tests have been carried out in South Africa as well as in The Netherlands in order to verify the expected switching behaviour of the various circuit configurations.

In South Africa, the measurements have been carried out in cooperation with ESKOM's Technology Group (Department: Electrical Technology, Section: Power Network Technologies). In The Netherlands, the measurements have been carried out in cooperation with KEMA, Eindhoven University of Technology (Faculty: Electrical Engineering, Group: Electrical Energy Systems), the utility Delta Nutsbedrijven and the Dutch Cooperating Electricity Producers Board. The measuring equipment data for these measurements can be found in appendix 3.

At the various substation sites, voltages and currents have been measured. Voltages have been measured through Haefely Voltage Dividers or by using Magnetic or Capacitive Voltage Transformers. In the case that voltage transformers were used, also their transfer function has been determined. Currents have been measured by using the substations current transformers or through special current transformers.

### *4.2 Measuring techniques*

Transient measurements in substations require very stringent instrumentation techniques. Especially the interfacing techniques and the coupling techniques are extremely important in the determination of a recorder data-signal of good quality.

IEC 60 [3.98], [3.99], [3.100], [3.101], [3.102] is the International Standard on "High Voltage Test Techniques". Specifications on complete measuring systems as well as on the operational procedures are described herein. Particular details on the set-up for the field measurements are given in the following sections.

### *4.2.1 Voltage Measurements*

Normally when field tests are undertaken, special high voltage dividers (Haefely) are used. They do not provide any isolation between the high busbar voltage and the low output voltage. From this output a measuring cable goes to an electro-optic transmitter, which in turn makes it possible that the data-signal is transmitted via a fibre optic link to a shielded measuring cabin. The divider must not load the circuit and must be able to cover a wide frequency range. The Haefely divider is a resistivity compensated capacitance divider. The high voltage arm(s) consists of a parallel circuit of a resistor and a capacitor. The low voltage arm is also build up from a parallel circuit of a resistor and a capacitor. The possibility to do measurements in a wide frequency spectrum is obtained by making the divider ratio time constants of the total high voltage arm equal to that of the low voltage arm.

It is good practice to do a step response test on dividers to determine their response time prior to measurements. Especially after any alterations to the dividers this should be done. During the measurements on the shunt capacitor bank at Apollo a faulty resistor was found in the low voltage part of one of the dividers. This was detected during the measurements. The faulty resistor expressed itself in a continuous rise of the trapped charge voltage after a de-energizing operation.

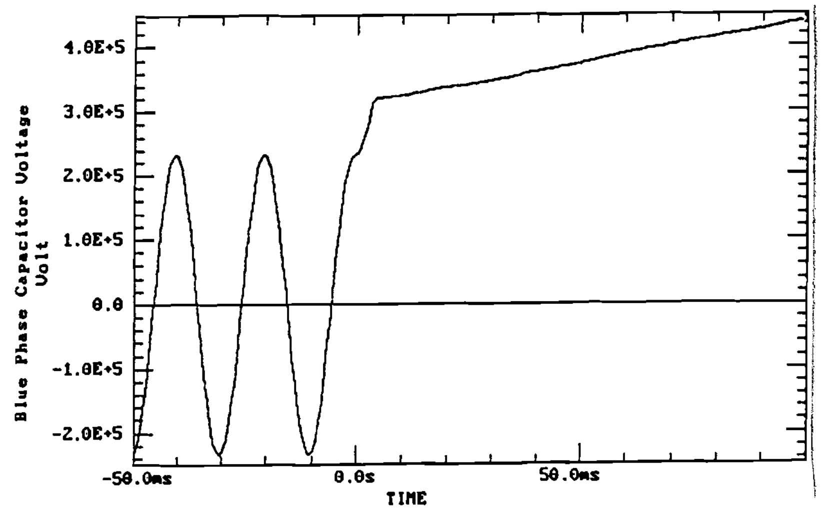


**Figure 1** - *Trapped charge voltage waveform on shunt capacitor bank de-energization as it was measured with the faulty Haefely divider.*

During the shunt capacitor bank measurements at Apollo two of the capacitive voltage transformers (White Phase and Blue Phase) were also monitored in parallel to the response of the Haefely divider. This output of the CVT's gave at the first look a strangely distorted signal.

A capacitive voltage transformer can be seen as a tuned circuit which is able to generate transients of its own during fast changing conditions. In the equivalent diagram of a CVT the elements of a band-pass filter are present, with the power system frequency of 50 Hz in the region of the mid-band. On energization of the capacitor bank the CVT will have two oscillation frequencies. These transients are superimposed on the system voltage. One of them is much lower than the power system frequency and exists between the series capacity and the magnetizing reactance (iron-cored).

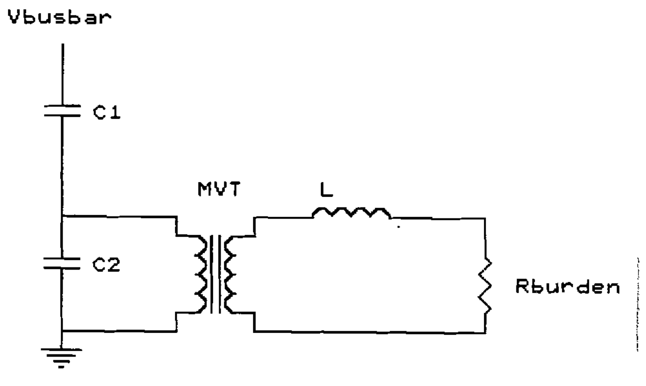


**Figure 2** - *Equivalent circuit diagram of a capacitive voltage transformer.*

The other one has a oscillation frequency which is higher than the power system frequency and is determined by the series reactance and the leakage capacitance. The severity of these transients are dependent on the point-on-wave at which the sudden voltage change happens. The time-span of the transients is dependant on the damping which is present in the circuit. The phenomena that were monitored with the CVT's are closely related to the complicated ferroresonance [3.106] phenomenon. The reader is referred to the appropriate literature for more background on this phenomenon.

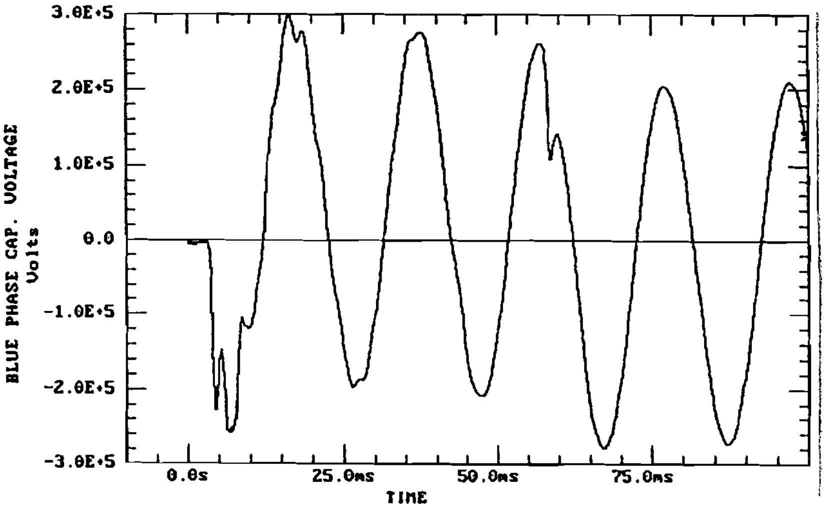


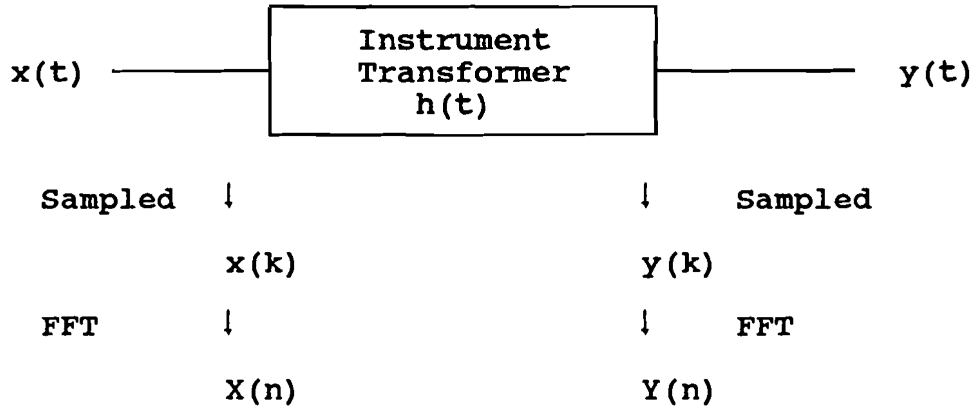
**Figure 3** - *Load side voltage on shunt capacitor bank energization at Apollo Substation, as it was measured with a capacitive voltage transformer.*

### *4.2.1.1 Transfer Functions of Voltage Transformers*

Within ESKOM, instrument transformers have been used in the past during various experimental field measurements to obtain data on voltage and current transients. However no evidence has been found that the used instrument transformers for these transient measurements are suitable and or acceptable. For shunt capacitor bank transient measurements, the frequency range up to say about 1 to 2 kHz is of interest with respect to the magnitude and phase of the measured output signal.

The behaviour of a linear system with one input and one output can be described with an impulse response h(t) or its transfer function H(jω). The method of system characterization by the analysis of its frequency behaviour is called Frequency Response Analysis (FRA) [3.94]. This relatively new technique is primarily used in the field of power transformer testing and diagnosing. A transformer possesses some major resonances which are governed by the constructional parameters (internal capacitances and inductances) of the transformer. An FRA can be used as a fingerprint for a transformer. If differences are to be found in successive FRA-tests over a certain period of time, a mechanical change inside the transformer has occurred.

A method to determine the frequency transfer characteristic of a voltage transformer would be to use a signal generator with an output voltage of a few hundred volts and a variable frequency, and to measure the input to output voltage ratio for the interested frequency range. This method is very well suited in a "clean" laboratory environment, and only for a limited frequency range. If no tranfer function correction is to be applied by means of software, this method can be used. The FRA technique can also be applied for testing instrument transformers [3.97]. The principle of the frequency transfer calculaton is as follows:



$$H(n) = \frac{Y(n)}{X(n)}$$

With the FRA technique for testing instrument transformers in the substation yard, an impulse source is used with a much higher input voltage to obtain a reasonable output signal. This is of course necessary because the 50 Hz ratio for a power transformer is only in the order of say up to about 10 : 1, but for an instrument transformer this can easily be in the order of 1000 to 6000 : 1.

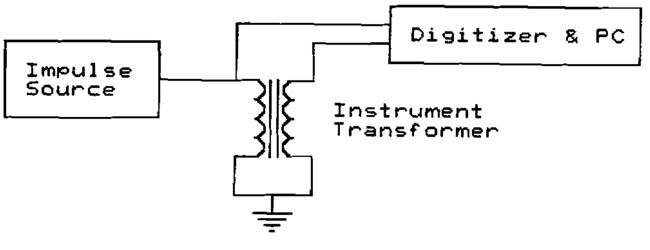


**Figure 4 -** - *Test set-up for a Frequency Response Analysis.*

The input and output voltages for the instrument transformer are sampled by a digitizer and stored for further processing. The two signals that are recorded in the time domain are then processed with the computer, using a Fast Fourier Transform algorithm. For each signal two functions are generated namely both the amplitude and the phase as a function of frequency. The transfer function of the voltage transformer can be determined by dividing the frequency spectrum of the output signal by the frequency spectrum of the input signal. Now we have a graphical function that describes the transformers ratio and phase at each frequency in the frequency spectrum.

With the help of this transfer function the resonant frequencies of the instrument transformer are known, and the voltage transfer at higher frequencies can be compared to the transfer at 50 Hz. The transfer is independent of the waveform of the test pulse, and responds only to the frequencies contained in the pulse. The input signal must contain energy spread over the frequency range of interest but also must be easily producable.

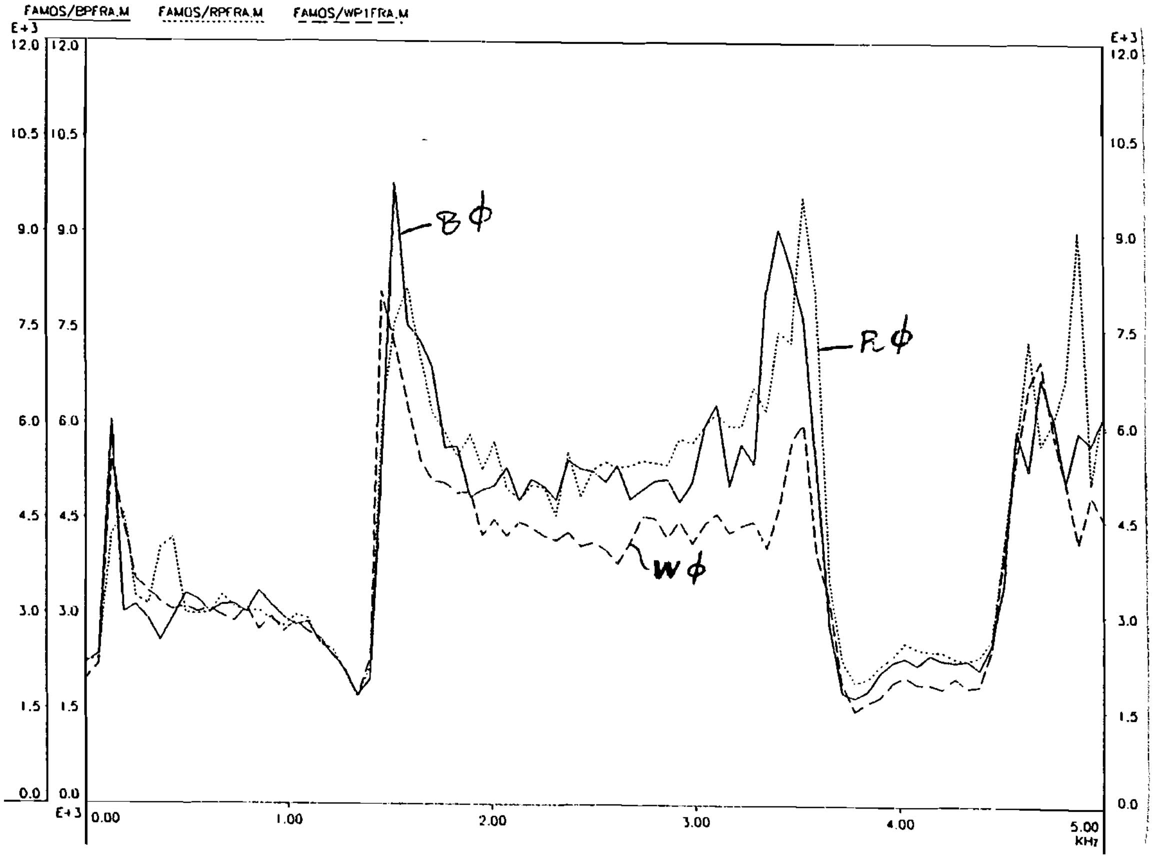


**Figure 5** - *Measured transfer function of a 275 kV Voltage transformer at Apollo Substation.*

The following results have been obtained for the 275 kV magnetic voltage transformers that were used for measuring the load side voltage during the filter bank measurements:

| | Red Phase | White Phase | Blue Phase |
|---|---|---|---|
| Highest frequency | ≈ 1000 Hz | ≈ 1000 Hz | ≈ 1000 Hz |

The following results have been obtained for the 275 kV magnetic voltage transformers that were used for measuring the busbar voltages during the shunt capacitor bank measurements:

| | Red Phase | White Phase | Blue Phase |
|---|---|---|---|
| Highest frequency | ≈ 1200 Hz | ≈ 1200 Hz | ≈ 1200 Hz |

The input voltage pulse was directly applied, the output pulse was measured from a free secondary winding (275 kV : 110 V). It must be reminded that we have undertaken no effort in investigating any transfer function correction algorithms as this was not the aim of our investigations. We were only interested in the frequency range that can be used directly without any software "juggling" having to be applied for corrective purposes. With these corrective algorithms, it is possible to extent the frequency range to be used for transient measurements.

Sensitivity to the burden impedance has not been investigated. However it was reported by Sakis Meliopoulos et al. [3.97] that sensitivity to burden impedance is small over most of the frequency range except for the regions near the transfer function resonance peaks. They investigated the frequency range of 60 to 1500 Hz, for instrument transformers in the 230 kV to 765 kV voltage range. They conclude that the magnetic voltage transformers can be used in this frequency range, but that a transfer function correction algorithm must be applied. They do not give the highest frequency for which a certain instrument transformer still shows linear behaviour with an acceptable magnitude and phase error.

Moraw and Brauner [3.96] also investigated the high frequency behaviour of instrument transformers. They came to the conclusion that there are big differences in transfer functions between different types of instrument transformers ($SF_6$ VT and conventional MVT). From about 300 Hz corrections have to be applied.

At the moment similar investigations are done with a Dutch utility in cooperation with KEMA. Their results so far agree with the results as they have been measured at Apollo. The general trend has been observed that magnetic voltage transformers for the lower voltage ranges have a bigger "linear' frequency range then the ones for the higher voltages.

Capacitive voltage transformers or better capacitively coupled magnetic voltage transformers cannot be used at all for transient measurements. Several units were tested. Each unit was subjected to three tests, namely the capacitive divider only, the magnetic voltage transformer only and the complete unit. The capacitive divider shows a good linearity over a large range up to more than 10 kHz for all tested units. The magnetic transformer (22 kV : 100V) showed linear behaviour up to 1,5 kHz. The combination of both, so the complete unit, showed resonances at different relatively low frequencies (600 Hz) as compared with magnetic voltage transformers.

Allthough the units were all of the same type, differences in transfer characteristics were found. This is most probably due to small differences in the manufacturing process due to different craftmanship but also because of the different constructional features that are possible [3.103], [3.104], [3.105]. Also the "suffering" of the instrument transformers during their service life so far must have had an impact on these differences. This can also be said of course for MVT's allthough no significant differences were measured. Altogether this lead to the conclusion that capacitive voltage transformers are not suited for frequencies higher than the power system frequency of 50 Hz.

However the linear behaviour of the capacitive divider opens the gate to another option, namely to use these dividers for voltage measurements in stead of using the haefely dividers. This trick has been succesfully used by several scientists so far. Generally there are different suitable capacitors available in a substation:

1. Capacitors of capacitive voltage transformers.
2. Carrier frequency capacitors.
3. Capacitive tappings of current transformers.
4. Capacitive tappings of bushings [3.92].

Using one of these options will always be preferrable above the use of a Magnetic Voltage Transformer.

It must be mentioned that instrument transformers are designed and constructed to operate correctly at the fundamental frequency of the power system. Their behaviour at higher frequencies will usually be completely different. As the frequency increases resonances are introduced between winding inductances and capacitances caausing peaks and dips in the transfer characteristic. In conclusion it can be said that voltage transformers can be used, depending on the frequency range, for transient measurements. A corrective algorithm might be necessary to compensate for resonances in the lower part of the transfer characteristic. It is advisable before it is intended to use a voltage transformer to do a FRA.

### *4.2.2 Fiber-Optic Signal Transmission Links*

These links have been used for measuring data transmission from close to the measuring point to the shielded measuring cabin on the truck. The big advantage of this system is that it provides an electric insulation of the sensitive measuring electronics of the transient recorder from the high voltage environment. In the transmitter the measured analog transient is converted into a modulated signal (FM and AM systems are generally used), this signal is transmitted via the fibre in the form of light impulses. In the truck these light impulses are then de-modulated to an electronic signal which is suitable for processing in the transient recorder. This system was used in both South Africa and The Netherlands.

With the newly designed KEMA transient recorder, also a control signal is transmitted with the fibre optics to activate the opto-electronic data transmitter only for the actual recording time in order to reduce battery draining. The data transmitters were located directly at the high-voltage RC dividers and the current shunt outputs. This in order to reduce to measuring cable to an absolute minimum because it is prone to electromagnetic interference. The Nicolet system that is in use with ESKOM does not have this battery activating system. Nicolet states that a charged battery is able to be used for typically 10 hours.

The fibre optic link determines in this way the upper limit for the frequency bandwidth. This might be a limiting factor for signals that are recorded with the so-called fast channels. The KEMA transient recorder is provided with slow and fast channels. A record of for example a fast reignition transient (or a restrike) represents a typical application for such a fast channel.

### *4.2.3 Current Measurements*

It is common practice to record phase currents from available substation bay current transformers to provide general test information and monitoring of the test sequence. Contrary to the voltage transformers (capacitive and magnetic), in general current transformers show a good linear behaviour at higher frequencies.

The FRA method can also be applied to determine the transfer function of current transformers, however this was not done because it is general known that a current transformer is linear in the frequency range that we are interested in for our shunt capacitor bank measurements. This can be explained by looking at the construction of a current transformer. Usually the primary winding consists of just a single conductor, and the secondary has multiple windings. The resonance points in the transfer function are therefore especially determined by the secondary winding. This makes it possible that parasitic resonances will only occur at much higher frequencies than these then are encountered in voltage transformers. However it would be interesting to do a check-up on this generally accepted good high frequency behaviour of current transformers.

It must be mentioned that the manner in which the measuring cable from the current transformer burden to the optical data transmitter is connected is heavily determinant factor for the quality of the measured signal for further processing but also for the bandwidth of the current measuring system as a whole. Special resistive burdens have been constructed to overcome interference problems. A centre-tapped coaxial resistive burden is often used.

If the burden-resistor is absolutely resistive, then its voltage drop would be equal to:

$$V_{Burden}(t) = R_{Burden} \cdot i(t)$$

It is very difficult to satisfy the requirement that the burden must be purely low ohmic resistive. The equivalent diagram of a low ohmic resistor always consists of a parasitic series inductance, which gives the following voltage drop:

$$V_{Burden}(t) = V_R(t) + V_L(t) = R \cdot i(t) + L \cdot \frac{di(t)}{dt}$$

Stray inductances are represented by the inductance L and they must be kept as small as possible to minimize the inductive voltage that appears with a high rate of change of the current. Especially on energizing high inrush frequencies play an important role, and the burden that is not low inductive will cause a considerable error in the signal that is recorded. This error will express itself in a too high peak current to be recorded, this might lead to the wrong conclusions. By appropriate design and a suitable choice of geometrical dimensions a low resistive low inductive shunt can be realized. Bifilar as well as coaxial and squirrel cage constructions [3.88] are used.

For transient current measurements normally a resistive burden is connected to a (preferably free) secondary winding of the current transformer. The use of a free winding is also preferred with voltage transformers because the leads that go from the secondary connections to protection relays or that are used for metering normally will work as antennas and be prone to pick-up of interference. Usually the current transformer has of a multi secondary winding. If this is the case, the highest ratio should be used. Higher ratios require lower magnetizing current and therefore give a better "copy" of the current that has to be measured.

Also a low ohmic resistive burden is important because this gives a low secondary voltage and thus a low magnetizing current. The voltage which is developed across this resistive burden is proportional to the current that has to be measured. Normally every current transformer is bonded to the earth math of the substation. Variation of the earth math potential due to switching operations might cause parasitic possibly damaging potentials at the current monitoring system. Therefore it is preferable if a separate burden is used for measuring, that this secondary measuring burden is properly earthed at the current transformer. A common earth for all three phases is preferred in this case. This is normally not a problem as the current transformers are usually standing next to one another.

Another cause of concern might be the saturation of the core of the current transformer. If the inrush current consists of a high DC component next to the AC component, it is possible that the core becomes biased and that saturation occurs. This results in a more or less heavily distorted secondary current.

So far the shunt was indicated as having a resistive character. Usually a specially designed low ohmic and low inductance shunt is used such as the one with the coaxial configuration. This is a tubular shunt with both primary current terminals at one end, and the measuring cable terminated at the other. The measuring lead is contained within the inner tube and as such it is shielded from external flux. The low ohmic low inductance resistive burden makes it necessary to increase the secondary chains resistance. As such it will disturb the circuit being measured, but on top of that it enhances the risk of an open secondary of the current transformer, due to insufficient connections. A damaged burden can also be responsible for an open circuit.

The ESKOM measuring crew use an interposing (1 : 1) current transformer which is closed off with a burden of 1,5 Ω. This is not a good solution !

The interposing CT is prone to parasitic capacitances and inductances as it the case with the substations current transformers. Resonances may occur between the transformers inductance and the stray capacitances or the connecting lead capacitances. It also increases the length of the measuring leads as well as the shielding problems. The burden that was originally used was not suitable, in that it was not low inductive.

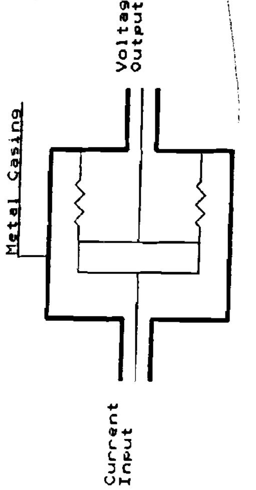


**Figure 6** - *Coaxial construction of a current shunt.*

A practical solution was used on site to improve this situation. A number of resistors was used in parallel and this parallel construction was made in such a way that it imitated to a certain extent the already discussed coaxial construction. Such a construction was also used in the early days of field testing [3.89], [3.90].

Also the shielding of the measuring cables from the substation current transformers secondary connections to the ESKOM interposing CT need more attention. Originally the ESKOM measuring crew used practically no protection against interference, this resulted in a large parasitic noisy signal superimposed on the current to be measured.

This is not necessary at all if proper measures are to be taken prior to any field tests. It is felt as an absolute necessity that this situation has to be improved immediately.

Transient recorders of good quality, however complicated to operate smoothly, are present but that is certainly not a guarantee for a good quality measurement.

In general it was felt that the measurements with the ESKOM measuring crew were not carried out in a satisfactory way. The crew was not fully aware of the specifications of the equipment, there was a serious lack of knowledge on the interfacing technique and instrumentation technique side. Also the awareness for EMC problems that can be encountered and also have been encountered was not present. Also a basic knowledge of the phenomena that can occur was lacking. In conclusion it can be said that the ESKOM field measurements were especially biased by pheripheral problems and not with the actual measuring problem itself. It is normal practice in some situations that equipment specifications are also based on the information from field tests. These strategic technical decisions in the field of transmission or substation design and optimization cannot be guaranteed with this working practice !! This situation needs immediate improvement !!

Finally some photo's of the interfacing equipment that was used at Doetinchem Substation. During these measurements the three load-side voltages were measured with KEMA in-house made RC voltage dividers suited to measure on the 50 kV system. The three phase currents were also measured by using a Pearson current transformer for each phase. Each Pearson was given a winding of 10 turns in order to produce a suitable output signal. This winding was put in series with the secondary circuit of the current transformer. From the switched object (tertiary reactor) and the circuit breaker the data was transmitted to a permanently based field cabin were the measuring equipment was temporarily installed next to the protection and metering boards. During these field tests the new transient recorder that has been developed at KEMA was used. The tests were done on a rainy day. Despite these weather conditions it was possible to do the measurements. The performance of the transient recorder on this trial run was satisfactory.

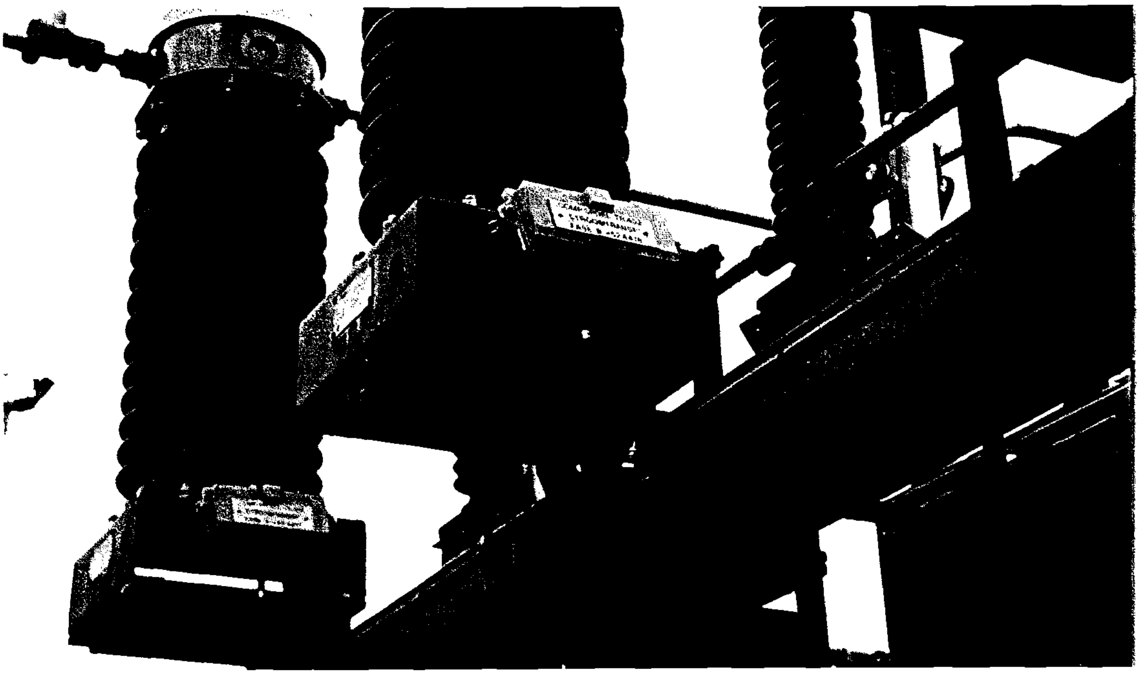


**Figure 7 -** - *A Pearson current transformer connected to one of the Shunt Reactors Current Transformers.*

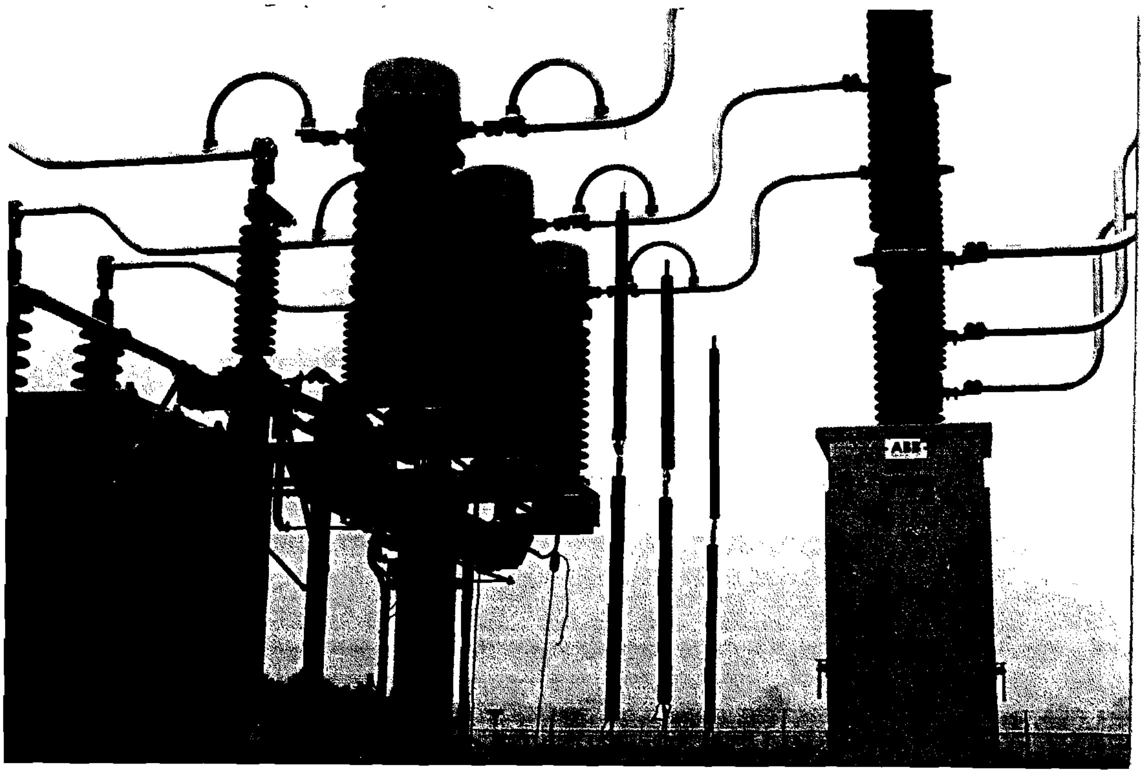


**Figure 8 -** - *Overall view, from left to right: Shunt reactor, earthing link, current transformer with Pearsons, KEMA's in-house made RC voltage dividers, the ABB three-pole operated circuit breaker.*

## *4.3 Analysis Experimental Field Measurements*

Experimental field tests have been carried out to examine the feasability of controlled switching for various applications. Random as well as controlled, closing and opening switching operations have been carried out at the following sites:

1. **28 & 29 January 1993 - ESKOM, Stikland Substation**, near Stellenbosch, Cape Province, Republic of South Africa.
2. **4 June 1993 - 12 July 1993 - ESKOM, Apollo Converter Station**, near Olifantsfontein, Transvaal, Republic of South Africa.
3. **21 & 22 September 1993 - PGEM, Doetinchem Substation**, The Netherlands.
4. **27 & 28 October 1993 - Delta Nutsbedrijven, Borssele Substation**, The Netherlands.

### *4.3.1 Stikland Substation*

*Scope* - At Stikland three 72 MVAr -132 kV, fuseless, double wye, neutral earthed via low voltage capacitors, shunt capacitor banks were to be commissioned. The capacitor banks were switched with Sprecher Energie HGF 112/1 $SF_6$ (145 kV, 3150 A, 31,5 kA) circuit breakers. The verify the transients occurring on single as well as on back-to-back operation, experimental field tests were carried out. Unfortunately only random switching operations were done because no controlled switching device was available yet.

*Measuring Programme* - Due to power system stability reasons, the local system voltage was high because of low loading of the system, therefore it was not possible to do a sufficient number of switching operations. On top of that also severe problems were encountered with the measuring and interfacing equipment on site during the measurements. These problems ranged from insufficient preparation for the field tests in Johannesburg up to false triggering of the measuring equipment on several of the only few allowed switchings. The insufficient preparations expressed themselves in lack of knowledge on the Nicolet system and that no sufficient countermeasures were taken against pick-up of interference. The Nicolet in the truck was fed by the substation power supply (380 V) through an Un-interruptable Power Supply (UPS).

At later field tests at Apollo it became clear that the UPS was malfunctioning and as such provided no sufficient separation from the substation power supply. After this discovery it was decided to do all the coming measurements at Apollo with the on-board diesel-generator set as a power supply. This was the solution for the false triggering of the Nicolet. Despite all the problems that were encountered during the field tests the useable data on the events given in table .. have been recorded and processed by the Power Network Technologies Department of Eskom's Technology Group.

The recorded measurements data that have been printed out can be found in appendix 6.

**Table 1** - *Recorded events during field tests at Stikland Substation.*

| Test No | Bank No 1 | Bank No 2 | Bank No 3 | Figure |
|---|---|---|---|---|
| 1 | Energize | Out | Out | 2 |
| 2 | De-energize | Out | Out | 3 |
| 3 | Energize | In | Out | 4 |
| 4 | In | Energize | Out | 5 |
| 5 | Energize | In | In | 6 |

***Experimental Set-Up*** - See appendix 6.

***Test Results***

Test No 1 - This was a case of single bank switching. The maximum value of the monitored overvoltage on this energization was 149 kV (1,38 pu). The transients damped out within one period. The most severe inrush lasted for about 2 ms. A maximum value of 5,2 kA was measured for the inrush current. The inrush frequency based on the current wave-forms was about 3 kHz, this is very high. The current from neutral to earth via one of the neutrals low voltage capacitors showed a maximum of almost 800 A, but also died out within about 2 ms to zero current. The unbalance inrush current showed peaks of 2,4 A and -1,5 A respectively and especially shortly after energizing a high frequency phenomenon was measured, also this current died away to about zero. The maximum neutral point voltages were 245 V and 224 V respectively. A relatively long transient phenomenon is present which dies out after about 1 cycle.

Test No 2 - This was a single bank de-energization. The capacitor bank trapped voltages decay in an exponential way to zero voltage. From this picture it is clear that the poles not operate simultaneously on opening. The non simultaneity between the first and the last pole to clear is about 6 ms. Unfortunately it was not possible to verify this by no-load tests or by another recording. About 100 ms after de-energization, the trapped charge is decayed from 110 kV to about 29 kV. From this it followd that the time constant is 75 seconds. The currents interrupt nicely in a current zero. The trapped charges on the neutral are -413 V and -447 V respectively. In about 100 ms they decay to about -120 V. This leads to the same time constant of about 75 sec.

**Test No 3** - This was a back-to-back switching case. Bank No 2 was already switched in when Bank No 1 was being energized. The overvoltage on this occasion was 124 kV (1,15 pu). The transient on the voltage died out very fast, within 1 ms. The currents were very high on this occasion. The maximum currents were 11,1 kA and 10,3 kA for the red and blue phase respectively. From this picture it can be concluded that the pole simultaneity on closing is good. The inrush frequency read from the current wave was about 2,5 kHz, this is not possible compared with Test No 1. The transients were vanished within 1 ms. The same phenomena were seen for the neutral to earth current, the unbalance current and the neutral voltages.

**Test No 4** - This was another back-to-back switching case, in which Bank No 1 was already switched in and Bank No 2 was being energized. The collapse of the busbar voltage was clearly visible in this case, however the collapse in this case is not as bad as in the case of single bank switching. The currents were not recorded but it can be said that they are of the same order as measured with Test No 3. The character of the neutral to earth current, the unbalance current and the neutral voltages was the same as in the previous tests and as such not very interesting.

**Test No 5** - This case was also back-to-back switching but now Bank No 1 was energized against Banks No 2 and 3 that were already in service. Also here the most severe transients were damped out within a few ms, the sine-waves looked smooth again within one cycle. The neutral to earth current for this case had two maximum values of 5,8 kA and 3,3 kA respectively, but decayed within a few ms.

***Discussion of Results*** - It is clear from the previous that a lot of the work that has been carried out by the measuring crew of the Technology Group is of bad quality. These results are not acceptable ! But unfortunately this is al that we got. Most of the interesting parameters were not available after the measurements. The measurements that are presented on the print-outs are over-processed, signals are filtered and smoothed so that a nice and clean text-book-picture was presented. The particulars of the smoothing and / or filtering action were not made available. By carrying out such operations, the recorded signal is distorted in such a way that it is not possible to draw any reliable conclusions, only a trend can be mentioned. It was not possible to derive a reliable value for the inrush frequencies from the presented graphs. The obtained values as reported on the previous pages are not correct. The inrush frequency for single bank energization should be much less then the inrush frequency for back-to-back switching. The inrush currents are very high, about 20 pu, in the case of back-to-back switching compared to the nominal current. The voltage collopse with bank-to-bank switching should be less then with single bank switching. The transients died away within a few ms.

**Table ..** - *Comparison of calculated, simulated and measured values of the inrush current and frequency.*

| Source | Manual Calculations | | ATP Simulations | | Field tests | |
|---|---|---|---|---|---|---|
| Event | $I_{Inrush}$ (kA) | $f_{Inrush}$ (Hz) | $I_{Inrush}$ (kA) | $f_{Inrush}$ (Hz) | $I_{Inrush}$ (kA) | $f_{Inrush}$ (Hz) |
| Single | 3,4 | 380 | 3 | 300 | 5,2 | ⊗ |
| One Bank Parallel | 10,5 | 2370 | 9 | 2250 | 11,1 | 2500 |
| Two Banks Parallel | 14,7 | 2500 | 12 | 2440 | ⊗ | ⊗ |

As it was already mentioned, the inrush phenomenon damps out very fast. This makes it difficult to estimate the inrush frequency from the measured data. It was not possible to do any further processing, the data was available but the test reference lists as they were made on site were lost. The capacitor voltages of Test Numbers 1, 3, 4 and 5, and the currents of Test No 2, showed spikes. These spikes were most probably generated by extraneous operations beyond our control. They did not occur at random but in the same comparable situations for different tests. It was not clear what caused these spikes.

*Conclusions* - It is clear that single bank switching presents a worst case condition for the power system and its connected equipment. The busbar voltage collapse is considerable and the inrush current moderate. The steep collapse of the busbar voltage can give rise to travelling wave phenomena and subsequent high overvoltages. Back-to-back switching represents a worst case condition from the circuit breaker point of view. Very high inrush currents of high frequency can damage the circuit breakers contacts on repetitive operations. Especially in the case that two banks are already energized and the third one is to be energized.

Seen from the measuring point of view, the measured values for the current can not be seen as definite maximum values. This has several reasons. One important factor is the interposing current transformers burden, this burden was not low inductive. The point-on-wave that the energization took place was determined at random because no controlled switching was used during the field tests. Some plots do not give any information at all because they are plotted with the wrong scales. In general the measurements are of poor quality. During these measurements many remarks were made on how to improve the situation for future field tests.

### *4.3.2 Apollo Substation*

Apollo was used as a substation in the main transmission system during the field tests. Due to the political situation it was not possible to run the normal station facilities. In normal operation Apollo should function as a Convertor Station. It is intended to re-commission the Convertor Station again in early 1996. It is a well known fact that the process of HVDC conversion is accompanied by two effects, namely the generation of harmonics but also the consumption of reactive power of rather more than half the active power converted. Hence at Apollo shunt filter networks and shunt capacitor banks are available.

Each filter branch consists of a resonant RLC series circuit which has a low impedance at a given frequency. The filter can act as a compensator of the reactive power absorbed by the convertor (at power frequency) and as a harmonic filter at the same time. The total amount of reactive power installed is directly related to the voltage regulation of the AC network. At Apollo about 600 MVAr is available from shunt capacitor banks, whereas the filters represent about the same amount of reactive power.

A representative parameter of a filter is its quality factor Q at its tuned frequency. A high Q filter gives a large increase in the filter impedance in the case of detuning. At Apollo the quality factor is 100. The inductances are equipped with on-load tap-changers, this makes it possible to tune into the harmonic frequency. Especially the capacitors of the filter change their value as a function of temperature and age.

#### *4.3.2.1 Filter Bank Measurements*

*Scope* - A 200 MVAr - 275 kV filter bank, with filter branches for the 5th, 7th, 11th and 13th harmonic and a high pass branch were used in the field tests. The filter was switched by a Delle PK4 airblast breaker and at the moment it is used as a capacitor bank for reactive power support. The scope was to do verify the transients occurring on single as well as on back-to-back operation with experimental field tests. Unfortunately only random switching operations were done because no controlled switching device was available yet.

*Measuring Programme* - The filter was energized as a single bank, or back-to-back with a 150 MVAr or a 300 MVAr shunt capacitor bank respectively.

*Experimental Set-Up* - See appendix 7.

*Test Results* - In appendix 7 a tabular overview is presented of the measurements that have been recorded, as well as an overview of the maximum values of voltages and currents on energizing are given.

*Discussion of Results* - 12 shots out of a total of 55 were not recorded completely, this is almost 22 %. Obviously this is too much and this situation needs drastic improvement. The stated reasons for not recording an event can easily be eliminated. The false triggering events were the same as at Stikland. Though this problem was known, no steps to investigate on how to solve this problem were undertaken. Only during the shunt capacitor bank measurements the problem was more less located to be the power supply to the truck. The Nicolet in the truck was fed by the substation power supply (380 V) through a not properly functioning UPS.

It was decided to do all the coming measurements at Apollo with the on-board diesel-generator set as a power supply. This was the solution for the false triggering of the Nicolet. Another serious problem that has to be solved is the shielding of the measuring cables and the connections to the measuring terminals. Far from sufficient shielding was used and also the connections made were questionable. This practice was responsible for the fact that all the current measurements were heavily contaminated with a noisy signal.

In the Nicolet data-processing-software smoothing and filtering functions can be used to polish up the signal. However this polishing up of the signal should not be used because important basic measuring data will be lost. The socalled initial transient making current, which is usually present and of very high frequency, will be lost. Also the inrush current will be distorted. Possible pre-arcing behaviour of the breaker will be camouflaged. Especialy on de-energizing the noisy signal is a problem. The amplitude of the noisy signal is so significant that no information can be obtained on any arc-instabilities or the chopping behaviour of the breaker. Again the remark that if smoothing or filtering is used, data will be "damaged" and a wrong picture on the breaker behaviour will be obtained.

There were no significant differences between the single and back-to-back switching events. The filter bank has relatively large inductances in its different filter branches, ranging from about 8,8 mH up to about 226 mH. These values are large compared with the source impedance, which is in the same range as the lowest inductance in the filter, and depending on the busbar arrangement. Each phase of the filter branches can be seen as a single phase RLC series circuit. Despite this it is not possible to make a statement on a possible worst case situation.

It appears that the maximum current lies around 3 kA, but also here the current shunt was not of a low-inductance, low resistance type so some caution must be used when interpretating the maximum current values. The currents in each phase of the different branches are superimposed, this gives a highly distorted current wave form. After the decay of the transients, the currents are smooth sine-waves. The overvoltages are also very moderate. The maximum measured overvoltage was 1,34 pu, all the other values are much lower. So the overvoltages are also not a real cause of concern. The decay of the transients takes quit long because of the relatively large time constants in the filter branches. Based on this information it can be said that from the viewpoint of inrush-currents and overvoltages, it is not very interesting to use the controlled closing technology for the filter bank. However the steep fall of the busbar voltage will stress insulation.

Certain types of equipment, like electronic equipment synchronized from the network voltage (a controlled switching device), are sensitive to voltage wave distorsion. When monitoring of the current is used, the filter current can have multiple zero-crossings within a cycle, this can give maloperation of controlled switching equipment. Voltage and / or current wave distorsions have to be considered with controlled switching. Especially in the case that multiple devices are energized within a short time-span. The probability that the inrush-transients have not died out to an acceptable level is present, this might endanger the controlled switching integrity.

**Conclusions** - Taking the relatively small inrush current peaks and overvoltages into consideration, no problems for the breaker have to be expected for either single or back-to-back switching. Controlled switching is not necessary to reduce transient levels, however if the impact of the steep fall of the busbar voltage must be eliminated controlled switching is a solution. As with the Stikland measurements, improvements on the mentioned points in the discussion is absolutely necessary.

#### *4.3.2.2 Shunt Capacitor Bank Measurements*

***Scope*** - A 2 x 150 MVAr - 275 kV shunt capacitor bank was also used for field tests. The capacitor bank was switched by a AEG S2-300 $SF_6$ puffer circuit breaker. The scope was to do verify the transients occurring on single as well as on back-to-back operation with controlled switching in experimental field tests.

***Measuring Programme*** - The capacitor bank was energized as a single bank, and back-to-back with the 200 MVAr filter bank. Controlled closing and controlled opening field tests were done. Also tests with earthing the capacitor banks neutral, in order to reduce circuit breaker stress on opening, through capacitors were carried out.

***Experimental Set-Up*** - See appendix 7.

***Test Results*** - In appendix 8 a tabular overview is presented of the measurements that have been recorded, as well as an overview of the maximum values of voltages and currents on energizing are given.

***Discussion of Results*** - These measurements also did not show any abnormalities in the behaviour of the circuit breaker during the different events. Random and controlled switching events were carried out. Controlled closing with this breaker was not possible because it was too slow but also the mechanical stability was insufficient. This showed itself of during the controlled closing events. It appeared that it is not possible do use this breaker for controlled closing purposes. Due to the slow closing speed a lot of pre-arcing was present on each closing operation. This will surely have its effect on the contacts of the breaker. The maximum measured inrush current was 4,5 kA, while the peak of the steady state current is about 0,45 kA. This is not a problem for the breaker. The maximum overvoltage was about 1,8 pu, this is much higher than in the case of the filter bank. Back-to-back operation with filter banks did not show any large increase in inrush currents this is due the large inductance values in the filter branches. Data set number 46 - CH2 has a C-O in the event column. Shortly after energization, the bank tripped. The cause of this trip was a faulty capacitor can, the fault was initiated by a loose connection which caused overheating and subsequent explosion of the connection. A photo of this faulty can is shown in appendix 3-1. The pre-arcing behaviour was responsible for serious distorsion of the busbar voltages. Long pre-arcing times have been measured. When having a closer look at the current waves it can be seen that on closing the inrush current has an intermittent behaviour. This can be related to the high-frequency arc-extinguishing behaviour of the breaker. The intermittent behavour is present on virtually all measured current graphs. However the current is not alternating in all these cases, as would be expected. It has not been possible to obtain a reasonable explanation for this behaviour. The measured current and voltage waves do not show any resemblance with ATP simulations, as with normally with ATP only ideal switches are used. The first pole to clear for random opening is also a random occurrence. Controlled opening tests (BC2 up to BC9) have also been carried out in order to check the behaviour of the breaker for short arcing times. Only arc instabilities have been measured with different arcing times. It must be said that also the opening times have a relatively large time spread and therefore also here it is very difficult to obtain a precise point-on-wave opening control. The neutral point of the double wye capacitor bank is normally un-earthed. A series of tests (CE5 up to CG6) has been conducted in which the bank neutral was earthed through a combination of capacitors. 2 x 12 capacitor cans that are normally used on the bank, have been mounted in parallel on two frames. Each frame with capacitors was switched from a neutral to earth. This made it possible to virtually reduce the neutral voltage to much less than 10 kV. This way of neutral treatment is similar to an earthed neutral. An advantage is, that the same protection scheme can still be used.

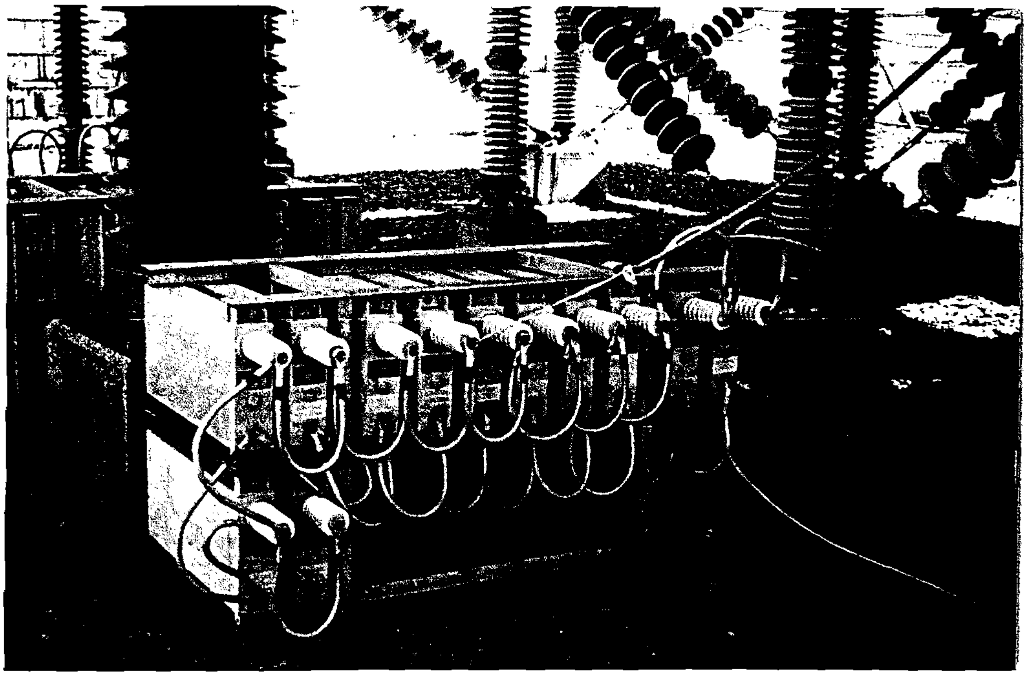


**Figure 9** - *Earthing of the capacitor bank neutral at Apollo through a parallel circuit of capacitor cans normally used on the bank itself.*

*Conclusions* - In conclusion it can be said that this breaker is not suitable to be used for controlled switching due the large time spread on closing as well as on opening. This is inherent to the pneumatic drive on the circuit breaker. There is not a big difference between single and back-to-back switching in this case, both situations seem to give about the same results. Earthing the neutral through capacitors is similar to using a direct earthing strategy. It is advantageous for the circuit breaker in the sence that it reduces the stress on opening.

### *4.3.3 Doetinchem Substation*

*Scope* - A 50 MVAr - 50 kV, tertiary switched shunt reactor was used to verify controlled opening in order to prevent reignitions. The reactor was switched by a three-pole operated mechanism with mechanical, so it was only possible to do the verification on one pole of the circuit breaker. The used circuit breaker was an ABB puffer type breaker.

*Measuring Programme* - Controlled opening operations were carried out in order to verify the reignition behaviour of the circuit breaker for different arcing times. An additional capacitance was also switched on to the source side by closing a disconnect switch that supplied a cable under no-load, in order to check its effect on the reiginition process.

*Experimental Set-Up* - See appendix 9.

*Test Results* - In appendix 9 an overview is presented of the measurements that have been recorded together with some characteristic values of the load-side voltages on de-energizing.

*Discussion of Results* - The extra capacitance was added in the form of a no-load cable with a length of about 160 meters (0,2 μF/km) and a capacitance of about 32 nF. This cable was brought connected through a disconnect switch only. This represents a potentially dangerous situation. In case of a cable-earth fault a considerable fault current will develop. The disconnect switch is not able to switch this current, so the circuit breakers on the 380 kV and 150 kV sides of the transformer have to operate. The station will be virtually shut down completely only because is this cable.

The circuit breaker was controlled on one phase only because it has a common mechanism for all three poles. After the first few shots it turned out that the middle phase was convenient, and all the following shots were based on this phase. The clock time was changed in time-steps of 0,2 ms for each successive measurement. By changing the arcing time with the setting of the clock, it was possible to make the breaker reignite after a current zero or to have a proper current extinction without reignitions. The reignition window for this breaker is very small and has a length of about 0,6 ms for the White Phase. This follows from the table with the results.

The cable influences the reignition process. Test set numbers 12 up to 15 showed this. For a clock time of 11,1 ms no reignition occurred with the cable connected whereas without the cable a reignition did occur. The cable seems to make the reignition window smaller.

The dividers that were used had a response time of about 5 μs. When stretching out the voltage wave around a reignition occurrence, it will be seen that the measured voltage equals the response of the voltage-dividers, or in other words that the actual load-side voltage changes faster than this 5 μs. The phase-to-ground overvoltages were not very high, the highest measured value was about 81,6 kV. This is not a problem. Normally an arrester will clip off any dangerous overvoltages, however the rate-of-change of the reignition transient is not changed by an arrester. If this rate-of-change is of too high value the insulation of the shunt reactor can be damaged.

In the different wave-forms three characteristic frequencies can be seen. Before a load side oscillation two frequencies have been measured of about 1,9 kHz and 2,6 kHz. The load side oscillation was about 7,4 kHz. This means that with a reactor inductance of about 0,16 H, a total load side capacitance of about 2,89 nF would be present. This agrees with values as stated in IEC's Draft Application Guide for Shunt Reactor Switching [3.16]. It was not the aim of these measurements to verify the current and voltage transients that occur on de-energizing. Therefore reference is made to the papers published in CIGRE Electra by Van den Heuvel and Papadias.

*Conclusions* - It can be concluded that it is possible with controlled opening to eliminate reignitions completely. The reignition window is relatively small therefore moderate timing stability of the breaker is allowed. An increase source-side capacitance tends to decrease the reignition window.

### *4.3.4 Borssele Substation*

*Scope* - At Borssele Substation commisioning tests of a commercially available controlled closing device have been carried out. A 100 MVAr - 150 kV un-earthed capacitor bank was the switched load.

*Measuring Programme* - No-load tests have been carried out on the circuit breaker prior to the controlled closing events, the results have been discussed in chapter 2. Two series of tests have been carried out. In the first series the capacitor bank was connected to the National Grid. During the second series the capacitor bank was connected to the Local Grid, which represented the situation as it would normally be.

*Experimental Set-Up* - See appendix 10.

*Test Results* - In appendix 10 an overview is presented of the measured busbar voltages.

*Discussion of Results* - The field tests consisted of two parts. During the first part of the tests, the capacitor bank was connected to the National Grid through a transformer (380 kV - 150 kV). This situation was used to bring the controlled switching device to the optimum timing for each phase. This device is micro-processor controlled and has a programmed algorithm to set the time delay on every next shot.
It is clear from the tables that the algorithm regulates the time delay in such a way that the optimum closing time instant is approximated better at each shot. The highest overvoltage at the last shot of the first series was about 1,30 pu. With the capacitor bank connected to the Local Grid, an enormous damping effect, due to the system loading, on the transients in the measured busbar voltages was seen. The highest overvoltage with the last shot of the second series was about 1,07 pu. In situation 1, the fault level on the busbar is 6 kA, in situation 2 this is 20 kA. The inrush frequency is about 200 Hz. In the first situation the transients decay over a long period of time (more than 6 cycles). In the second situation this is virtually within one cycle.

*Conclusions* - The measurement results are promising, though one has to be carefull. It is can not be said that the controlled closing is the way to forget the inrush problems. For the coming months every switching action will be recorded. This will make it possible in a later stage to make a statement on the practical experience.

### 4.4 Summary

Good measuring techniques are very important in obtaining a reliable impression on switching transients. Especially the interfacing techniques and the working procedures determine to a large extent the quality of the measured data.

It is also recommended to use controlled switching for all future field tests. Otherwise every shot is a random one. To determine the possible worst case conditions a lot of switching operations must be done in such a case. This can be detrimental, and is thus not desirable from a system operations point of view, but also from the involved power equipment point of view.

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# Chapter 5 - Conclusions

## *MAIN RESULTS*

*General* - The large amount of planned shunt reactive power to be installed in South Africa in the near future, necessitates to evaluate the presently used switching technologies, and to compare them to the novel controlled switching technology. The future Subsaharan Grid is characterised by remote generation and remote load centre's, this makes a carefull consideration of the possibly applicable switching technologies an absolute necessity.

*Controlled Switching* - Controlled switching is not applicable in general yet.

*Controlled Switching Device* - A device was designed and constructed and also applied in the experimental field tests at Apollo Substation.

*Characteristics of the Circuit Breaker* - The mechanical stability and inherent delay are of prime importance for a succesfull controlled switching installation. The breaker should have sufficient operating speed and the operating times should be as small as possible and on top of that have a time spread smaller than 1 ms.

*Energizing of Shunt Capacitor Banks* - A discrepancy must be made between critical and non-critical installations. A carefull assesment must be made of possible faults. Based on this and on amongst others economical factors, an appropriate switching scheme must be chosen. A failure of the controlled switching device has to considered as well. A controlled switching device cannot yetbe considered as to replace series damping reactors. The time spread must be small, preferably much less than 1 ms.

*Neutral Treatment of Shunt Capacitor Banks* - On ESKOM's fuseless shunt capacitor banks the neutral is earthed via low-voltage high capacitance capacitors. This is virtually the same (for the circuit breaker) as a direct solid earthing connection of the banks neutral, and reduces the stress on the circuit breaker.

*De-Energizing of Shunt Reactors* - By applying a controlled opening scheme it is possible to prevent current interruption at short arcing times. Thus it is possible to prevent reignitions. The spread on operating time is not a real problem in this case as the control-window for reignition-free contact-parting is relatively large. Thus no adaptive control is needed. Surge arresters are still necessary in case of a faulty controlled opening device. A reignition detector with feedback to the timing control loop is possible and actually applied in Japan.

## *RECOMMENDATIONS*

***Characteristics of the Circuit Breaker*** - Only circuit breakers with a spring drive should be considered for controlled switching purposes. More investigations are necessary on the suitability of hydraulic drives and pneumatic drives.

***Energizing of Shunt Capacitor Banks*** - For non-critical installations a series damping network is usually sufficient. For critical installations a combination of controlled switching and a series damping network is recommended. An adaptive control is recommended because the timing requirements are very strictly defined.

***Neutral treatment of Shunt Capacitor Banks*** - In order to reduce stress on the circuit breaker, it is especially recommended at the higher voltages (275 kV), to use and earthed neutral. Earthing via low-voltage high capacitance capacitors has proven to be a good method, and must be considered on future installations.

***De-Energizing of Shunt Reactors*** - De-Energizing of shunt reactors for the highest transmission voltage levels (400 kV and 765 kV) by means of controlled opening is recommended.

***Future Field Measurements*** - In all future field measurements the use of controlled switching is absolutely recommended.

## *NECESSARY IMPROVEMENTS*

***Characteristics of the Circuit Breaker*** - Circuit breaker response time measurements should be done in a consistent way. A standard protocol must be developed for adequate no-load testing.

***Future Field Measurements*** - Sufficient attention must be given to the development of adequate measuring techniques. It was generally found that interfacing techniques and working procedures must be better developed.

## *FUTURE INVESTIGATIONS*

***Future Field Measurements*** - Interfacing techniques and working procedures must be validated in the field.

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Appendices to EG/93/699

FACULTY OF ELECTRICAL ENGINEERING

Group Electrical Energy Systems

# Appendices

## Controlled switching in high voltage power networks

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EG/93/699

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Eindhoven, December 1993.

EINDHOVEN UNIVERSITY OF TECHNOLOGY

THE NETHERLANDS

# APPENDIX 1

# CIRCUIT BREAKER OPERATING MECHANISMS

### *Pneumatic operating mechanisms*

In these mechanisms compressed air stored in air receivers is used as the energy source. A motor driven compressor charges the air receiver to the required pressure after an operation of the breaker or to make up for losses due to air-leakage, therefore the air-system has to be monitored continuously. Pressures up to about 40 bar are used. In figure 1 the principle of a pneumatic operating mechanism with a compressor and de-hydrator is illustrated. The breaker is opened and closed by compressed air. A tank on the circuit breaker serves as an energy accumulator. In the field tests at Apollo Substation an AEG S2-300 single pole operated circuit breaker equiped with a pneumatic drive was used, see figure 2 for a side-view. This breaker will be discussed as an example in the following.

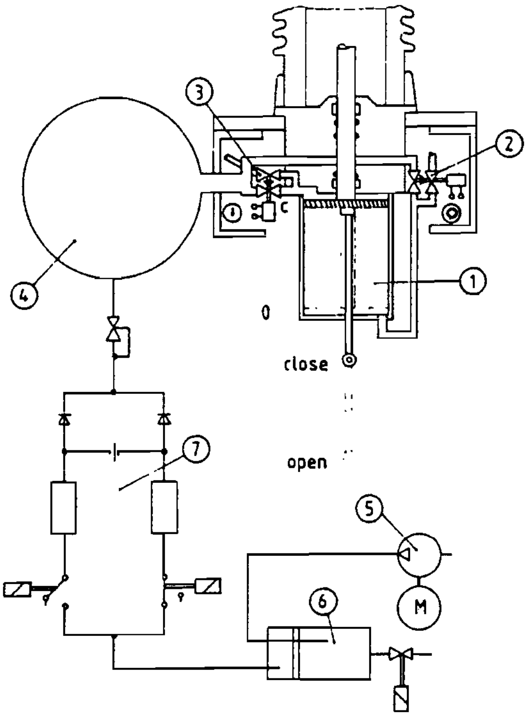


**Figure 1** - *Principle of a pneumatic operating mechanism.*

Legenda on figure 1 [2.19]:

1. Drive
2. Control Valve "Close"
3. Control Valve "Open"
4. Air Receiver
5. Compressor
6. Drain
7. Drying Unit

The S2-300 is of the single pressure puffer type. This means that the breaker itself generates the quenching medium pressure during the breaking process (puffer action). A twin head has two break chambers, both of them are mounted to the gear box, see figure 2 [2.20] and 3 [2.20]. Inside of the gear box the vertical movement of the operating rod is transferred into a horizontal movement for the drive of the breaks. The current path consists of a fixed contact which is connected to the terminal flange and of a moving contact together with the SF$_6$-puffer which both are connected to the the gear. Parallel to the two breaks grading capacitors are mounted.

Each circuit-breaker has a control system. All components like contactors, relays, etc. are placed in a control cubicle. The control system comprises of $SF_6$ density monitoring, functional lock-outs, signalling and compressed air monitoring. To avoid corrosion due to condensation a heater is installed in the control cubicle. The auxiliary switch is coupled directly mechanically to the pneumatic drive. Its angle of rotation is $90^0$. A red/green disc is directly connected to the shaft of the auxiliary switch and acts as a visual position indicator. The sliding contacts are made of copper and are silver faced. Contact pressure is obtained by a plate spring. This spring does not carry current. Each pole has its own electro-pneumatic drive with the associated control valves for opening and closing of the breaker. The drive air required for the rated switching sequence (O - 0,3 sec - CO - 3 min - CO) is stored in the air receiver of the breaker. The closing pulse is given electrically to the coil of the closing operating valve. From this valve some other pistons, valves, intermediate air receivers and a pneumatic impulse lengthener are passed until in a last stage the air moves the drive piston from the Open to the Closed position. The breaker is now closed. The travel of the drive piston operates the auxiliary switch and the position indicator mechanically via a lever. Switching of the auxiliary switch causes the Close control circuit to be electrically interrupted. Due to the pneumatic impulse lengthener, the switching action is always independent of the length of the electrical closing impulse. The minimum closing impulse duration is approximately 10 ms.

Immediately after closing of the Close control valve, the driving air is vented from the drive cylinder. Each drive is equipped with two independent trip-coils. The first pneumatic stage of the opening valve is also duplicated. The electrical tripping impulse is given to the coil of the tripping operating valve. This valve converts the electrical impulse into a pneumatic signal and again this is passed through the air system, until the drive piston moves and opens the breaker.

Two major protections are build into the controls of the breaker, namely the **anti-pumping** feature and the **pole-discrepancy** relay. The anti-pumping device prevents repeated closing and opening (oscillating) of the circuit breaker when there is a sustained Close signal and Trip signal (i.e. pumping). The pole-discrepancy relay will operate if the poles don't close or open with a certain pole simultaneity. In The Netherlands a lot of these relays are set at approximately 10 ms. ABB also recommends this setting when controlled switching of capacitor banks is used.

In figure 5 the break chamber of the S2-300 is shown in the stages during an opening action. The gas compartments of the break chambers and the support insulators are filled with $SF_6$ at the same pressure. The $SF_6$ pressure which is required for quenching the arc in the insulating nozzle is generated on the so called puffer-principle. This means that by the movement of the contacts the gas is compressed in the cylinder to a higher pressure for quenching. The stationary (fixed) contact is connected to the flange of the break chamber. The moving contact is moved together with cylinder over a fixed piston during opening, whereby the gas present in this cylinder is compressed and flows through the insulating nozzle. When breaking large currents (like the breakers rated current) the nozzle is partially blocked by the large arc. The amount of $SF_6$ which escapes through the insulating nozzle, during the arcing time up to current zero, is kept to a minimum as it is not used for quenching. With breaking of large currents a very large pressure is build up within the cylinder. This leads to a powerful flow of quenching medium shortly before current zero. The pressure caused by the arc with small currents is small. With the interruption of small currents a flow of quenching gas already occurs at the beginning of the movement of the contacts, when there is only a small pressure difference. This type of breaker thus has a switching characteristic matched to the current being switched. The dielectric strength and switching capacity of the breaker are dependent on the density of the $SF_6$ gas. The break chambers and the insulation of all three poles make up a common gas compartment.

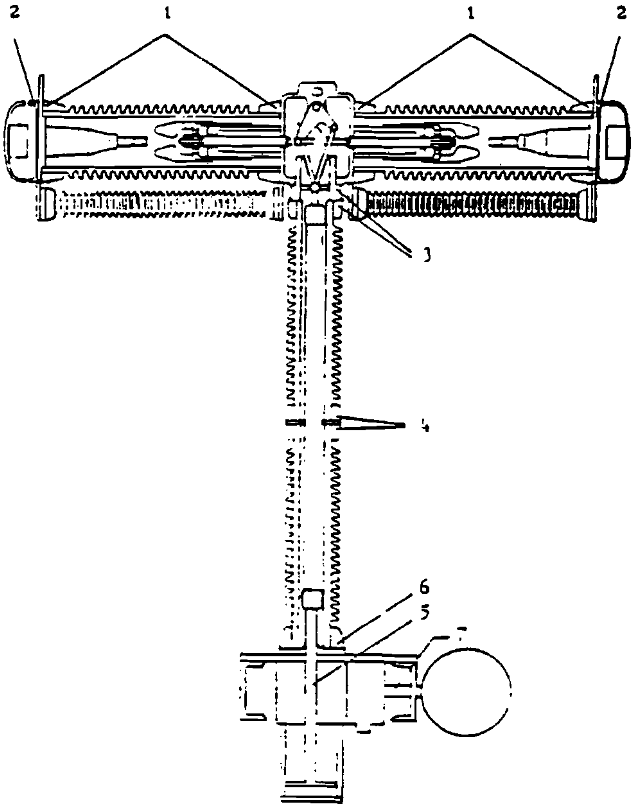


**Figure 2** - *AEG S2-300 pole column with two breaking chambers.*

Legenda on figure 2:

1. Twin head.
2. Top cover
3. Post insulator
4. Guide
5. Guide flange
6. Drive
7. Valve arrangement

Legenda to figure 5 [2.20] on page 5:

1. Top cover
2. Filter
3. Terminal pad
4. Fixed contact
5. Break chamber
6. Insulating nozzle
7. Moving contact
8. Cylinder
9. Piston

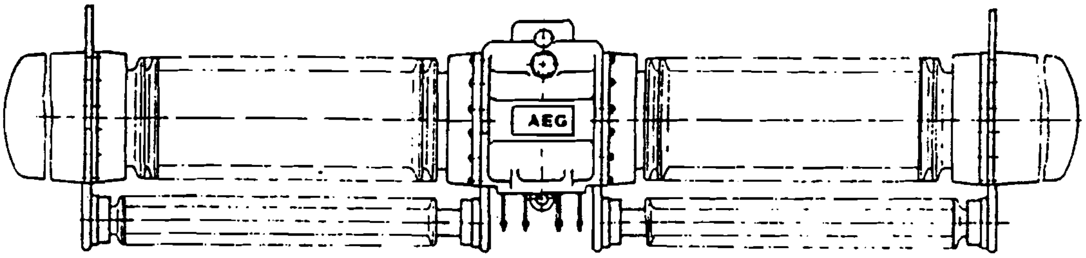


**Figure 3** - *The AEG S2-300 twin head breaking chambers with grading capacitors.*

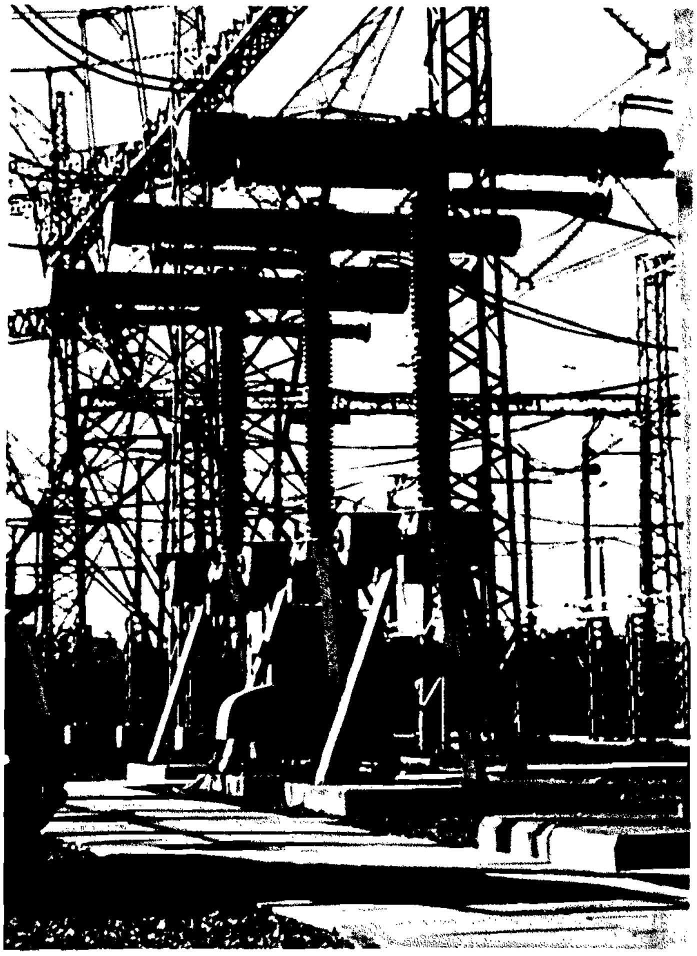
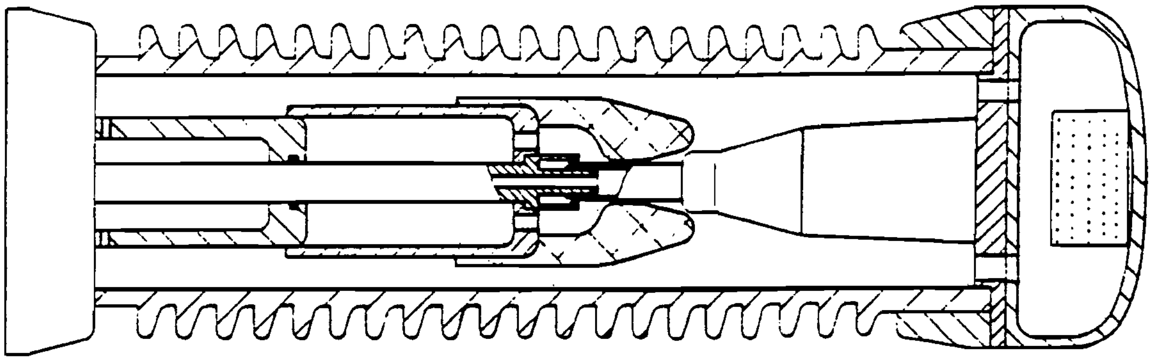
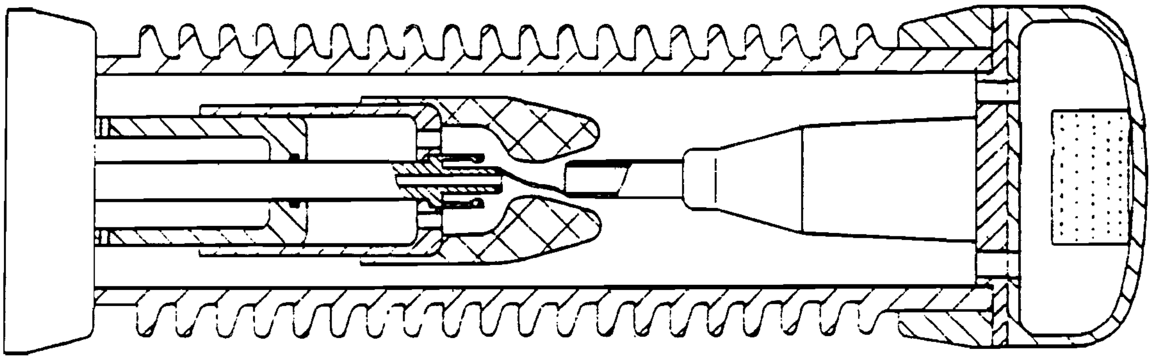


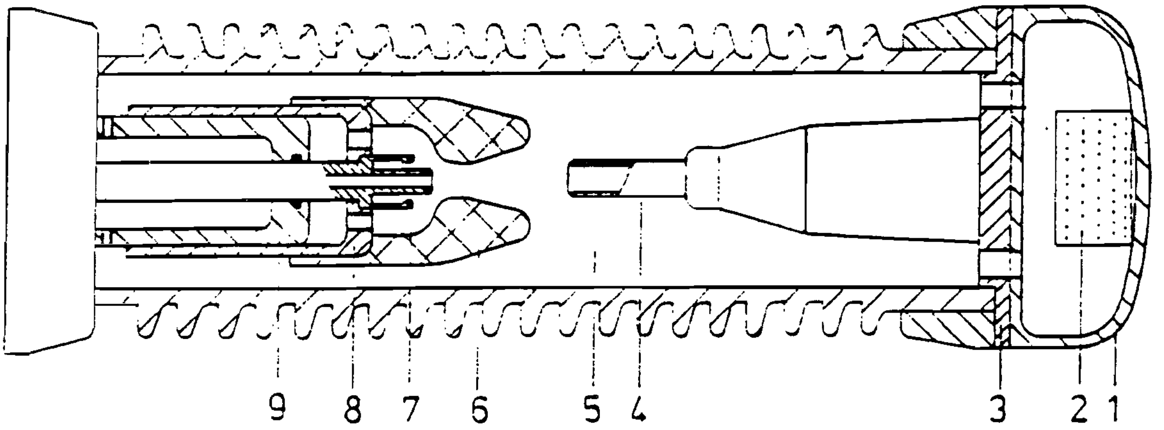
**Figure 4** - *The AEG S2-300 Capacitor Bank Circuit Breaker as it is installed at ESKOM's Apollo Substation near Olifantsfontein. Capacitor Bank Rating: 2 x 150 MVAr, 275 kV, neutral un-earthed.*



Closed



During opening

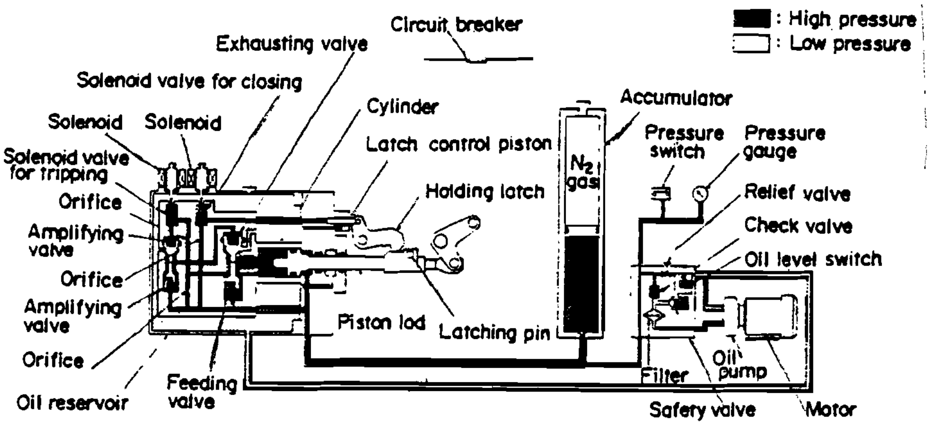


OPEN

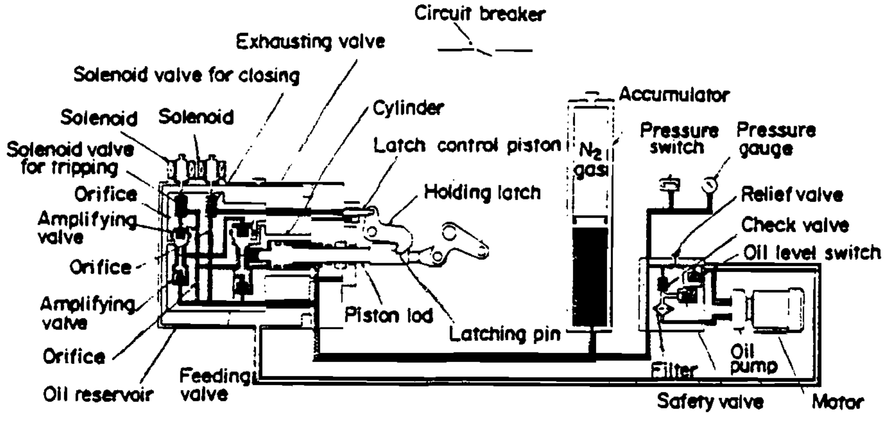
**Figure 5** - *Break Chamber section during an opening action.*

### *Hydraulic operating mechanisms*

Compressed nitrogen in a piston type accumulator is usually used as energy source. The full operating pressure can be in the order of 300 to 400 bar. The hydraulic pressure has to be monitored continuously, to recharge after an operation and to make up for losses due to leakage. Springs can also be combined with this operating mechanism, they are used as an energy source. The breaker is both closed and opened by hydraulic means. Damping of the closing and opening motion is also by hydraulic means. During the field test that were carried out or witnessed no circuit breaker with a hydraulic mechanism was used.



(a) Closed position



(b) Open position

**Figure 6** - *Principle of an electro-hydraulic operating system [2.21].*

*Spring operating mechanisms*

These mechanisms [2.22], [2.24] store their energy in springs. These springs can be of the helical or spiral type. Also disc springs are used. Usually the closing spring is charged by a motorgear train arrangement of some type. A combination with hydraulics is also possible. The release of the closing spring means that the circuit breaker contacts are closed. Usually at the same time the separate opening spring is charged. The only monitoring that has to be applied here is the indication that the springs are charged. In the field tests at Stikland Substation a Sprecher & Schuh HGF 112/1 three pole operated $SF_6$ circuit breaker was used. An interesting thing in the type test report supplied by the manufacturer [2.23] is the statement that the breaker is restrike free, with arcing times ranging from 0 to 10 ms, for different voltage and current conditions. Unfortunately we had no equipment available on site during the field tests to perform controlled switching and to check this statement. In stead of controlled switching a small number of random switching tests have been done. It was only possible to do a few switching operations because of system-stability reasons and also due to problems encountered with the measuring equipment.

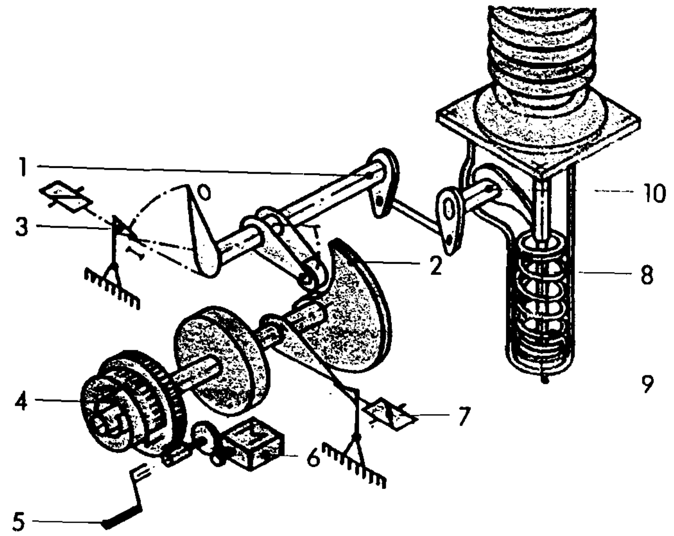


**Figure 7** - *Principle of motor-spring-storage mechanism.*

Legenda on figure 7:

1. Cam follower shaft
2. Cam
3. Trip latch and solenoid
4. Closing Spring
5. Hand cranck (for emergencies)
6. Spring winding motor
7. Close latch and solenoid
8. Trip spring
9. Mechanism housing
10. Pole shaft with seal

# APPENDIX 2

# ENERGIZING OF CAPACITIVE AND INDUCTIVE LOADS

## *GENERAL*

To understand the basic phenomena of energizing inductive and capacitive loads the optimum and the worst case conditions will be deducted in the following.

The voltage sources are represented as a (co)sine wave of
basic system frequency. The following expression is used for the source voltage:

$$u(t) = U_{peak} \cos(\omega t + \psi) \qquad (1)$$

In this expression:

$\omega$ = Basic system frequency [rad/s], this is

$$\omega = 2\pi 50 \ [rad/s] \qquad (2)$$

$\psi$ = The phase-angle of the voltage at time t = 0 [rad];
$U_{peak}$ = The maximum value or amplitude of the voltage [V].

The current can be expressed as follows:

$$i(t) = I_{peak} \cos(\omega t + \psi - \varphi) \qquad (3)$$

In which: $\varphi$ = The phase-angle between the voltage and the current [rad].

We can deduct differential equations for the current with time after a switching operation in a circuit has taken place. This differential equation can be solved by dividing the current into two components. One of the components which satisfies the differential equation is the steady-state current which developes under the action of the voltage impressed on the circuit. The other component is also determined by the differential equation for the circuit, however the source-voltage must be taken as zero. This component changes with time as if the source-voltage is replaced by a short connection. No driving voltage is present for this second component, it vanishes gradually. It represents a current that only flows for a short time and which intervenes between the current immediately before and some time after the switching operation. Together with these transient currents also transient voltages develop at the various parts of the circuit. These transient voltages are independent of the source-voltage and they decay with the say time-constant as the transient currents.

The total switching transient can be expressed as in the following equation:

$$u = f(i, \frac{di}{dt}, \int i\,dt) \tag{4}$$

As explained before we split the current in a steady-state part (i') and a transient (i") part:

$$i = i' + i'' \tag{5}$$

Equation (5) subtituted in equation (4) gives:

$$u = f\{\ (i' + i''),\ \frac{d(i' + i'')}{dt}, \int (i' + i''dt)\ \} \tag{6}$$

If the capacitance C, the resistance R or the inductance L (or M) are not constant, no subdivison into transient and steady-state parts of the differential equations (because then they are not linear any more) is possible. In the case that the inductance L, the resistance R and the capacitance C are constant, these differential equations can be split in two components:

$$u = f\ (i', \frac{di'}{dt}, \int i'dt) \tag{7}$$

for the steady state or stationary current which developes under the action of the source-voltage u long after the switching operation has taken place.

$$0 = f\ (i'', \frac{di''}{dt}, \int i''dt) \tag{8}$$

for the transient current which developes without the action of any driving source-voltage and therefore dies out after some time.

From these differential equations, the number of which is determined by the number of branches and nodes in the circuits, the current as a function of time can be calculated.

The magnitude of the transient current is determined by the fact that the electromagnetic state of the circuit before and after the switching process must join without any physical impossibility.

For a capacitance C it means that a sudden discontinuous change in the voltage across it, a infinite current will be generated, as the current in a capacitance is defined as:

$$i_C = C\frac{du_C}{dt} \tag{9}$$

However it is not possible that the current becomes infinite. At the instant of switching t = 0, the following equation is valid for the voltage across the capacitance C:

$$u_C = (t = -0) \quad = \quad u_C = (t = +0) \tag{10}$$

For a self-inductance L this means that a sudden discontinuous change of current would produce an infinite voltage, because:

$$u_L = L\frac{di}{dt} \tag{11}$$

At instantaneous switching the current in the self-inductance L can therefore not change instantaneously. Thus, at the instant of switching t = 0, the following equation is valid for the current in the self-inductance L:

$$i_L\ (t = -0) \quad = \quad i_L\ (t = +0) \tag{12}$$

In equation (5) we have split the current into two components, one for the steady-state and one for the transient current. The same can be done for the voltage across the capacitor C, or the current in an inductance L, or in fact with any voltage or current related to the components x in the circuit.

$$i_L = i_L^{\prime} + i_L^{\prime\prime} \qquad u_C = u_C^{\prime} + u_C^{\prime\prime}$$

$$\text{Generally :} \tag{13}$$

$$i_x = i_x^{\prime} + i_x^{\prime\prime} \qquad u_x = u_x^{\prime} + u_x^{\prime\prime}$$

After a considerable time the transient components of voltage and current (according to equation (8)) have vanished and only the steady-state components (according to equation (7)) remain. In branches of the circuit under study which only contain a resistance R, the currents and voltages can and will change momentarily during the switching process without any transients being developed.

In general it can be said that in circuits with inductance and capacitance, the currents, voltages or related parameters, do not change momentarily when a switching process takes place. A transient current or voltage will develop, these will decay with increasing time. This gives a gradual transition from the state of the circuit before switching to the new state after the switching process has taken place. The initial values of the transient currents or voltages are given by the changes which the stationary currents and voltages in the circuit undergo because of the switching process. From this it follows that these initial values are equal to the differences between the steady-state values before and after the switching process. The transients decay as if they alone were present in the final circuit without any source-voltage. The transients will occur on any variation within the structure of the electric system, this can be because of switching, interrupting (by a fuse) or short-circuiting of a part of the circuit.

## *CAPACITIVE CIRCUITS*

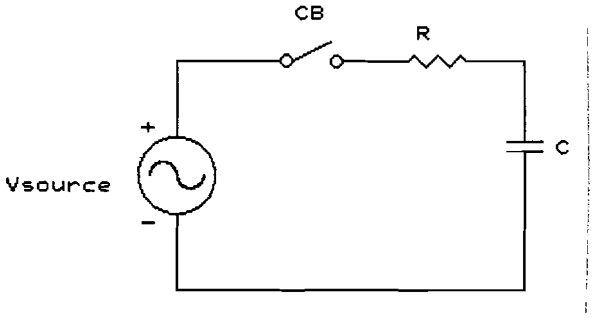


**Figure 1** - *The capacitive circuit under study.*

We consider a capacitive circuit with a resistance R and a capacitance C in series as in figure 1. The source-voltage is:

$$u = U_{peak}\cos(\omega t + \psi) \tag{14}$$

The differential equation for this circuit is:

$$U_{peak}\cos(\omega t + \psi) = \frac{1}{C}\int i\,dt + Ri \tag{15}$$

This equation can also be written as a function of the capacitor voltage, this gives:

$$U_{peak}\cos(\omega t + \psi) = RC\frac{du_C}{dt} + u_C \tag{16}$$

These equations can be solved by dividing the capacitor voltage and the current into two components:

$$u_C = u_C' + u_C'' \qquad i = i' + i'' \tag{17}$$

In which the first terms represent the steady-state parts and the second terms the transient parts of voltage and current.
If we substitute this in the differential equation, we get:

$$\begin{aligned} U_{peak}\cos(\omega t + \psi) &= RC\frac{du_C'}{dt} + u_C' \\ 0 &= RC\frac{du_C''}{dt} + u_C'' \end{aligned} \tag{18}$$

The steady state current is:

$$i'(t) = \frac{U_{peak}}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} \cos(\omega t + \varphi) \tag{19}$$

For the phase-angle of the current with respect to the voltage the following equation is valid:

$$\tan(\varphi - \psi) = \frac{1}{\omega CR} \tag{20}$$

For the steady state value of the capacitor voltage we can write:

$$u'_C(t) = \frac{1}{C}\int i'(t)\,dt = \frac{I_{peak}}{\omega C}\sin(\omega t + \varphi)$$
$$\text{with} \quad U_{C_{peak}} = \frac{I_{peak}}{\omega C} \tag{21}$$

The solution of the differential equation for the transient capacitor voltage is:

$$u''_C(t) = C e^{-\frac{t}{RC}} \tag{22}$$

For the actual capacitor voltage, if we combine equations (17), (21) and (22), we can write:

$$\boxed{u_C(t) = \frac{I_{peak}}{\omega C}\sin(\omega t + \varphi) + C e^{-\frac{t}{RC}} \qquad (23)}$$

For t = 0 we get:

$$u_C(t{=}0) = U_{C_{peak}}\sin\varphi + C = 0$$
$$\text{with} \quad C = -U_{C_{peak}}\sin\varphi \tag{24}$$

For the actual capacitor voltage we can now write:

$$u_C(t) = U_{C_{peak}}\left(\sin(\omega t + \varphi) - \sin\varphi\, e^{-\frac{t}{RC}}\right) \qquad \textbf{(25)}$$

By differentiating the transient voltage we get the transient current:

$$i''(t) = C\frac{du_C''(t)}{dt} = C\left(-U_{C_{peak}}\right)\sin\varphi\left(-\frac{1}{RC}\right)e^{-\frac{t}{RC}}$$

$$= \frac{U_{C_{peak}}}{R}\sin\varphi\; e^{-\frac{t}{RC}} = \frac{I_{peak}}{\omega CR}\sin\varphi\; e^{-\frac{t}{RC}} \qquad \textbf{(26)}$$

Finally we can write for the actual current the following equation:

$$\boxed{i(t) = \frac{U_{peak}}{\sqrt{R^2 + (\frac{1}{\omega C})^2}}\left(\cos(\omega t + \varphi) + \frac{\sin\varphi}{\omega CR}\, e^{-\frac{t}{RC}}\right) \qquad (27)}$$

From equation (27) it can be concluded that if **φ = 0°** at the instant of switching (t = 0), no transients will occur and the steady-state components will flow from the instant of energising. If **φ = 90°**, then the current would pass through zero at the instant of switching, and a heavy transient occurs, which in general is much greater (because the resistance is usually very small) then the steady-state current and consists of a decaying direct current. The inrush currents may reach high values, however if the time-constant of the circuit is small, the duration of the transient currents is also small. At the instant of switching a transient voltage develops in such a way that the actual capacitor voltage will be zero.

***In conclusion, for CAPACITIVE LOADS energizing:***

1. ***At voltage zero is most favourable.***
2. ***At maximum voltage gives the worst case condition.***

## *INDUCTIVE CIRCUITS*

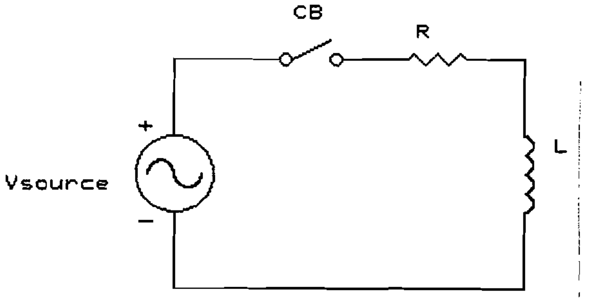


**Figure 2** - The inductive circuit under study.

We consider an inductive circuit with a resistance R and a inductance L in series as in figure 2.
The source-voltage is:

$$u = U_{peak}\cos(\omega t + \psi) \tag{28}$$

The initial current is:

$$i_0 = 0 \tag{29}$$

The differential equation for this circuit is:

$$U_{peak}\cos(\omega t + \psi) = L\frac{di}{dt} + Ri \tag{30}$$

The differential equation can be solved by splitting the total current into two components:

$$i = i' + i'' \tag{31}$$

Equation (30) can therefore be written as follows:

$$\begin{aligned} U_{peak}\cos(\omega t + \psi) &= L\frac{di'}{dt} + Ri' \\ 0 &= L\frac{di''}{dt} + Ri'' \end{aligned} \tag{32}$$

The solution of the first of these equations is:

$$i'(t) = \frac{U_{peak}}{\sqrt{R^2 + (\omega L)^2}} \cos(\omega t + \varphi) \tag{33}$$

For the phase angle of the current with respect to the voltage the following equation is valid:

$$\tan(\varphi - \psi) = -\frac{\omega L}{R} \tag{34}$$

The solution of the second differential equation is:

$$i'' = C\, e^{-\frac{R}{L}t} \tag{35}$$

The constant C must be determined from the initial condition of the circuit. If equations (29), (31), (33) and (35) are combined for t = 0, we get:

$$i_0 = I\cos\varphi + C = 0 \qquad \textit{this gives} \qquad C = -I\cos\varphi$$

$$\textit{with } I = \frac{U_{peak}}{\sqrt{R^2 + (\omega L)^2}} \tag{36}$$

With equation (31) and equations (33) and (35), we get for the total current after switching on the following equation:

$$\boxed{i(t) = \frac{U_{peak}}{\sqrt{R^2 + (\omega L)^2}} \left(\cos(\omega t + \varphi) - \cos\varphi\, e^{-\frac{R}{L}t}\right) \qquad (37)}$$

The transient part is a direct current which decays exponentially with a time constant L over R of the circuit. The transient current can give a considerable distortion of the stationary current. This depends on the phase angle φ which the stationary current would have at the instant of switching.

For **φ = 0° or 180°** the stationary current will pass its maximum, and the transient will have its full value. This represents the worst case condition. If **φ = ± 90°** at the instant of switching the stationary current will now pass through zero, and as can be seen from equation (37) no transient will develop. The superposition of the steady-state current and the transient current causes the actual current to develop into a value which can go up to twice the value of the steady-state current. This extreme value develops if the time constant is so much greater than the period of the alternating current that the transient decays only slowly. The successive zero-crossings can be more then 10 ms separated, and the rate of change of current can be of higher value then the steady-state value. If the time-constant is small compared with the period of the current, the transient current decreases during the first halve cycle and there is no exessive current development.

*In conclusion, for INDUCTIVE LOADS energizing:*

1. *At voltage zero gives the worst case condition.*
2. *At maximum voltage is the most favourable (inductive case).*

# APPENDIX 3

## RESULTS OF VARIOUS NO-LOAD TESTS

No-load tests have been carried out in order to establish the operating times of the different circuit breakers. During these no-load tests, the influence of variation of parameters such as control voltage, $SF_6$- pressure and stored energy were investigated. The following circuit-breakers have been subjected to no-load tests (results can be found in the tables):

1. **AEG S2-300**, $SF_6$ puffer breaker with a pneumatic operating mechanism (Elnumatic), at Apollo Substation, ESKOM. Single phase operation.

   Table 1 - No-load results from KEMA Report 600-86 [2.41].
   Table 2 - Close and Open for various air pressures.
   Table 3 - Close for same initial air pressure.
   Table 4 - Open for same initial air pressure.

2. **Delle Alsthom PK6**, Airblast Breaker at Ens Substation.

3. **ABB - HPL 245/25 B1**, $SF_6$ breaker with spring mechanism (BLG 1002), at KEMA High Power Laboratory DZL5, The Netherlands. The breaker is provided for three phase operation only.

   Table 5 - 110 V, 0,45 MPa $SF_6$-pressure, intermediate relay, open
   Table 6 - 250 V, 0,45 MPa $SF_6$-pressure, direct, open.
   Table 7 - 250 V, 0,45 MPa $SF_6$-pressure, direct, close.
   Table 8 - Various voltages, 0,45 MPa $SF_6$-pressure, direct, close.
   Table 9 - 250 V, 0,50 MPa $SF_6$-pressure, direct, close.
   Table 10 - 200 V, 0,50 MPa $SF_6$-pressure, direct, close.
   Table 11 - 250 V, 0,50 MPa $SF_6$-pressure, direct, open.
   Table 12 - 200 V, 0,50 MPa $SF_6$-pressure, direct, open.
   Table 13 - Various voltages, 0,50 MPa $SF_6$-pressure, direct, open.

4. **ABB - HPL 170 A1**, $SF_6$ breaker with spring mechanism (BLG 1002), at KEMA High Power Laboratory DZL5. The breaker is provided for single phase operation.

   Table 14 - Various voltages, 0,62 MPa $SF_6$-pressure, direct, open.
   Table 15 - Various voltages, 0,62 MPa $SF_6$-pressure, direct, open.
   Table 16 - 250 V, 0,62 MPa $SF_6$-pressure, direct, close.
   Table 17 - Various voltages, 0,62 MPa $SF_6$-pressure, direct, close.
   Table 18 - 250 V, 0,70 MPa $SF_6$-pressure, direct, close.
   Table 19 - 250 V, 0,70 MPa $SF_6$-pressure, direct, open.

Table 20 - Various voltages, 0,70 MPa $SF_6$-pressure, direct, open.

5. **ABB - LTB 170 D1,** $SF_6$ breaker with spring mechanism (BLK 52), at Borssele Substation.

   Table 21 - 110 V, close.
   Table 22 - 110 V, open coil 1.
   Table 23 - 110 V, open coil 2.
   Table 24 - 110 V, open coil 3.

Some of the results that are tabulated are also visualized in different figures for the different breakers.

***Test-Circuit Data:***

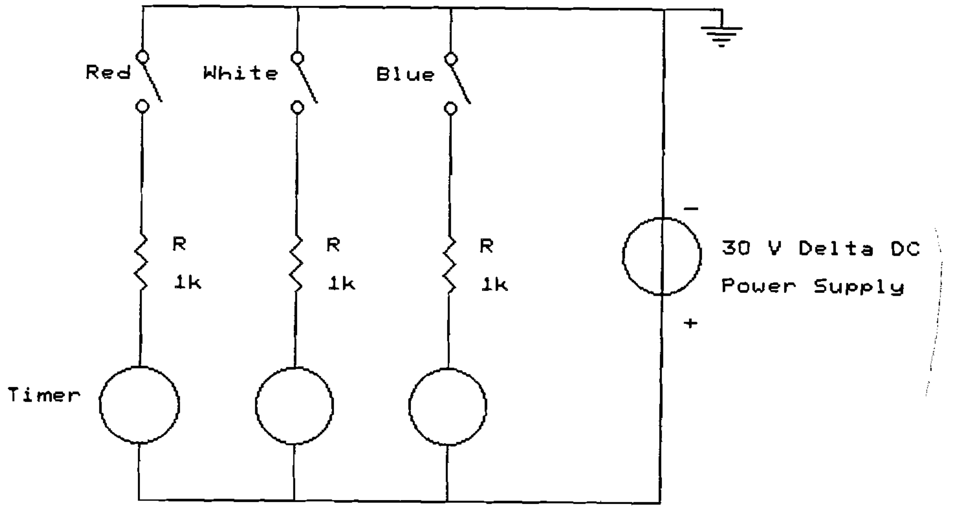


***Figure 1 - Test circuit-diagram for no-load tests on circuit breaker closing.***

In South Africa a CBS, Type CBT4, time measuring device was used for no-load tests. This particular CBT-4 could only be used with a sampling rate of 2 kHz. This implicates that the smallest time-step that could be measured was 0,5 ms. At KEMA a self-made device (Type Damstra) was used, see also figure 1 and 2 for the principle diagram. The smallest time-step that could be measured was 0,01 ms. At Borssele Substation a Program Electric TM1600 time measuring device, with a resolution of 0,1 ms was used. The results of the no-load tests can be found in tables 1 to 24.

With the interactive software package MATLAB the mean value, standard deviation, and the minimum and maximum value of a vector can be calculated quick and easy. The mean of a group of values is the average. The Greek symbol $\mu$ is used to represent the mean value, as shown in the following equation, which uses the

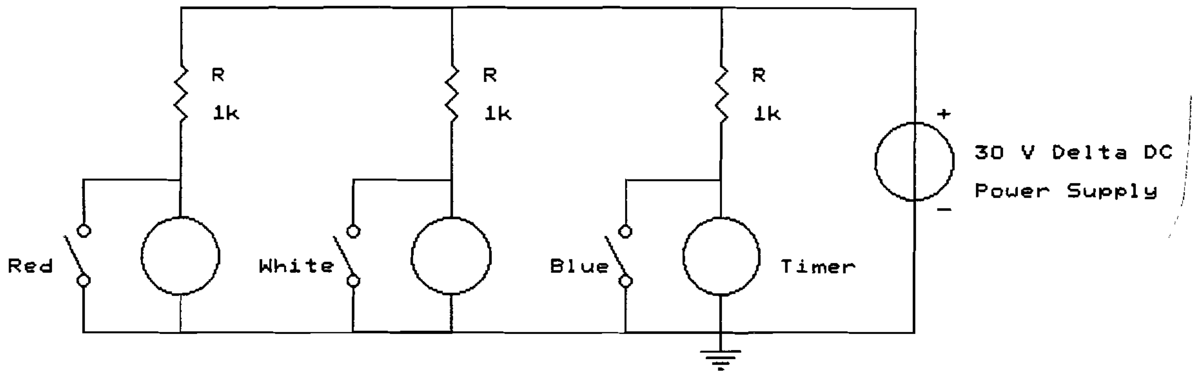


*Figure 2 - Test circuit-diagram for no-load tests on circuit breaker opening.*

summation notation to define the mean:

$$\mu = \frac{\sum_{k=1}^{N} t_k}{N}$$

This summation must be seen in the following way:

$$\sum_{k=1}^{N} t_k = t_1 + t_2 + \cdots + t_N$$

The standard deviation is defined to be the square root of the variance, as follows:

$$Std = \sqrt{\sigma^2} = \sqrt{\frac{\sum_{k=1}^{N} (t_k - \mu)^2}{N - 1}}$$

The term $t_k - \mu$ is the difference or deviation of $t_k$ from the mean. This value is squared so that it allways has a positive value. Then all the squared deviations for all the data points in the vector are added, and divided by **N - 1**, which approximates an average. The larger the deviation (or variance), the more the values fluctuate around the mean value.

It must be noted that in general not enough data points have been measured for applying statistics on them. However to give an indication the standard deviation is given in some of the tables.

## *AEG S2-300*

Switching duty: Capacitor-Bank Switching: 300 MVAr, 275 kV, Unearthed Neutral.

Characteristics of the circuit-breaker according to the breaker name-plate and the manufacturers operating instructions:

The circuit breaker has two interrupting elements per pole, with a parallel capacitance of 800 pF per element. The insulating medium in the circuit breaker is SF6.

Manufacturer : AEG-TELEFUNKEN
Type : S2-300
Rated voltage : 275 kV
Rated frequency : 50 Hz
Rated nominal current : 3150 A
Breaking current, symmetric : 50 kA

**Operating times (tolerance ± 10 %):**
**Make-time : 120 ms**
**Break-time : 50 ms**
**Make-break-time : 80 ms**

Rated operating sequence : O - 0,3s - CO - 3min - CO
Provided for rapid auto-reclosure, three-phase operation and single-phase operation.

Power-consumption per closing coil : 170 W
Power-consumption per opening coil : 130 W
Control voltage : 220 V DC
Number of tripping systems : 2

Elektric-pneumatic drive : ELNUMATIC
Operation pressure range : 3,0 - 3,7 MPa

Air-consumption, 3-phase (1 bar, 15 °C):
Closing operation : 0,60 m$^3$
Breaking operation : 1,35 m$^3$
Auto-reclosing (O-C) : 2,05 m$^3$
Leakage air-consumption : 0,01 m$^3$
Volume of air receiver : 3 x 0,25 m$^3$/h
Design pressure : 4,2 MPa

It is interesting to note that the KEMA-Report 600-86 [2.41] on this AEG S2-300 breaker gives other values for the operating times. The KEMA-Report was made available by AEG. In this report the following data can be found:

Voltage : 300 kV
Normal current : 4000 A
Breaking Current, symmetric : 50 kA
TRV: $U_C$ : 515 kV peak
RRRV : 2000 V/$\mu$s
Making current : 128 kA peak at 300 kV/60 Hz
98 kA peak (500 - 1000 Hz)
Short-time current:
Peak value : 128 kA peak
RMS-value : 50 kA during 3s

Operating voltage : 220 V DC
**Operating pressure : 36 bar (abs.)**
Operating sequence : O - 0,3s - CO - 3min - CO

Summary of tests carried out at KEMA:

1. No-load tests.
2. Capacitor bank charging current interruption tests:
   108 kV - 4,8 kA
   143 kV - 6,2 kA
   175 kV - 6,5 kA
3. Capacitor bank inrush making current tests:
   42 kV DC up to 195 kV DC
   29,0 kA peak up to 101 kA peak
   with 800 Hz up to 970 Hz

Data of mechanism:
Stored energy opening (pneumatic).
Stored energy closing (pneumatic, released by spring).

Rated supply voltage closing coil : 220 V DC
Rated supply voltage opening coil : 220 V DC
**Rated operating pressure : 32 bar (abs.)**

**TABLE 1** - *No-load test results of the AEG S2-300 circuit breaker, according to KEMA-Report 600-86.*

| Operation | Operating Pressure (bar abs.) | Closing Time (ms) | Opening Time (ms) | Pole Number |
|---|---|---|---|---|
| Open | 31 | / | 28 | 1 |
| Close | 32 | 87 | / | 1 |
| Open | 31 | / | 28 | 1 |
| Close | 32 | 87 | / | 1 |
| Open | 31 | / | 28 | 1 |
| Close | 32 | 87 | / | 1 |
| Close | 32 | 97 | / | 2 |

**TABLE 2** - *Operating times of AEG S2-300, as measured at Apollo Substation, with different initial air pressures at every test.*

| Test Number | Pressure (MPa) | Red Phase | | White Phase | | Blue Phase | |
|---|---|---|---|---|---|---|---|
| | | Close | Open | Close | Open | Close | Open |
| 1 | 3.50 | 128.0 | / | 123.0 | / | 122.5 | / |
| | 3.30 | / | 28.0 | / | 28.0 | / | 28.0 |
| 2 | 3.20 | 137.0 | / | 131.5 | / | 131.0 | / |
| | 3.10 | / | 32.0 | / | 32.0 | / | 32.0 |
| 3 | 3.40 | 133.5 | / | 128.0 | / | 129.5 | / |
| | 3.30 | / | 31.0 | / | 32.0 | / | 32.0 |
| 4 | 3.30 | 136.0 | / | 133.0 | / | 132.5 | / |
| | 3.20 | / | 29.5 | / | 31.0 | / | 31.5 |
| 5 | 3.25 | 135.0 | / | 132.0 | / | 133.0 | / |
| | 3.15 | / | 30.0 | / | 31.5 | / | 31.0 |

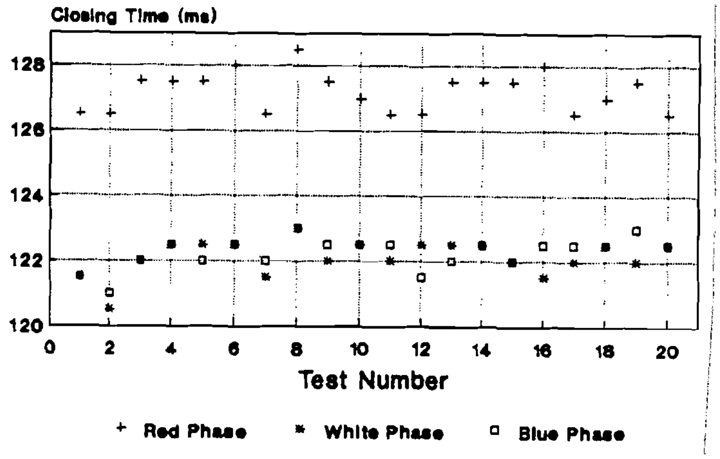
**TABLE 3** - *Closing times of AEG S2-300 as measured at Apollo Substation, with same initial air pressure before every test initiation.*

| Test Number | Red Phase Time [ms] | | White Phase Time [ms] | | Blue Phase Time [ms] | |
|---|---|---|---|---|---|---|
| | Gap A | Gap B | Gap A | Gap B | Gap A | Gap B |
| 1 | 126.5 | 126.5 | 121.5 | 121.5 | 121.5 | 121.5 |
| 2 | 126.5 | 126.5 | 120.5 | 120.5 | 121.0 | 121.0 |
| 3 | 127.5 | 127.5 | 122.0 | 122.0 | 122.0 | 122.0 |
| 4 | 127.5 | 127.5 | 122.5 | 122.5 | 122.5 | 122.5 |
| 5 | 127.5 | 127.5 | 122.5 | 122.5 | 122.0 | 122.0 |
| 6 | 128.0 | 128.0 | 122.5 | 122.5 | 122.5 | 122.5 |
| 7 | 126.5 | 126.5 | 121.5 | 121.5 | 122.0 | 122.0 |
| 8 | 128.5 | 128.5 | 123.0 | 123.0 | 123.0 | 123.0 |
| 9 | 127.5 | 127.5 | 122.0 | 122.0 | 122.5 | 122.5 |
| 10 | 127.0 | 127.0 | 122.5 | 122.5 | 122.5 | 122.5 |
| 11 | 126.5 | 126.5 | 122.0 | 122.0 | 122.5 | 122.5 |
| 12 | 126.5 | 126.5 | 122.5 | 122.5 | 121.5 | 121.5 |
| 13 | 127.5 | 127.5 | 122.5 | 122.5 | 122.0 | 122.0 |
| 14 | 127.5 | 127.5 | 122.5 | 122.5 | 122.5 | 122.5 |
| 15 | 127.5 | 127.5 | 122.0 | 122.0 | 122.0 | 122.0 |
| 16 | 128.0 | 128.0 | 121.5 | 121.5 | 122.5 | 122.5 |
| 17 | 126.5 | 126.5 | 122.0 | 122.0 | 122.5 | 122.5 |
| 18 | 127.0 | 127.0 | 122.5 | 122.5 | 122.5 | 122.5 |
| 19 | 127.5 | 127.5 | 122.0 | 122.0 | 123.0 | 123.0 |
| 20 | 126.5 | 126.5 | 122.5 | 122.5 | 122.5 | 122.5 |
| Mean | 127.20 | | 122.13 | | 122.25 | |
| Std | 0.62 | | 0.56 | | 0.50 | |
| Min | 126.50 | | 120.50 | | 121.00 | |
| Max | 128.50 | | 123.00 | | 123.00 | |

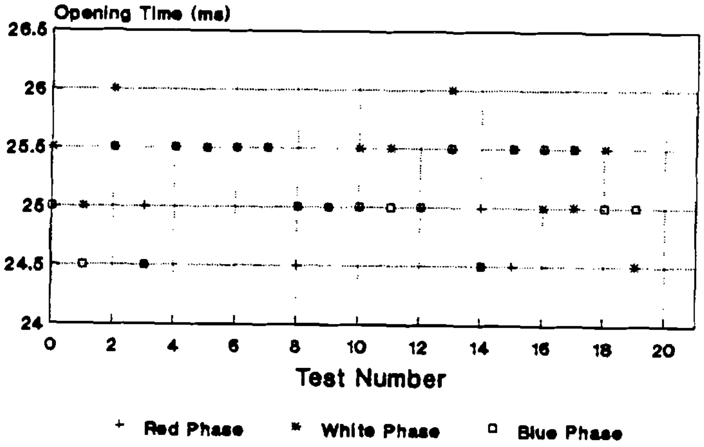
**TABLE 4** - *Opening times of AEG S2-300 as measured at Apollo Substation, with same initial air pressure before every test initiation.*

| Test Number | Red Phase Time [ms] | | White Phase Time [ms] | | Blue Phase Time [ms] | |
|---|---|---|---|---|---|---|
| | Gap A | Gap B | Gap A | Gap B | Gap A | Gap B |
| 1 | 25.5 | 25.5 | 25.5 | 25.5 | 25.0 | 25.0 |
| 2 | 25.0 | 25.0 | 25.0 | 25.0 | 24.5 | 24.5 |
| 3 | 25.5 | 25.5 | 26.0 | 26.0 | 25.5 | 25.5 |
| 4 | 25.0 | 25.0 | 24.5 | 24.5 | 24.5 | 24.5 |
| 5 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| 6 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| 7 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| 8 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| 9 | 24.5 | 24.5 | 25.0 | 25.0 | 25.0 | 25.0 |
| 10 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| 11 | 25.0 | 25.0 | 25.5 | 25.5 | 25.0 | 25.0 |
| 12 | 25.5 | 25.5 | 25.5 | 25.5 | 25.0 | 25.0 |
| 13 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 | 25.0 |
| 14 | 25.5 | 25.5 | 26.0 | 26.0 | 25.5 | 25.5 |
| 15 | 25.0 | 25.0 | 24.5 | 24.5 | 24.5 | 24.5 |
| 16 | 24.5 | 24.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| 17 | 25.5 | 25.5 | 25.0 | 25.0 | 25.5 | 25.5 |
| 18 | 25.5 | 25.5 | 25.0 | 25.0 | 25.5 | 25.5 |
| 19 | 25.5 | 25.5 | 25.5 | 25.5 | 25.0 | 25.0 |
| 20 | 24.5 | 24.5 | 24.5 | 24.5 | 25.0 | 25.0 |
| Mean | 25.20 | | 25.25 | | 25.15 | |
| Std | 0.38 | | 0.44 | | 0.37 | |
| Min | 24.50 | | 24.50 | | 24.50 | |
| Max | 25.50 | | 26.00 | | 25.50 | |

## Table 3
## AEG S2-300



## Table 4
## AEG S2-300



*Comment Table 1* - In the KEMA-Report 600-86 [2.41] on this AEG S2-300 breaker other values for the operating times are given. The KEMA-Report was made available by AEG.

*Comment Table 2* - The AEG S2-300 was subjected to several no-load switchings on site prior to controlled switching measurements. The dependence of the operating times on the air pressure becomes very clear when successive no-load operations are carried out. With lower air pressures the breaker becomes much slower on opening as well as on closing.

*Comment Table 3* - Before every test the initial pressure was 3,7 MPa. The difference between the red phase pole and the other two is 5 ms, this is very large. Normally the poles should have a better simultaneity. On the basis of this timing it can be said that this breakers pole simultaneity must be adjusted, because if this gets worse, there might be danger for the integrity of the insulation of the capacitor banks neutral to earth. The breaker is also equiped with a pole discrepancy relay, so if the set discrepancy is exceeded a warning signal will be given. The breaker is also relatively slow witch causes pre-arcing. The difference between the minimum and the maximum time, which is about 2 ms, is too large to obtain sufficient accuracy for controlled closing.

*Comment Table 4* - Also here, before every test the initial pressure was 3,7 MPa. The pole simultaneity on opening is good. The difference between the minimum and the maximum time, is about 1 ms, this is acceptable for controlled opening purposes. The closing operations were done with an air pressure of 3,85 MPa, the opening operations with 3,8 MPa.

## *DELLE ALSTHOM PK6*

Switching duty: Transmission Line Switching.

| | | |
|---|---|---|
| Manufacturer | : | Delle Alsthom |
| Type | : | PK6 |
| Serial Number | : | 448390/00/1972 |
| Rated voltage | : | 380 kV |
| Rated frequency | : | 50 Hz |
| Rated nominal current | : | 2500 A |
| Breaking current, symmetric | : | 50 kA |
| | | |
| Power-consumption per closing coil | : | 500 W |
| Power-consumption per opening coil | : | 500 W |
| Control voltage | : | 220 V DC |
| Close coil: | | |
| Minimum voltage | : | 187 V DC |
| Maximum voltage | : | 242 V DC |
| Trip Coils: | | |
| Minimum voltage | : | 154 V DC |
| Maximum voltage | : | 242 V DC |
| Number of tripping systems | : | 2 |
| | | |
| Air consumption, 3-phase: | | |
| Closing operation | : | 1800 liter |
| Breaking operation | : | 16200 liter |
| Open-Close-Open | : | 34200 liter |

During no-load tests at Ens Substation the described bouncing and rebound phenomenon was recorded with a UV-recorder (UV = Ultra Violet). A no-load test with this kind of equipment gives an indication that all control coils are functioning correct. This can be seen from the control coil current wave shape. If there is a faulty coil the current-wave-shape can be used as an indicator. The inter-gap and inter-pole simultaneity can be seen in one view, however precise timing information cannot be obtained with this kind of measurement. Therefore the UV-recorder is not suitable to determine the consistency and the exact values of the operating times for controlled switching purposes.

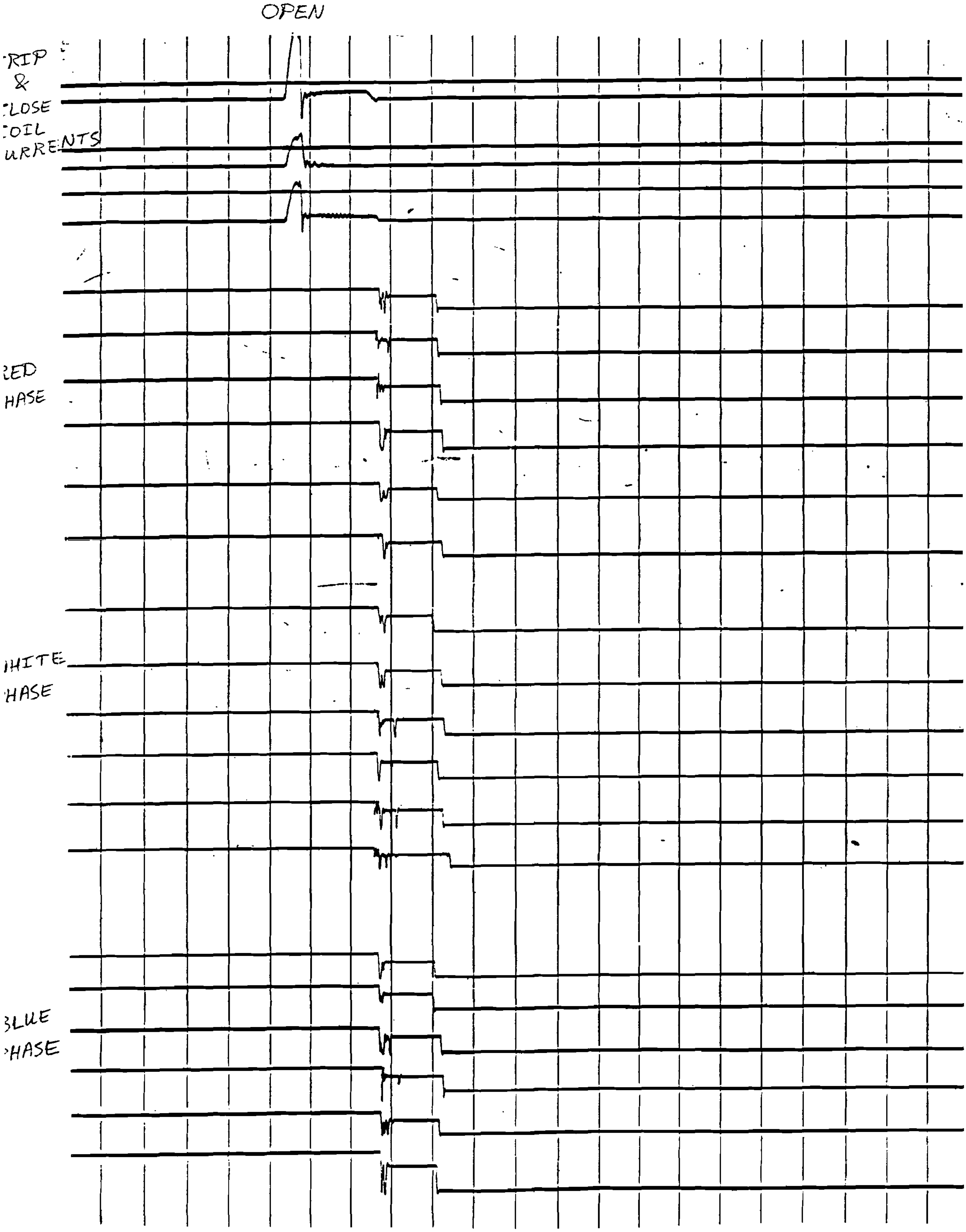


**Figure 3** - *Output of UV-Recorder for the Delle PK6 at Ens.*

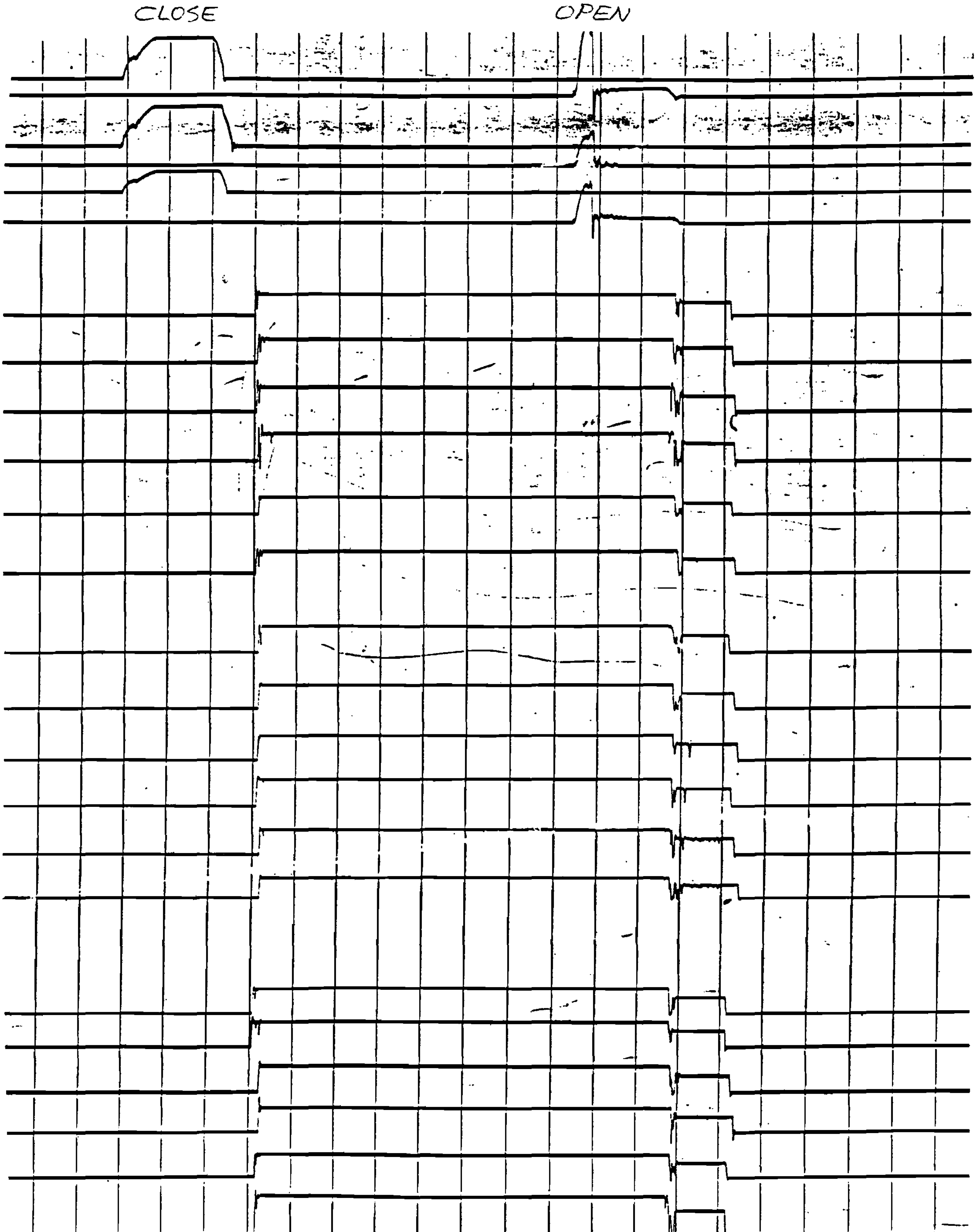


**Figure 4** - *Output of UV-Recorder for the Delle PK6 at Ens.*

## *HPL 245/25 B1*

Switching duty: Auxiliary breaker in KEMA's High-Power-Laboratories.

Characteristics of the circuit-breaker according to the breaker name-plate and the manufacturers operating instructions:

The insulating medium in the circuit breaker is SF6. The breaker is provided for **three-phase operation only**, and has one interrupting element per pole.

| | | |
|---|---|---|
| Manufacturer | : | ABB |
| Type | : | HPL 245/25 B1 |
| Rated voltage | : | 245 kV |
| Rated frequency | : | 50 Hz |
| Rated nominal current | : | 2500 A |
| Breaking current, symmetric | : | 40 kA |

Data of mechanism:

| | | |
|---|---|---|
| Drive | : | BLG 1002 |
| Serial Number | : | 7756 845 |

Spring-operated.

| | | |
|---|---|---|
| Control voltage | : | 110 V DC |
| Number of tripping systems | : | 1 |

SF6 Gas pressure:

| | | |
|---|---|---|
| Maximum working pressure | : | 0,80 MPa |
| Filling pressure (20 °C) | : | 0,50 MPa |
| Signalling pressure (20 °C) | : | 0,45 MPa |
| Blocking pressure (20 °C) | : | 0,43 MPa |

The first tests were carried out with an intermediate relay between the time measuring device and the breakers control coil for opening. These results showed a big time-spread, see table 5. The same tests were also carried out without the intermediate relay. The timer was then directly coupled to the breakers control coils. Also a pulsed source was used to feed the control coils. This source consisted of a capacitor (100 $\mu$F per coil) that was charged to different voltages (250 V, 200 V, 150 V and 100 V). In this way it is possible to overexcite the control coils and thus to shorten the electrical delay time of the total close time. This gives a good impression of the mechanical stability (travel time) of the breaker.

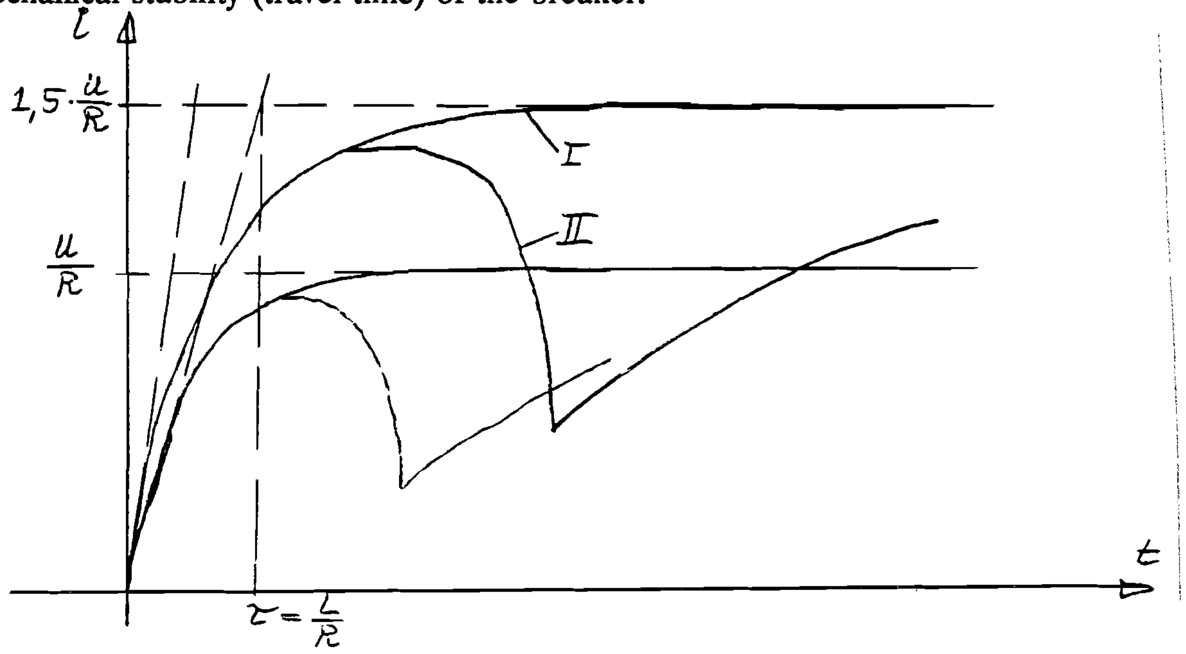


**Figure 5** - *Current-wave-shape for the control coils and the influence of the control voltage on the operating time.*

The universal differential equation for the control coil circuit is:

$$u = R \cdot i + \frac{d\phi}{dt} \qquad (4)$$

Assuming linear behaviour of the magnetic circuit, then:

$$\phi = L(x) \cdot i \qquad (5)$$

The flux is a function of the current and the distance between the static part and the moving part of the coil core:

$$\phi = \phi(i, x) \qquad (6)$$

Substituting (3) in (1), gives:

$$u = R \cdot i + \frac{\partial \phi}{\partial i} \cdot \frac{di}{dt} + \frac{\partial \phi}{\partial x} \cdot \frac{dx}{dt} \tag{7}$$

In this equation we have:
u is the control coil voltage (station battery voltage).
Ri is the resistive voltage drop.
The next part is the voltage drop on the self-inductive part and the last part is the voltage drop cause by the motion of the moveable part of the core.
If the moveable part is blocked, then the velocity is zero and the final part of equation 4 is zero. The solution for the current in this case is:

$$\frac{di}{dt} = \frac{u - R \cdot i}{L} \rightarrow i = \frac{u}{R} \left( 1 - e^{\frac{-t}{\frac{L}{R}}} \right) \tag{8}$$

This is a well known exponential function, which is marked as I in figure 7. If the moveable part is placed back in its initial position and the coil is excited again, then the current-wave-shape is according to curve II in figure 7. In this case the following equation is valid:

$$\frac{di}{dt} = \frac{u - R \cdot i - i \cdot \frac{dL}{dt} \cdot v}{L} \tag{9}$$

From figure 7 it follows that the curves I and II have the same initial wave shape. The current increases gradually because of the self-inductance and is therefore small in the beginning. The magnetic field is then also small as well as the force on the moveable part. This gives a small acceleration and hence a small velocity of the moving part. After some time the velocity increases considerably and the derivative of the current to time becomes smaller. The initial part of the current wave-shape is the part with which it is possible to manipulate the operating time of the breaker. For this initial part the following equation is valid for the tangent if the ohmic voltage drop is neglected:

$$\frac{di}{dt} = \frac{u}{L} \tag{10}$$

From this formula it follows that if a higher coil voltage is chosen, the tangent will increase proportionally. The higher this voltage the higher the tangent, however after a certain value of the coil voltage the time-profit will not be very much because the tangent will not increase much more. Also the thermal limits of the coil have to be adhered to.

**TABLE 5** - *Test results with 110 volt opening coil voltage, 0,45 MPa $SF_6$ pressure. The opening coil activated via an intermediate relay.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 29.84 | 29.62 | 29.00 |
| 2 | 28.08 | 28.58 | 27.68 |
| 3 | 27.99 | 28.43 | 27.62 |
| 4 | 28.30 | 28.54 | 27.86 |
| 5 | 28.54 | 29.07 | 28.30 |
| 6 | 28.79 | 29.37 | 28.54 |
| Mean | 28.59 | 28.94 | 28.17 |
| Std | 0.68 | 0.49 | 0.54 |
| Minimum | 27.99 | 28.43 | 27.62 |
| Maximum | 29.84 | 29.62 | 29.00 |

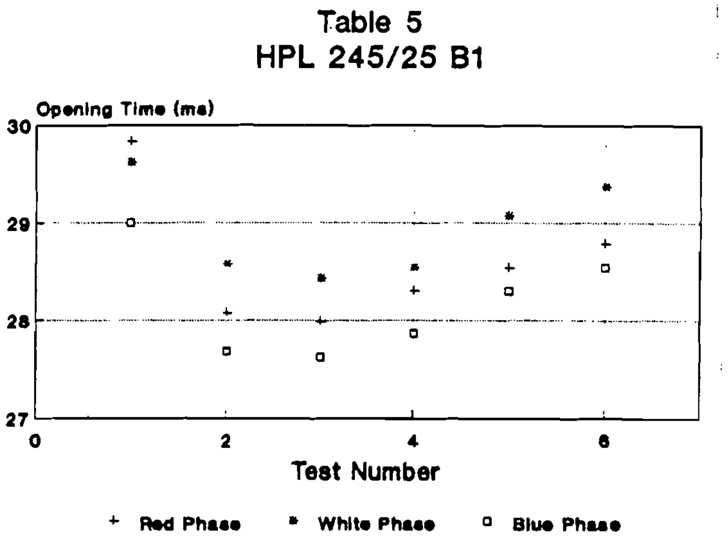


**TABLE 6** - *Test results with 250 Volt volt opening coil voltage pulsed from a capacitor, 0,45 MPa SF$_6$-pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 20.26 | 20.59 | 20.01 |
| 2 | 20.28 | 20.61 | 20.01 |
| 3 | 20.32 | 20.71 | 19.61 |
| 4 | 20.27 | 20.64 | 19.70 |
| 5 | 20.33 | 20.62 | 19.58 |
| 6 | 20.27 | 20.66 | 19.81 |
| 7 | 20.33 | 20.63 | 20.03 |
| 8 | 20.27 | 20.78 | 19.91 |
| 9 | 20.25 | 20.71 | 19.94 |
| 10 | 20.28 | 20.59 | 19.70 |
| Mean | 20.29 | 20.65 | 19.83 |
| Std | 0.03 | 0.06 | 0.17 |
| Minimum | 20.25 | 20.59 | 19.58 |
| Maximum | 20.36 | 20.78 | 20.03 |

Table 6
HPL 245/25 B1

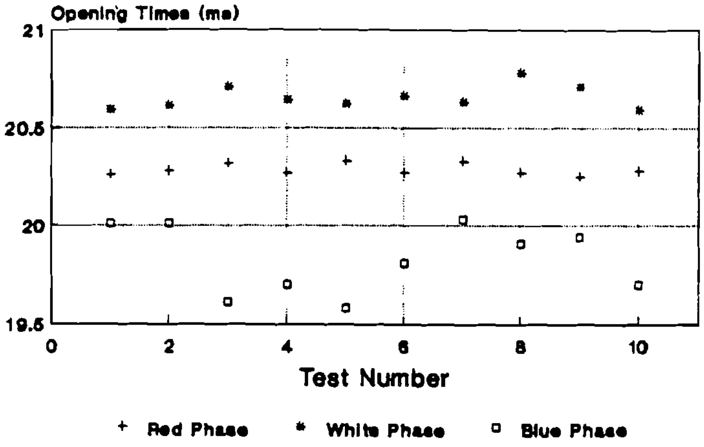


**TABLE 7** - *Test results with 250 Volt closing coil voltage pulsed from a capacitor (100 uF), 0,45 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 56.48 | 57.54 | 56.97 |
| 2 | 57.56 | 56.79 | 57.10 |
| 3 | 57.60 | 57.82 | 57.07 |
| 4 | 56.00 | 57.39 | 57.08 |
| 5 | 57.58 | 57.67 | 56.93 |
| 6 | 57.38 | 57.61 | 56.89 |
| 7 | 57.65 | 57.81 | 57.20 |
| 8 | 57.45 | 57.12 | 57.79 |
| 9 | 56.54 | 57.03 | 56.97 |
| 10 | 56.13 | 57.79 | 57.20 |
| Mean | 57.04 | 57.46 | 57.12 |
| Std | 0.67 | 0.36 | 0.26 |
| Minimum | 56.00 | 56.79 | 56.89 |
| Maximum | 57.65 | 57.82 | 57.79 |

Table 7

HPL 245/25 B1

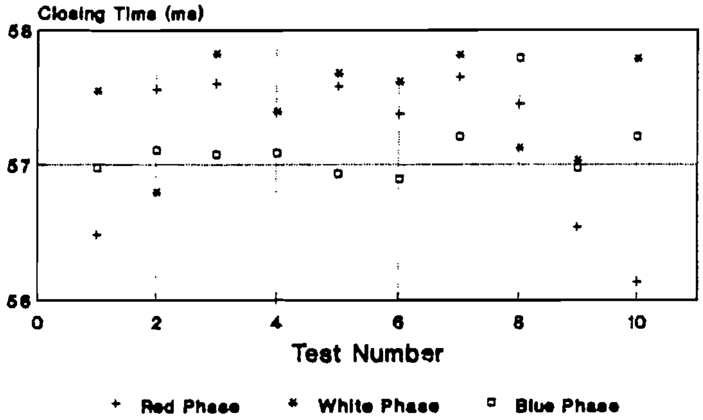


**TABLE 8** - *Test results with different closing coil voltages pulsed from a capacitor (100 uF), 0,45 MPa SF6 pressure.*

| Test Number | Closing Coil Voltage (Volt) | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|---|
| 1 | 250 | 57.78 | 57.12 | **113.08 ☚** |
| 2 | | 56.22 | 57.90 | 57.90 |
| 3 | | 57.44 | 57.03 | 57.11 |
| 4 | | 57.50 | 57.69 | **113.17 ☚** |
| 5 | 200 | 57.80 | 57.24 | 57.19 |
| 6 | | 57.78 | 57.30 | 57.99 |
| 7 | | 56.69 | 57.98 | 57.90 |
| 8 | 150 | Not enough energy in the capacitor to energize the close coil. | | |
| 9 | 200 | 57.92 | 58.26 | 57.91 |

During test numbers 1 and 4 the clamps on the breakers were loosened by the vibration of the breaker structure during the switching operations. Also an oxide layer on the contacts could be a possible source of error.

**TABLE 9** - *Test results with 250 Volt closing coil voltage pulsed from a capacitor (100 uF), 0,50 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 57.64 | 57.14 | 57.30 |
| 2 | 56.65 | 57.94 | 57.34 |
| 3 | 57.80 | 57.55 | 57.21 |
| 4 | 56.66 | 57.11 | 57.82 |
| 5 | 57.75 | 57.11 | 57.17 |
| 6 | 56.02 | 56.77 | 56.84 |
| 7 | 57.49 | 56.57 | 57.71 |
| 8 | 57.32 | 56.77 | 57.09 |
| 9 | 56.33 | 57.51 | 56.85 |
| 10 | 57.53 | 56.44 | 57.17 |
| 11 | 57.38 | 56.75 | 57.01 |
| 12 | 57.77 | 57.41 | 57.65 |
| Mean | 57.20 | 57.09 | 57.26 |
| Std | 0.62 | 0.45 | 0.32 |
| Minimum | 56.02 | 56.44 | 56.84 |
| Maximum | 57.80 | 57.94 | 57.82 |

Table 9
HPL 245/25 B1

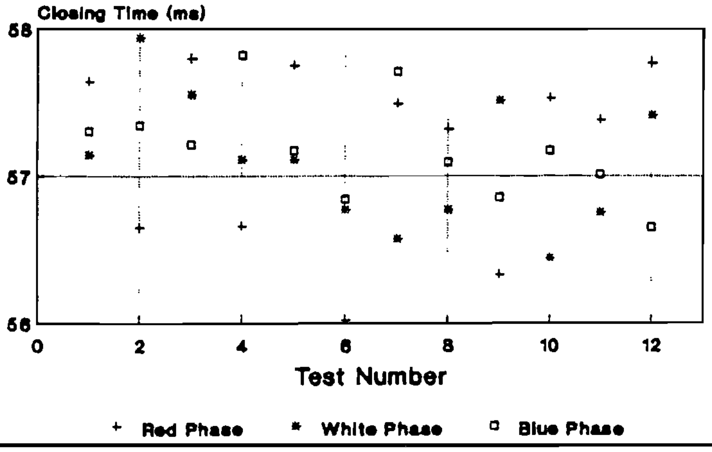


**TABLE 10** - *Test results with 200 Volt closing coil voltage pulsed from a capacitor (100 uF), 0,50 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 57.66 | 56.90 | 57.95 |
| 2 | 57.80 | 58.01 | 57.26 |
| 3 | 57.74 | 57.30 | 58.01 |
| 4 | 57.71 | 57.67 | 57.99 |
| 5 | 56.69 | 57.53 | 58.02 |
| 6 | 55.97 | 57.88 | 57.11 |
| Mean | 57.26 | 57.55 | 57.72 |
| Std | 0.76 | 0.41 | 0.42 |
| Minimum | 55.97 | 56.90 | 57.11 |
| Maximum | 57.80 | 58.01 | 58.02 |

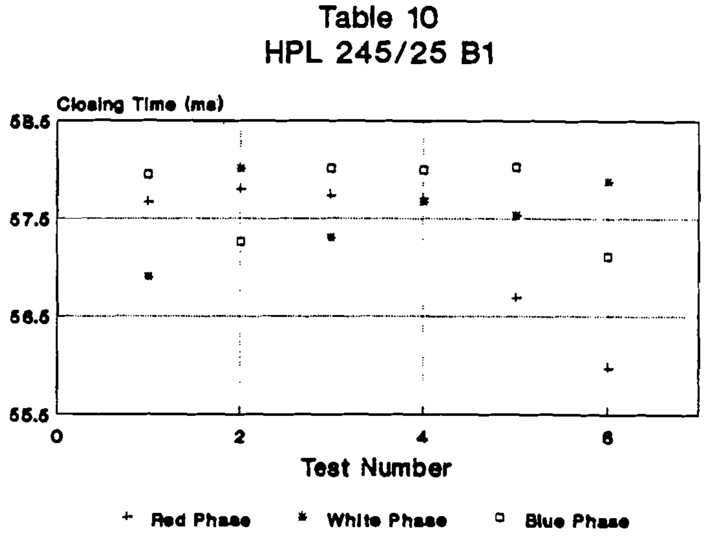


**TABLE 11** - *Test results with 250 Volt opening coil voltage pulsed from a capacitor (100 uF), 0,50 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole ms) |
|---|---|---|---|
| 1 | 20.81 | 20.59 | 19.57 |
| 2 | 20.37 | 20.74 | 19.63 |
| 3 | 20.73 | 20.71 | ☹<br>Clamp fell off breaker. |
| 4 | 20.45 | 20.90 | 20.03 |
| 5 | 20.86 | 20.88 | 20.02 |
| 6 | 20.31 | 20.67 | 19.74 |
| 7 | 20.28 | 20.56 | 19.61 |
| 8 | 20.89 | 20.65 | 19.74 |
| 9 | 20.30 | 20.77 | 19.98 |
| 10 | 20.70 | 20.51 | 19.58 |
| 11 | 20.55 | 20.70 | 19.62 |
| 12 | 20.86 | 20.64 | 19.71 |
| 13 | 20.88 | 20.71 | 20.01 |
| Mean | 20.60 | 20.69 | 19.77 |
| Std | 0.25 | 0.12 | 0.19 |
| Minimum | 20.28 | 20.51 | 19.57 |
| Maximum | 20.88 | 20.90 | 20.03 |

Test number 3 is rejected in the calculations of the mean and standard deviation.

**TABLE 12** - *Test results with 200 Volt opening coil voltage pulsed from a capacitor (100 uF), 0,50 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 21.01 | 20.95 | 20.27 |
| 2 | 21.12 | 20.90 | 19.97 |
| 3 | 21.10 | 20.88 | 20.19 |
| 4 | 21.05 | 20.32 | 20.26 |
| 5 | 21.00 | 20.83 | 20.26 |
| 6 | 20.58 | 20.82 | 19.91 |
| 7 | 21.00 | 20.80 | 20.05 |
| 8 | 20.46 | 20.40 | 20.31 |
| 9 | 20.43 | 20.82 | 20.18 |
| 10 | 20.92 | 20.98 | 19.81 |
| 11 | 20.57 | 20.36 | 19.99 |
| Mean | 20.84 | 20.73 | 20.11 |
| Std | 0.27 | 0.25 | 0.17 |
| Minimum | 20.43 | 20.32 | 19.81 |
| Maximum | 21.12 | 20.98 | 20.31 |

Table 11
HPL 245/25 B1

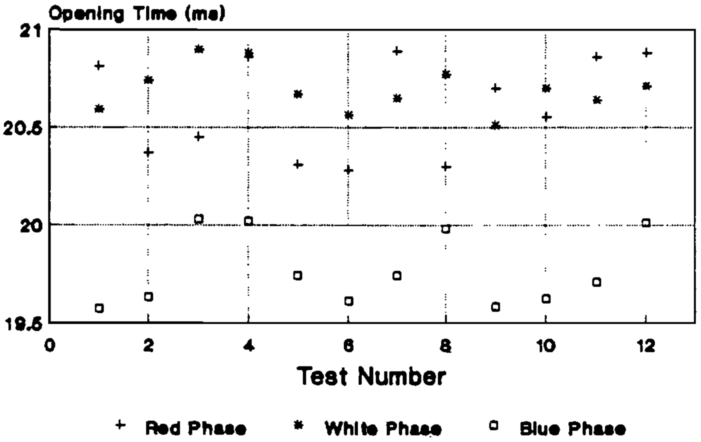


Table 12
HPL 245/25 B1

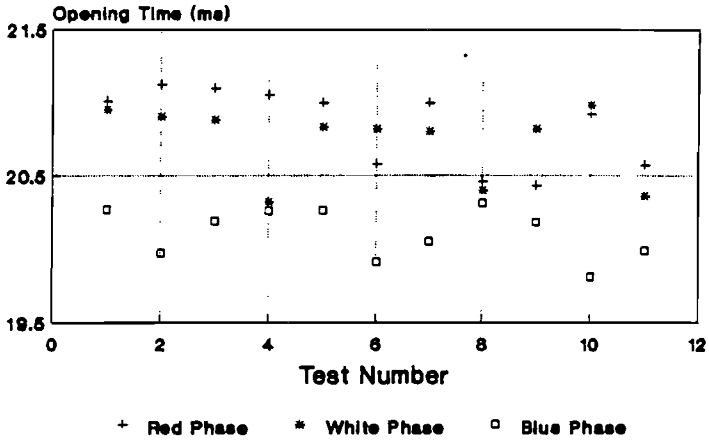


**TABLE 13** - *Test results with different opening coil voltages pulsed from different capacitor combinations, 0,50 MPa SF6 pressure.*

| Test Number | Opening Coil Voltage & Capacitor Value | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|---|
| 1 | 150 V & 200 μF | 21.49 | 21.41 | 20.32 |
| 2 | | 21.04 | 21.49 | 20.75 |
| 3 | | 21.41 | 20.79 | 20.73 |
| 4 | | 21.51 | 21.61 | 20.36 |
| 5 | | 21.58 | 21.51 | 20.63 |
| 6 | | 21.53 | 21.38 | 20.41 |
| 7 | | 21.59 | 21.58 | 20.36 |
| 8 | 100 V & 200 μF | Not enough energy in the capacitors to energize the opening coil. | | |
| 9 | 100 V & 300 μF | 22.14 | 22.59 | 21.73 |
| 10 | | 22.43 | 22.38 | 21.64 |
| 11 | 150 V & 300 μF | 21.56 | 21.47 | 20.40 |
| 12 | | 21.52 | 21.53 | 20.77 |
| 13 | | 21.52 | 21.47 | 20.82 |
| 14 | 250 V & 300 μF | 20.70 | 20.60 | 19.65 |
| 15 | | 20.69 | 20.66 | 19.64 |
| 16 | 250 V & 100 μF | 20.65 | 20.62 | 19.64 |

## *HPL 170 A1*

Switching duty: Auxilliary breaker in KEMA's High-Power-Laboratories.

Characteristics of the circuit-breaker according to the breaker name-plate and the manufacturers operating instructions:

The insulating medium in the circuit breaker is SF6. The breaker is provided for **single-phase operation**. and has one interrupting element per pole.

| | | |
|---|---|---|
| Manufacturer | : | ABB |
| Type | : | HPL 170A1 |
| Rated voltage | : | 170 kV |
| Rated frequency | : | 50 Hz |
| Rated nominal current | : | 4000 A |
| Breaking current. symmetric | : | 63 kA |

Data of mechanism:

| | | |
|---|---|---|
| Drive | : | BLG 1002 |
| Serial Number | : | 2943 2074-10 |

Spring-operated.

| | | |
|---|---|---|
| Control voltage | : | 110 V DC |
| Number of tripping systems | : | 1 |

SF6 Gas pressure:

| | | |
|---|---|---|
| Maximum working pressure | : | 0.80 MPa |
| Filling pressure (20 °C) | : | 0.70 MPa |
| Signalling pressure (20 °C) | : | 0.62 MPa |
| Blocking pressure (20 °C) | : | 0.60 MPa |

**TABLE 14** - *Test results with 250 Volt opening coil voltage pulsed via a 300 μF, 0,62 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 18.68 | 18.68 | 18.71 |
| 2 | 18.72 | 18.55 | 18.60 |
| 3 | 18.57 | 18.58 | 18.67 |
| 4 | 18.56 | 18.57 | 18.50 |
| 5 | 18.61 | 18.55 | 18.50 |
| 6 | 18.65 | 18.60 | 18.58 |
| 7 | 18.60 | 18.53 | 18.44 |
| 8 | 18.63 | 18.60 | 18.53 |
| 9 | 18.57 | 18.53 | 18.60 |
| 10 | 18.70 | 18.60 | 18.42 |
| 11 | 18.62 | 18.55 | 18.62 |
| Mean | 18.63 | 18.58 | 18.56 |
| Std | 0.05 | 0.04 | 0.09 |
| Minimum | 18.56 | 18.53 | 18.42 |
| Maximum | 18.72 | 18.68 | 18.71 |

Table 14
HPL 170 A1

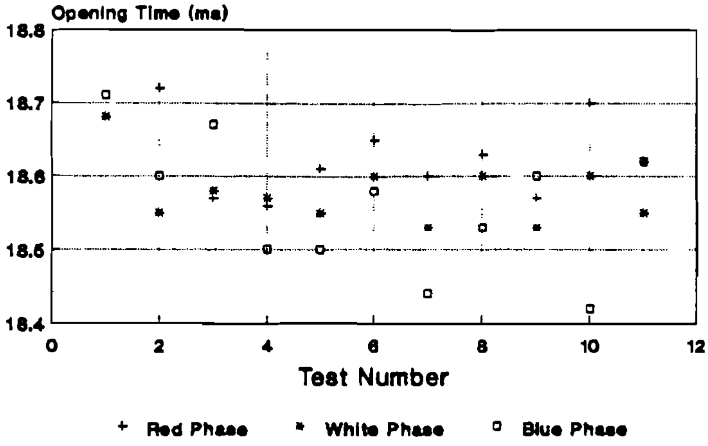


**TABLE 15** - *Test results for different opening coil voltages pulsed via different capacitor combinations, 0,62 MPa SF6 pressure.*

| Test Number | Opening Coil Voltage & Capacitor Value | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|---|
| 1 | 200 V & 300 μF | 18.98 | 18.87 | 18.81 |
| 2 | | 18.96 | 18.93 | 18.93 |
| 3 | | 18.99 | 18.85 | 18.90 |
| 4 | 150 V & 300 μF | 19.12 | 19.00 | 18.91 |
| 5 | | 20.00 | 19.56 | 19.39 |
| 6 | | 19.91 | 19.59 | 19.31 |
| 7 | 100 V & 300 μF | 20.33 | 22.35 | 19.61 |
| 8 | | ☹ | ☹ | 21.30 |
| 9 | | ☹ | ☹ | 21.17 |
| 10 | | ☹ | ☹ | 21.91 |
| 11 | 100 V & 200 μF | ☹ | ☹ | ☹ |

Test numbers 18. 19. 20. 21 and 22. gave completely different results. It was only possible to switch the blue phase pole. with the applied voltage / capacitor combination.

**TABLE 16** - *Test results with 250 Volt closing coil voltage pulsed via a 300 μF capacitor, 0,62 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 68.57 | 69.50 | 66.07 |
| 2 | 67.77 | 67.33 | 66.69 |
| 3 | 67.26 | 68.02 | 66.60 |
| 4 | 68.04 | 69.28 | 64.77 |
| 5 | 68.42 | 66.81 | 65.78 |
| 6 | 68.86 | 68.23 | 64.50 |
| 7 | 69.18 | 67.63 | 65.34 |
| 8 | 67.96 | 67.34 | 65.07 |
| 9 | 68.44 | 67.14 | 65.63 |
| 10 | 68.28 | 67.32 | 67.44 |
| 11 | 68.40 | 67.28 | 64.70 |
| 12 | 69.59 | 67.04 | 65.22 |
| 13 | 68.95 | 68.18 | 65.01 |
| 14 | 68.03 | 68.68 | 65.94 |
| 15 | 68.11 | 68.11 | 65.97 |
| 16 | 67.49 | 68.19 | 65.46 |
| Mean | 68.33 | 67.88 | 65.64 |
| Std | 0.61 | 0.79 | 0.80 |
| Minimum | 67.26 | 66.81 | 64.50 |
| Maximum | 69.59 | 69.50 | 66.69 |

Table 16
HPL 170 A1

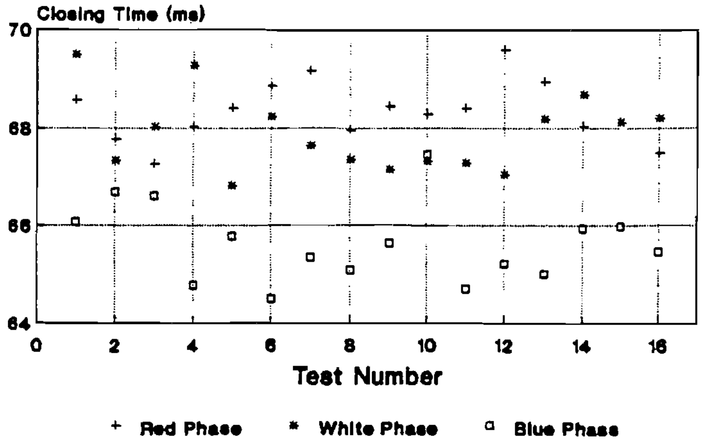


**TABLE 17** - *Test results with different closing coil voltages pulsed via a 300 µF capacitor, 0,62 MPa SF6 pressure.*

| Test Number | Closing Coil Voltage (Volt) | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|---|
| 1 | 200 | 69.50 | 68.61 | 66.46 |
| 2 | | 68.00 | 66.70 | 65.37 |
| 3 | | 68.39 | 67.98 | 66.97 |
| 4 | | 68.12 | 66.67 | 66.19 |
| 5 | | 69.20 | 68.23 | 68.07 |
| 6 | 150 | 69.14 | 67.26 | 66.46 |
| 7 | | 68.23 | 67.79 | 67.15 |
| 8 | | 68.67 | 68.66 | 66.05 |
| 9 | | 69.76 | 68.54 | 64.95 |
| 10 | | 67.90 | 68.68 | 66.72 |
| 11 | 100 | 70.00 | 67.24 | 66.17 |
| 12 | | 71.06 | ☹ | ☹ |
| 13 | | 70.31 | 69.48 | 68.35 |
| 14 | | ☹ | ☹ | ☹ |

**TABLE 18** - *Test results with 250 Volt closing coil voltage pulsed via a 300 μF capacitor, 0,70 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 67.87 | 67.61 | 65.33 |
| 2 | 69.28 | 67.81 | 66.21 |
| 3 | 69.28 | 66.39 | 65.87 |
| 4 | 67.13 | 68.18 | 66.56 |
| 5 | 68.09 | 68.00 | 65.73 |
| 6 | 67.74 | 66.25 | 67.32 |
| 7 | 68.41 | 67.05 | 65.37 |
| 8 | 68.79 | 67.34 | 66.95 |
| 9 | 68.49 | 69.24 | 65.71 |
| 10 | 69.01 | 68.28 | 64.81 |
| 11 | 67.67 | 67.67 | 67.28 |
| 12 | 68.12 | 67.76 | 65.37 |
| Mean | 68.32 | 67.63 | 66.04 |
| Std | 0.68 | 0.82 | 0.82 |
| Minimum | 67.13 | 66.25 | 64.81 |
| Maximum | 69.28 | 69.24 | 67.32 |

**TABLE 19** - *Test results with 250 V opening coil voltage pulsed via a 300 μF capacitor, 0,70 MPa SF6 pressure.*

| Test Number | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|
| 1 | 18.70 | 18.64 | 18.55 |
| 2 | 18.68 | 18.52 | 18.67 |
| 3 | 18.55 | 18.60 | 18.51 |
| 4 | 18.60 | 18.54 | 18.39 |
| 5 | 18.63 | 18.52 | 18.46 |
| 6 | 18.56 | 18.58 | 18.48 |
| 7 | 18.59 | 18.50 | 18.48 |
| 8 | 18.66 | 18.45 | 18.53 |
| 9 | 18.72 | 18.57 | 18.45 |
| 10 | 18.53 | 18.52 | 18.45 |
| 11 | 18.64 | 18.69 | 18.51 |
| 12 | 18.65 | 18.59 | 18.69 |
| 13 | 18.60 | 18.52 | 18.43 |
| 14 | 18.72 | 18.56 | 18.57 |
| 15 | 18.73 | 18.44 | 18.52 |
| Mean | 18.64 | 18.55 | 18.51 |
| Std | 0.06 | 0.07 | 0.08 |
| Minimum | 18.53 | 18.44 | 18.39 |
| Maximum | 18.73 | 18.69 | 18.69 |

Table 18
HPL 170 A1

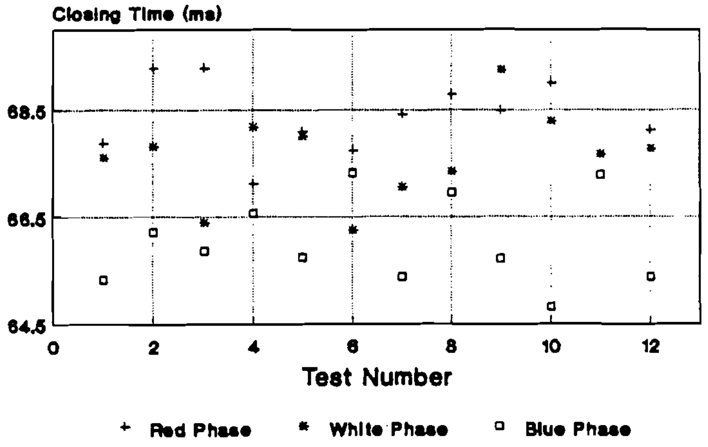


Table 19
HPL 170 A1

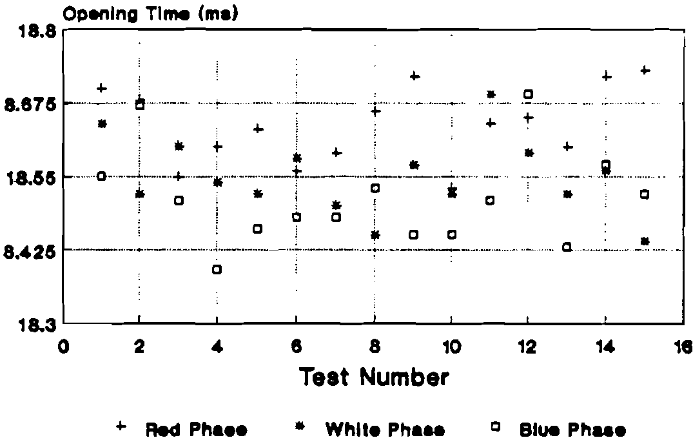


**TABLE 20** - *Test results with different opening coil voltages pulsed via a 300 μF capacitor, 0,70 MPa SF6 pressure.*

| Test Number | Opening Coil Voltage (Volt) | Red Phase Pole (ms) | White Phase Pole (ms) | Blue Phase Pole (ms) |
|---|---|---|---|---|
| 1 | 150 | 18.93 | 18.89 | 18.75 |
| 2 | | 19.27 | 18.98 | 18.86 |
| 3 | | 20.14 | 22.07 | 19.34 |
| 4 | | 19.92 | 22.07 | 19.41 |
| 5 | | 20.07 | 19.67 | 19.42 |
| 6 | | 20.07 | 19.67 | 19.42 |
| 7 | 100 | 20.41 | 22.23 | 19.54 |
| 8 | | ☹ | ☹ | 21.54 |
| 9 | | ☹ | 22.58 | 21.23 |
| 10 | | ☹ | ☹ | ☹ |
| 11 | | ☹ | ☹ | ☹ |
| 12 | 150 | 19.98 | 19.65 | 19.37 |

## *LTB 170 D1*

Switching duty: Capacitor Bank Switching: 100 MVAr - 150 kV. neutral unearthed.

Characteristics of the circuit-breaker according to the breaker name-plate and the manufacturers operating instructions:

The insulating medium in the circuit breaker is SF6. The breaker is provided for **single-phase operation.** and has one interrupting element per pole.

| | | |
|---|---|---|
| Manufacturer | : | ABB |
| Type | : | LTB 170 D1 |
| Data of mechanism: | | |
| Drive | : | BLK52 |
| Control voltage | : | 110 VDC |
| Number of tripping systems | : | 3 |

Table 21
LTB 170 D1

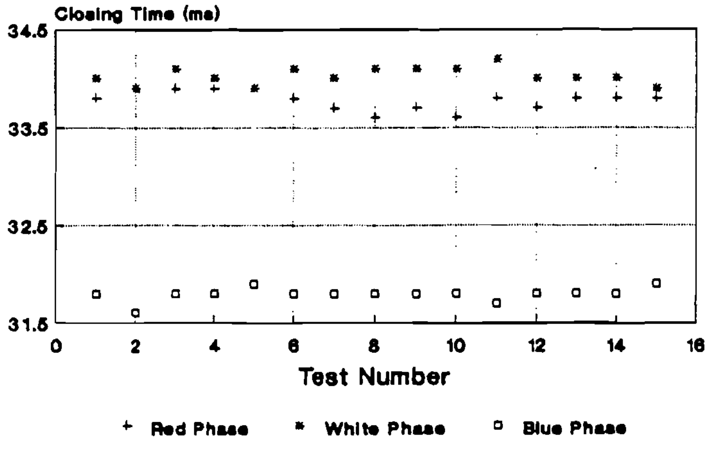


**TABLE 21** - *Test results for breaker closing with rated coil voltages and $SF_6$ pressures.*

| Test Number | Red Phase [ms] | White Phase [ms] | Blue Phase [ms] |
|---|---|---|---|
| 1 | 33.8 | 34.0 | 31.8 |
| 2 | 33.9 | 33.9 | 31.6 |
| 3 | 33.9 | 34.1 | 31.8 |
| 4 | 33.9 | 34.0 | 31.8 |
| 5 | 33.9 | 33.9 | 31.9 |
| 6 | 33.8 | 34.1 | 31.8 |
| 7 | 33.7 | 34.0 | 31.8 |
| 8 | 33.6 | 34.1 | 31.8 |
| 9 | 33.7 | 34.1 | 31.8 |
| 10 | 33.6 | 34.1 | 31.8 |
| 11 | 33.8 | 34.2 | 31.7 |
| 12 | 33.7 | 34.0 | 31.8 |
| 13 | 33.8 | 34.0 | 31.8 |
| 14 | 33.8 | 34.0 | 31.8 |
| 15 | 33.8 | 33.9 | 31.9 |
| Average | 33.78 | 34.03 | 31.79 |
| Std | 0.10 | 0.09 | 0.07 |
| Minimum | 33.60 | 33.90 | 31.60 |
| Maximum | 33.90 | 34.20 | 31.90 |

**TABLE 22** - *Test results for breaker opening (trip coil 1) with rated coil voltages and $SF_6$-pressures.*

Opening Operations (Open 1):

| Test Number | Red Phase [ms] | White Phase [ms] | Blue Phase [ms] |
|---|---|---|---|
| 1 | 24.1 | 23.2 | 24.5 |
| 2 | 23.6 | 22.9 | 24.8 |
| 3 | 23.9 | 23.4 | 24.4 |
| 4 | 24.1 | 23.1 | 24.1 |
| 5 | 24.0 | 23.7 | 24.7 |
| Average | 23.94 | 23.26 | 24.50 |
| Std | 0.21 | 0.31 | 0.27 |
| Minimum | 23.60 | 22.90 | 24.10 |
| Maximum | 24.10 | 23.70 | 24.80 |

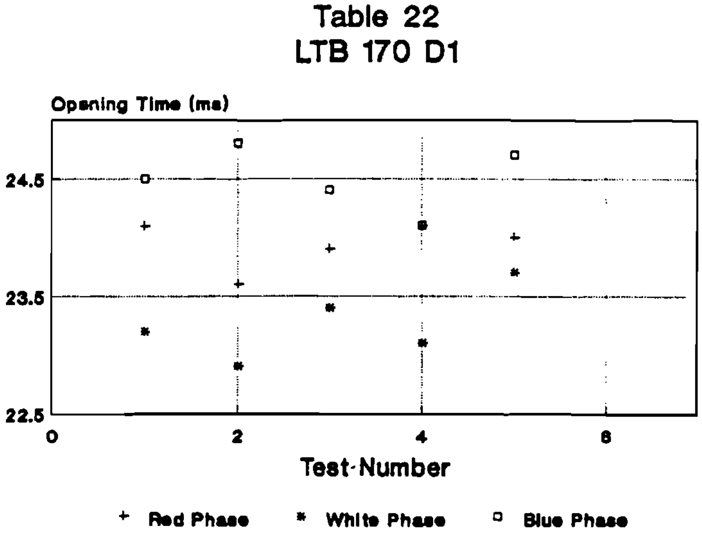


**TABLE 23** - *Test results for breaker opening (trip coil 2) with rated coil voltages and $SF_6$-pressures.*

Opening Operations (Open 2):

| Test Number | Red Phase [ms] | White Phase [ms] | Blue Phase [ms] |
|---|---|---|---|
| 1 | 23.7 | 23.5 | 25.0 |
| 2 | 24.1 | 23.4 | 24.3 |
| 3 | 24.3 | 24.6 | 24.6 |
| 4 | 24.3 | 23.4 | 25.0 |
| 5 | 24.3 | 23.5 | 25.1 |
| Average | 24.14 | 23.68 | 24.80 |
| Std | 0.26 | 0.52 | 0.34 |
| Minimum | 23.70 | 23.40 | 24.30 |
| Maximum | 24.30 | 24.60 | 25.10 |

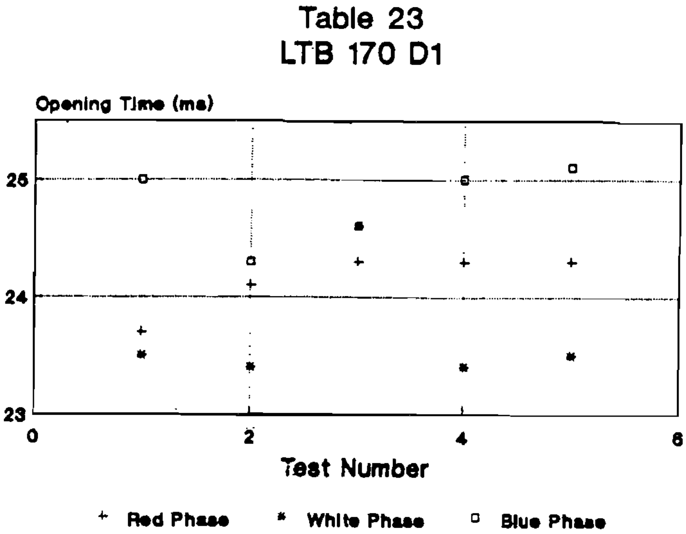
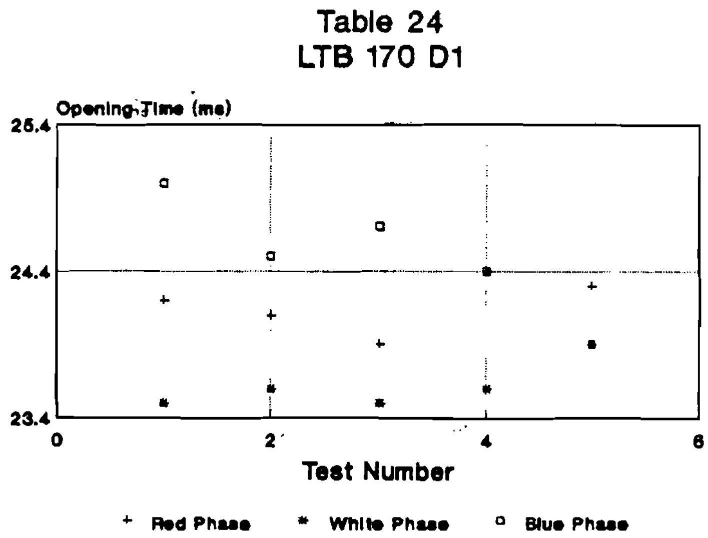


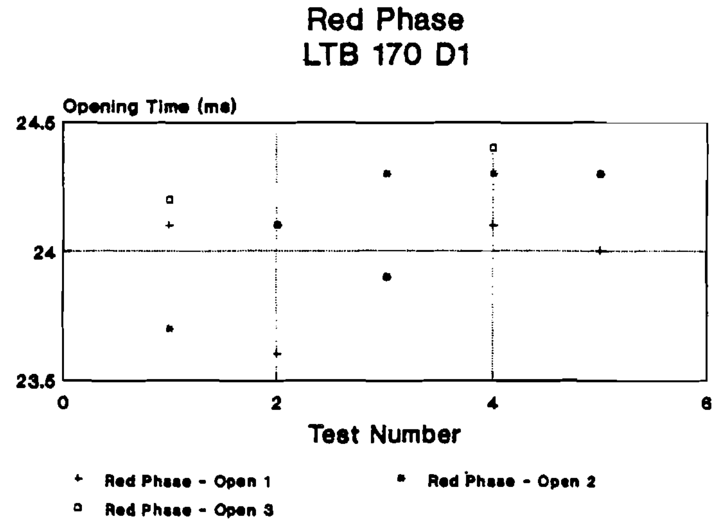
**TABLE 24** - *Test results for breaker opening (trip coil 3) with rated coil voltages and $SF_6$-pressures.*

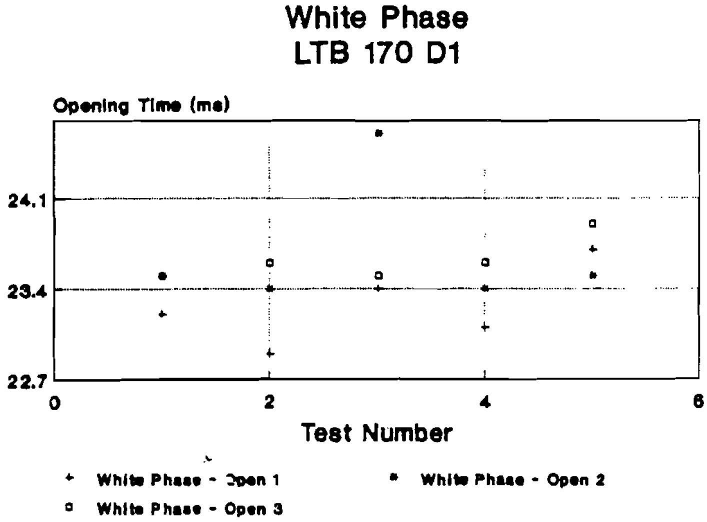
Opening Operations (Open 3):

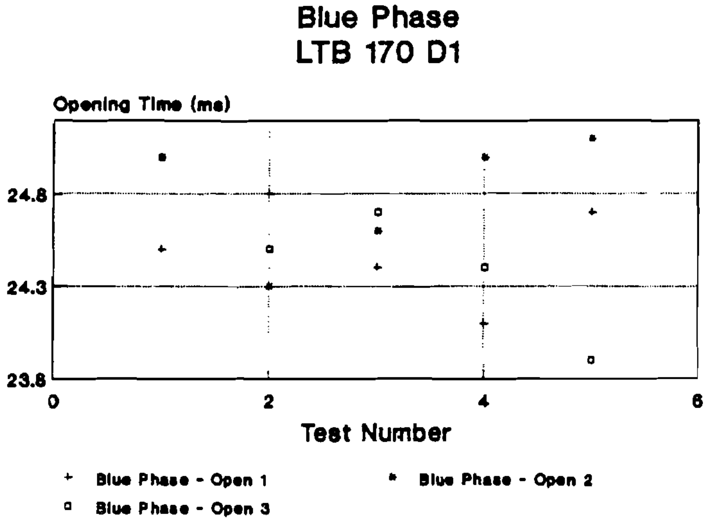
| Test Number | Red Phase [ms] | White Phase [ms] | Blue Phase [ms] |
|---|---|---|---|
| 1 | 24.2 | 23.5 | 25.0 |
| 2 | 24.1 | 23.6 | 24.5 |
| 3 | 23.9 | 23.5 | 24.7 |
| 4 | 24.4 | 23.6 | 24.4 |
| 5 | 24.3 | 23.9 | 23.9 |
| Average | 24.18 | 23.62 | 24.50 |
| Std | 0.19 | 0.16 | 0.41 |
| Minimum | 23.90 | 23.50 | 23.90 |
| Maximum | 24.40 | 23.90 | 25.00 |



Influence of the trip coil on the operating time of the circuit breaker:







### *Discussion and Conclusions*

These tables lead to the following conclusions:

- The $SF_6$ pressure has no influence on the operating times.

- The control voltage can have a significant influence. In general the operating time becomes longer with a lower voltage, and becomes shorter with an increase of the control voltage.

- The different opening coils can give different results for the operating times, this can be concluded from the Borssele no-load tests. The same coils should be used with successive measurements if comparisons are necessary.

- The air pressure for a pneumatic drive has a significant influence on the operating time of the AEG breaker, this makes it difficult to apply for controlled switching because this is a too big restriction.

- The strange effect can be seen that for the LTB breaker the time spread on closing is smaller than the time-spread on opening. This is strange because the opening time is smaller than the closing time. For all the other breakers the oppossite effect has been measured which can be expected. However this effect becomes clear if the breakers are studied more carefully. The LTB breaker is of the self-blast type whereas the HPL breaker is of the puffer type. The differences in extinguishing principle change the demand of operating power to a large extent. The LTB has a more optimized dielectric withstand which causes that the contact speed can be less, especially for the case of gap voltage zero switching. For the LTB breaker, the closing spring also charges the opening spring. In conclusion, the lower speed and also a lower force on the latch gives a bigger spread in opening times.

- The main breaker chambers should be used for timing measurements. If the auxiliary switches are used, wrong information will be obtained with respect to the breakers operating times. There is usually a significant differences with the main chambers timing and the auxiliaries timing.

- The first most important shot is very often missed, ie not measured, with no-load tests. Most of the times the reason for this were faulty leads, improper connections to the breaker chambers, or wrong instrument settings. This problem can be solved if a dedicated person carries out these tests.

- The use of an ordinary intermediate relay gave timing results with a large time-spread. If an intermediate relay is necessary, it should be fast and have a stability which is better than the controlled relay.

- The pole simultaneity was acceptable for all breakers, except for the AEG it was found to be too much. This is probably due to improper mechanical adjustments on commisioning or aging. It might also be very well possible that there is a defective air valve.

- Bouncing and rebound effects were measured on closing as well as on opening. The no-load measurements were carried out with low voltage and low current. The measured effects are due to shortcomings of the measuring equipment, with an appropriate filtering of the measured signal, it is possible to get a defined "contact touch". Most important is however that the bouncing has no effect on the circuit breakers switching performance.

- Micro second resolutions on the operating times are not possible from a mechanical point of view. So it is sufficient to use a smallest time step of 0,1 ms at no-load tests. A step of 0,5 ms is considered as being too large.

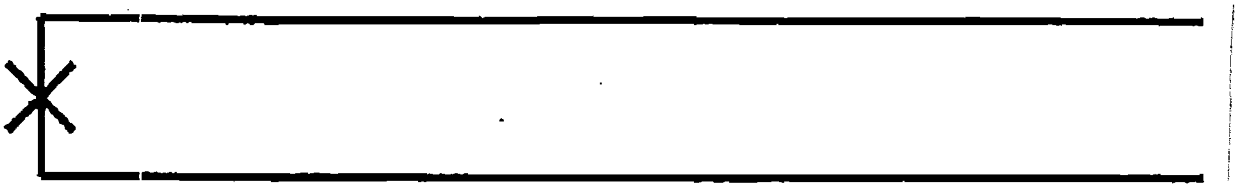
- The operating times are more consistent with a higher coil operating voltage.

# Appendix 4

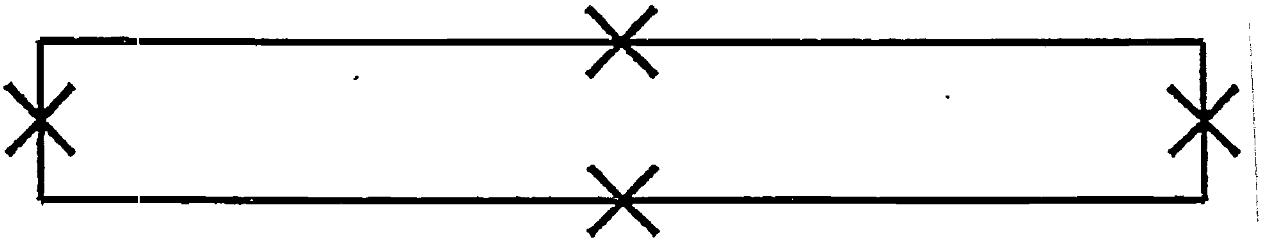
## Substation Layouts, Shunt Capacitor Banks and Shunt Reactors

***Substations*** - Four standard substation busbar arrangements are in use:

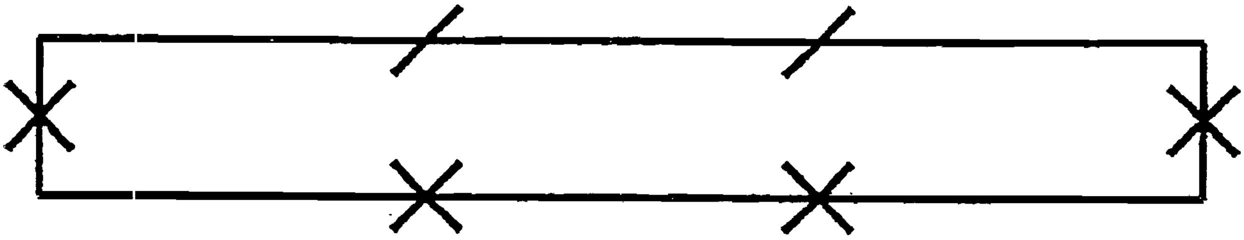
1. Duplicate busbar and one bus coupler, in *figure 1*:



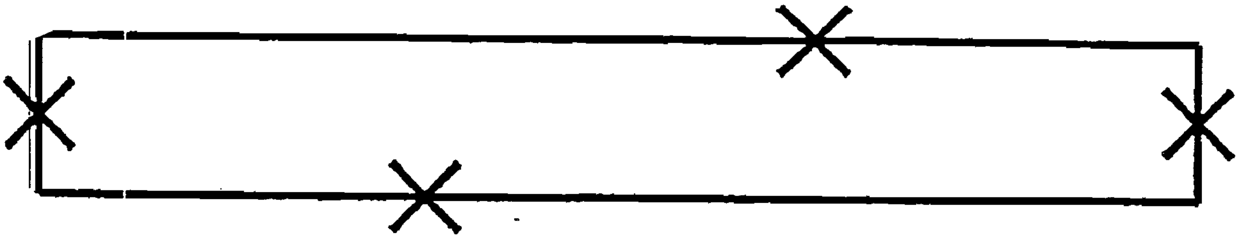
2. Duplicate busbar, both busbars sectionalized and one bus coupler on each section, in *figure 2*:



3. Main and hospital busbar, main busbar sectionalized and one bus coupler on each end section, in *figure 3*:



4. Duplicate busbar, both busbars sectionalized and one bus coupler on each section, in *figure 4*:



These busbar arrangements are used in ESKOM's Main Transmission System [3.17]. Other type of substations busbar arrangements are the breaker and a half design which is found in many stations in the USA, a lot of mesh type substations are found in the United Kingdom. In South Africa as well as in The Netherlands most of the station layouts are of the double busbar type.

***Shunt Capacitor Banks*** - Within the Eskom Power System three types of capacitor banks are in use:
1. Internally fused capacitor banks.
2. Externally fused capacitor banks.
3. Fuseless capacitor banks.

In figure 5 an overview of these types is given.
The three common connections [3.2] for the capacitor banks are:
1. Delta.
2. Solidly Grounded single or double Y connected banks.
3. Floating single or double Y connected banks

Since about 7 years also grounding using a low voltage neutral capacitor is applied. Within the Eskom system this method is applied at Merapi [3.3] and Stikland [3.5] Substation. Most of the banks in the Eskom system use the floating neutral double Y connection. The choice of the bank connection depends on the voltage level of the power system, the rating of the bank, the voltage rating of the capacitor cans used, the power system earthing and the required relay protection. Eskom has standardized its shunt capacitor banks on an un-earthed neutral double Y connected configuration. The neutral is isolated against the full line voltage. Two standard MVAr-ratings are in use for each system voltage.

If the capacitors are externally fused, the faulty unit is isolated from the rest of the bank by the unit fuse operation, after several unit internal sections are short-circuited by faulty elements. Then overvoltage conditions become even more severe across the remainder of the units of the affected group. Eventually other units will fail due to the voltage stress until the out-of-balance protection isolates the entire bank from the system. For internally fused units, the fuse operations isolate the associated faulty elements within the affected units. Overvoltages become more and more severe across the element groups of the affected unit every time a fuse operates. The out of balance protection should switch out the bank before overvoltages reach a level to cause partial discharge inception within the unit dielectric with detrimental effects on the insulating fluid. In a fuseless capacitor bank, when element sections in a string are short circuited, as a result of section element failures, the voltage increase is equally distributed across the remaining healthy sections of the string. As there are many capacitor sections in a string, the increase in voltage across the healthy sections remains below accepted limits even after several section failures.

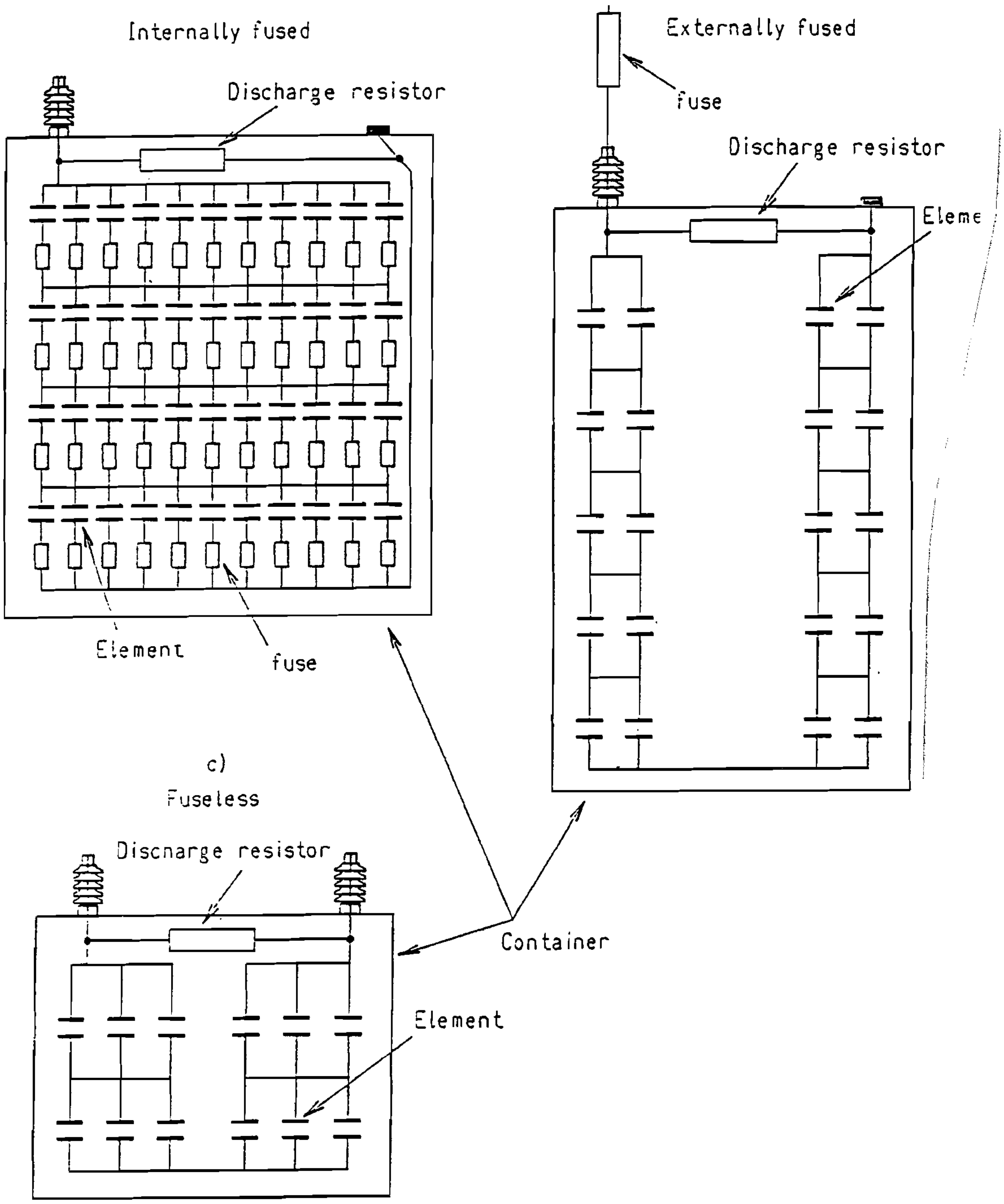


**Figure 5** - *Internally fused, externally fused and fuseless capacitors.*

To a large extent, a capacitor bank's performance depends on the particular technology used to build the bank. For the past 30 years all of Eskom's shunt capacitor banks have been built using internally or externally fused capacitor units. The advantages and disadvantages have been debated over this period, but no definite conclusion was reached. The new technology of fuseless capacitor units was recently introduced into the Eskom system at Merapi (February 1992) and Stikland (February 1993) Substations.

In a fused capacitor bank, overvoltages, which arise as result of internal element failures, stress mainly the remainder of the elements within the affected unit. This leads other unit elements to fail and unit internal overvoltages to increase even further.

*Characteristics of internally fused [3.4], [3.10], [3.11] capacitor banks:*
Advantages:
1. Loss of element does not mean that the whole unit will be tripped. This means that especially in smaller banks tripping is unnecessary which gives greater availability.
2. The construction of the capacitor bank is simple.

Dis-advantages:
1. There is no visible indication of failure of a capacitor unit.
2. Difficult to test bank and unit in the field.
3. Gradual loss of capacity in service.
4. Limited voltage rating.
5. Poor unbalance current sensitivity in ***large high voltage banks***. It is also very difficult to find and isolate a faulty unit in a capacitor bank that contains several hundreds of capacitor units.

*Characteristics of externally fused [3.4], [3.10], [3.11] capacitor banks:*
Advantages:
1. Visible indication of a faulty capacitor unit.
2. Easy field checking is possible.
3. Higher unbalance currents. This means that the unbalance protection can be less sensitive.
4. Capacitor units for higher voltages than the internally fused units are available, this implies that a simpler construction is possible, especially for the higher voltage banks.
5. The capacitor unit does not have to be replaced in the case of false fuse operation.

Dis-advantages:
1. Fuse assemblies corrode in hostile environments.
2. For the ***smaller banks***, a loss of an element means the loss of the entire bank.

This means that this bank is less reliable than the internally fused one.

3. Some extra space is needed for fuse clearances.

*Characteristics of fuseless banks:*

Fuses were essential with the other capacitor designs to prevent case rupture. Fuses are still provided for this purpose in modern capacitor units allthough the probability of case rupture is much less nowadays. The principal function of the fuse is to disconnect a faulty element in the case of an internally fused unit. For an externally fused unit the faulty unit will be removed. The capacitor bank can continue its operational duties in these cases. The probability of case rupture can be eliminated by a suitable robust capacitor design and by a reduction of the parallel discharge energy. In the internally and externally fused banks the capacitor units are arranged in a series and parallel configuration. The parallel discharge will be reduced to a great extent if the cross-bonding between the series groups is eleminated. In this case the bank would consist of a number of independent strings of capacitor units which are connected in series. When modern capacitors (polypropylene film) fail, an internal solid short-circuit is produced between the two bushings. This short-circuit is able to carry the load-current without the nasty effects like gassing or arcing. These two features mean that the fuses can be eliminated.

Overvoltages are taken care of by ensuring that there are enough series elements in a string of series capacitor units. The fuseless technology is therefore also known as the low energy-no fuse technology. This novel technology offers a largely improved reliability because problems with fusing are eliminated. So the first line of protection against dielectric failure of a capacitor element is the stable weld which occurs naturally at the point of puncture. The design of the protection for a fuseless capacitor bank focuses on the unbalance protection to provide tripping in the event of a severe unbalance within the bank and alarm for the presence of unbalance indicating unit failure(s). The short circuiting of one capacitor unit in a fuseless bank gives the same unbalance signal as the operation of a capacitor fuse. Also the requirements for the overcurrent relays and circuit breakers are the same for fuseless and fused banks. The following points have to be pointed out for the fuseless technology [3.4], [3.7], [3.8], [3.9], [3.10] in comparison with the fused technology:

1. *Simplicity* - There is no requirement for fuse rails, insulators, fuses, and the space between units required for proper fuse operation. Elimination of the fuses increases the reliability of the bank because part of the failures of the fused bank are associated with fuse failures. The use of series strings of units in the fuseless construction gives the same increase in availability without the need for fuses.

2. *Varment protection* - The exposed live parts are covered in the same way as pole mounted distribution capacitor equipment. This should increase the

availability of the bank because many banks have been tripped or damaged by varments getting into the bank.

3. *Size* - The fuseless bank is usually about one third the physical volume of a fused bank. This results from the elimination of the fuses and the spacing between units to provide proper fuse operation.

4. *Field assembly* - Pre-assembly and the elimination of the need for field fusing will substantially reduce field assembly labor.

5. *Losses* - The elimination of all fuses eliminates all the $I^2R$ losses associated with the fuses. Also lower voltage capacitor units are used. The lower voltage units means also that there will be lower discharge resistor losses.

6. *Minimum bank size* - Fused capacitor banks must have enough parallel units in each group so that the operation of one fuse does not result in excessive voltages across the remaining units. This requirement usually results in the use of many small capacitor units. With the fuseless bank operation is possible with only one string of units. This results in a substantial reduction in the total number of units and the physical size for a small capacitor bank.

7. *Parallel energy* - In the power industry there is a lot of discussion going on about fusing and the protection of capacitor cans against rupture because of energy dumped into a fault from parallel capacitors. The use of the fuseless technology with the capacitors in strings eliminates the concern for case rupture.

Taking all the foregoing into consideration, it can be said that shunt capacitor banks of middle and higher voltage ratings become more reliable by adopting the fuseless capacitor technology. The use of internally and externally fused capacitor banks is recommended for shunt capacitor applications at voltages below 44 kV. The fuseless technology will not improve the bank reliability and will not be economical at voltages lower then 44 kV. Standardization and application flexibility are improved as fuseless capacitor units of the same rating can be used to construct banks of different size from 44 kV to 400 kV. It is also possible to apply the fuseless technology successfully for the construction of series capacitor installations.

The use of low voltage capacitors [3.6], [3.11] connected from the high voltage capacitor bank neutral to ground can provide improved protection. The protection using the low voltage capacitors consists of one or more parallel low voltage capacitor and an isolation transformer which feeds a trip relay. Normally the unbalance current transformer and burden are inductive and on energizing very large voltages can appear across the current transformer. Protective devices (surge arresters) are required to protect the transformer from damage. The low voltage capacitors have a high continuous current carrying capability and also have a low impedance to harmonics which makes it easy to accomodate harmonic currents, but also gives reduced harmonic voltage across the protection relays. The low voltage capacitors are not fused.

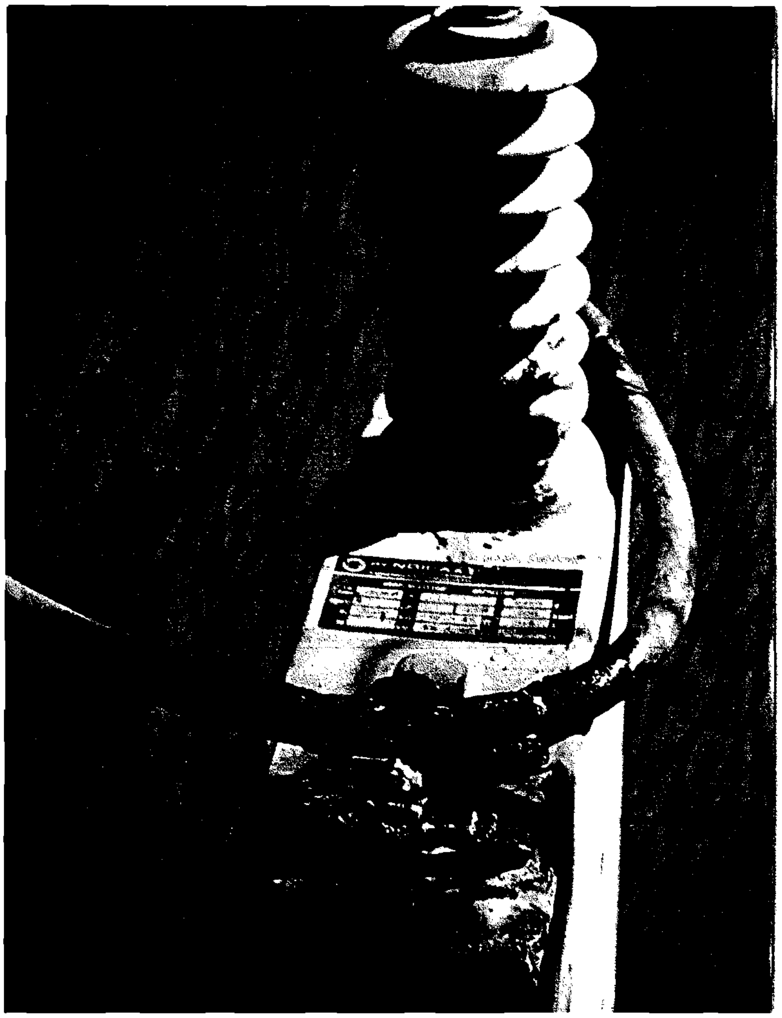


**Figure 6** - *A loose connection caused overheating and resulted in the shown damage.*

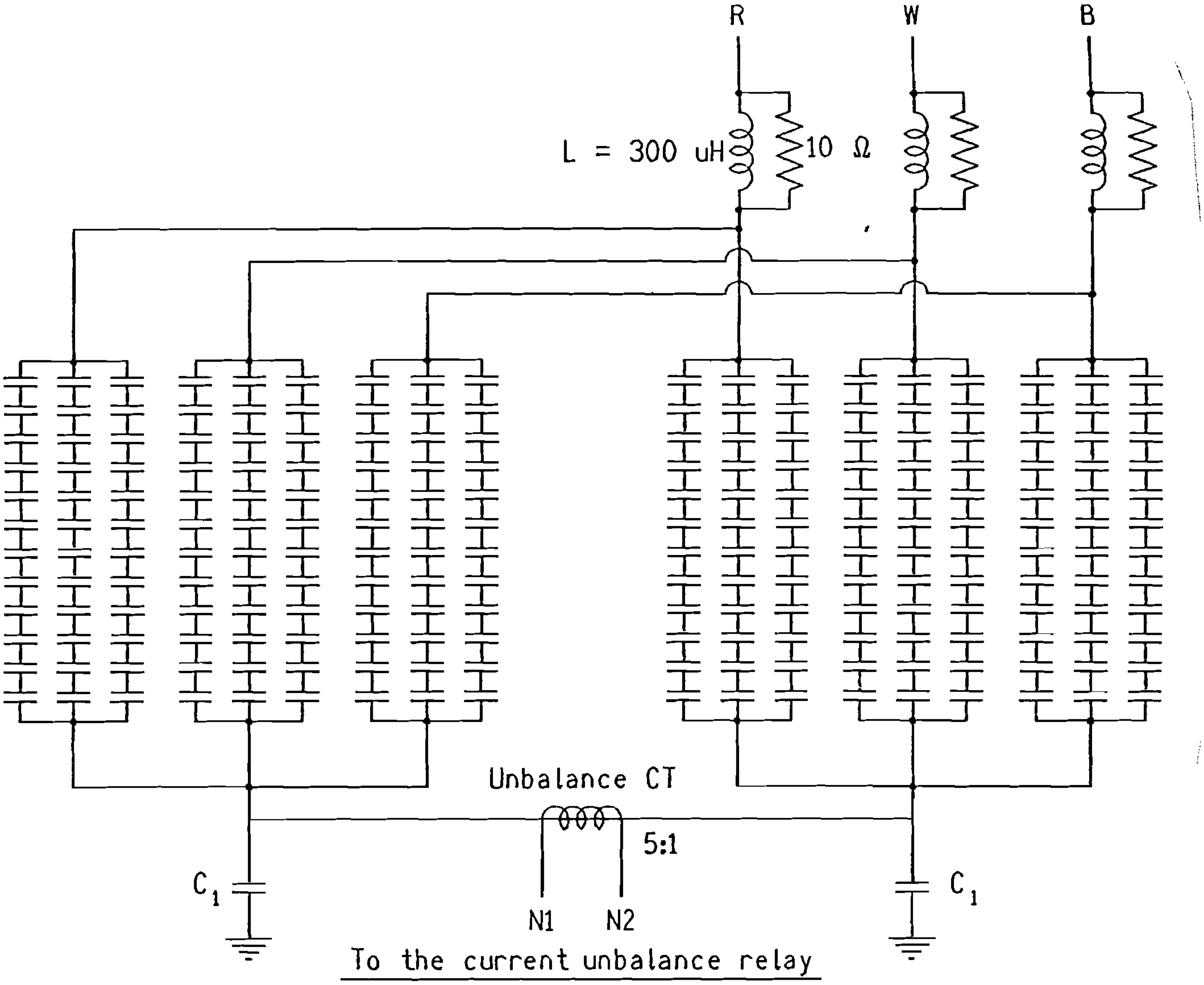
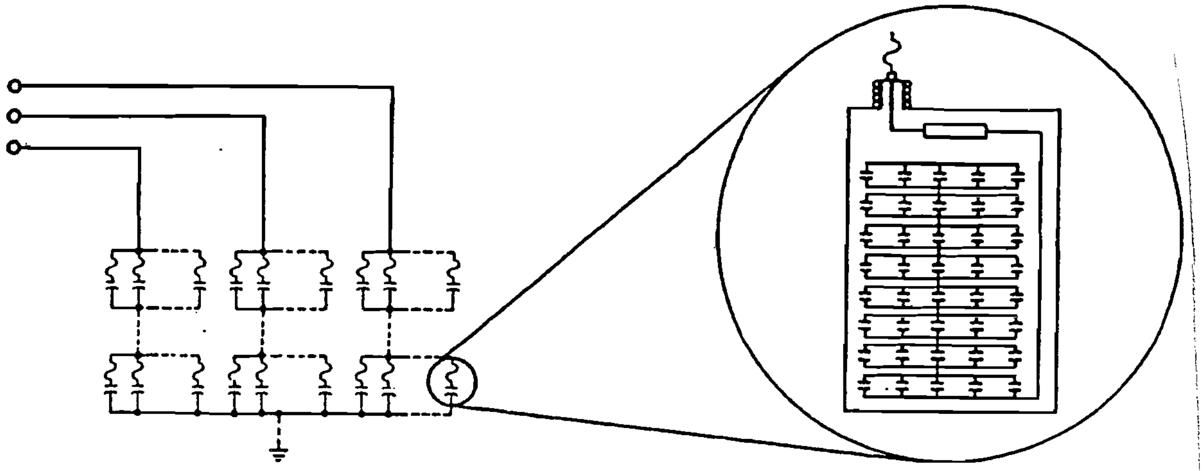


Figure 7 - *Schematic diagram of Stikland's fuseless capacitor bank with neutral earthed using low voltage capacitors.*



(a)

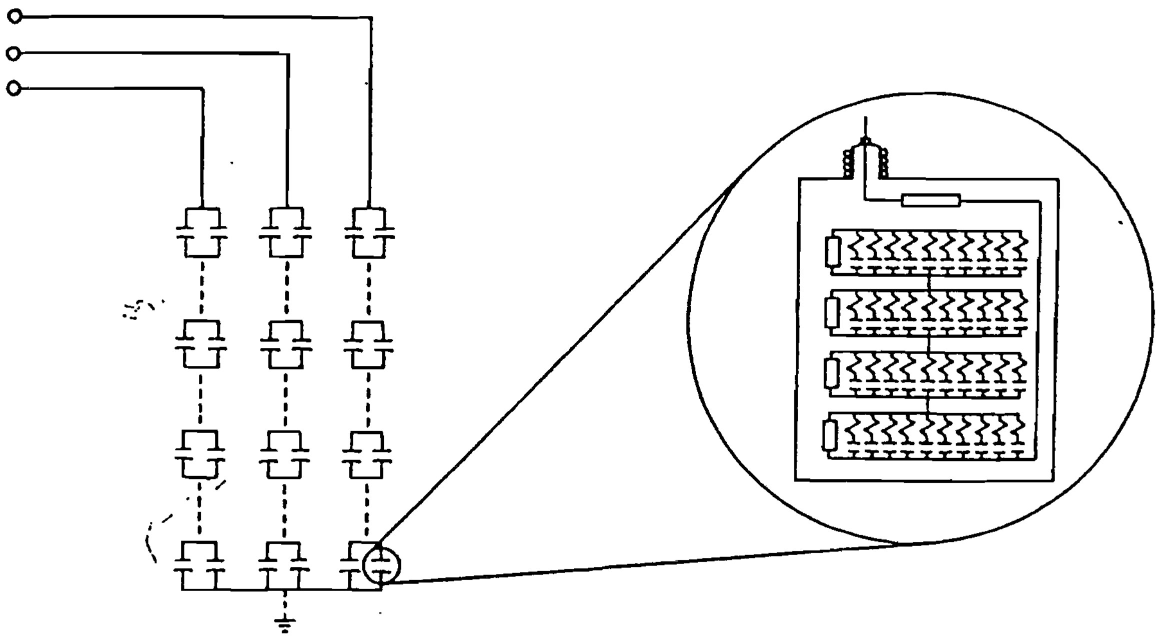


**Figure 8** - *Typical connection of fused capacitor units in one phase of a double star, floating neutral capacitor bank.*

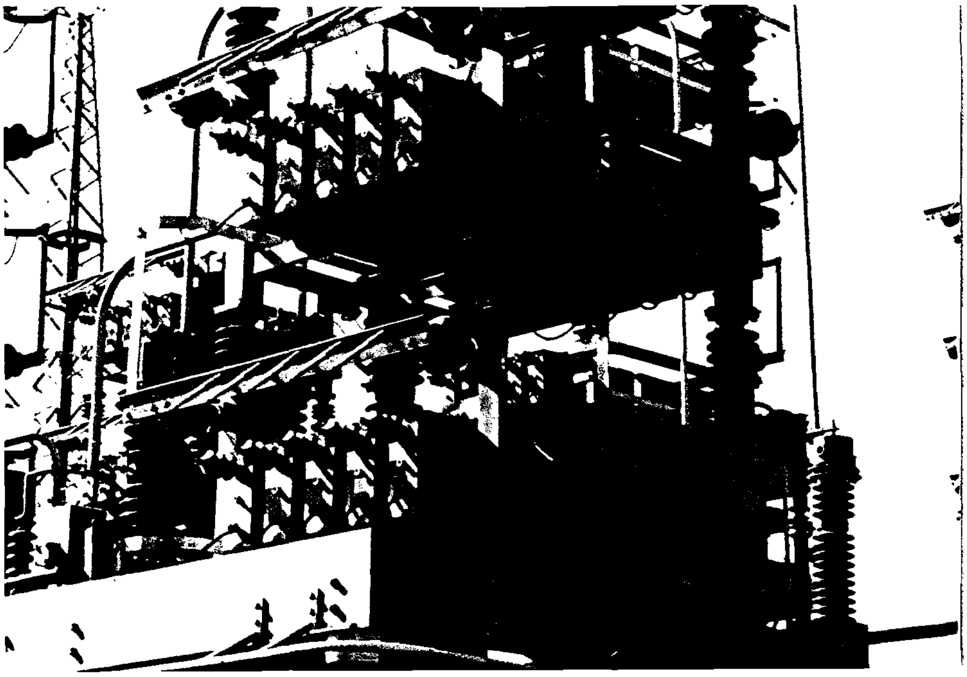


**Figure 9** - *Detail of the 200 MVAr - 275 kV externally fused filter bank at Apollo Substation, South Africa.*

***Shunt Reactors*** - At Doetinchem Substation a 50 MVAr tertiary switched shunt reactor at 50 kV was used. In South Africa at Beta Substation a 400 MVAr shunt reactor is in use at 765 kV. First of all it has to be remarked that both these reactor ratings are not mentioned in the new Application guide for shunt reactor switching for AC high-voltage circuit breakers [3.16] which is currently under preparation by IEC Sub-Committee 17A. It appears that every time when somebody writes about the characteristics and features of shunt reactors, reference is made to [3.14] of 1984 also in this reference these ratings are not covered. Shunt reactors can be divided into two groups according to the type of core installed inside the winding, namely the gapped-core type and the air-core type with a magnetic shield.

The characteristics of reactors [3.12], [3.13], [3.14], [3.15] & [3.16] depends to a great extent on the design, which can be:

1. 3-legged gapped iron-core
2. 5-legged gapped iron-core
3. shell-type (early designs from the 1950's)
4. coreless (air-cored)

During the 1960's there was some controversy, affected by prestige, about the question whether reactors of shell-type or core-type were preferable. At present it can be said that well-designed units of both kinds are providing good service, but that technical development has favoured the core-type reactor. The factor that opened the way to the manufacturing of really large core-type reactors was the technique of securing the laminations in the core segments by means of bonding or moulding in thermosetting resin instead of by means of rivets or bolts. The spacers around the gap area must be able to withstand a long period of operation and be effective in reduction of electromagnetic vibrations. Core blocks and spacers are layered alternately and then molded into a common limb body. Together with the top and bottom yokes, the core limbs for three phases are tightened uniformly with non-magnetic tie bolts.

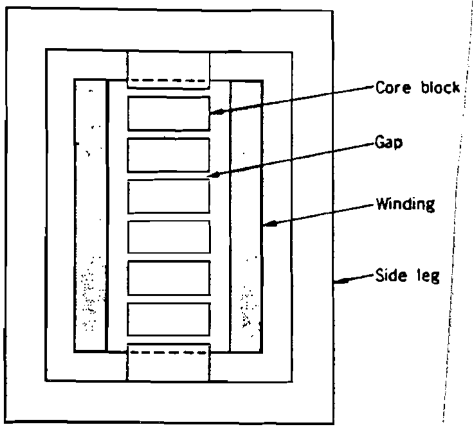


**Figure 10** - *Cross-sectional view of single phase three-legged gapped-core reactor.*

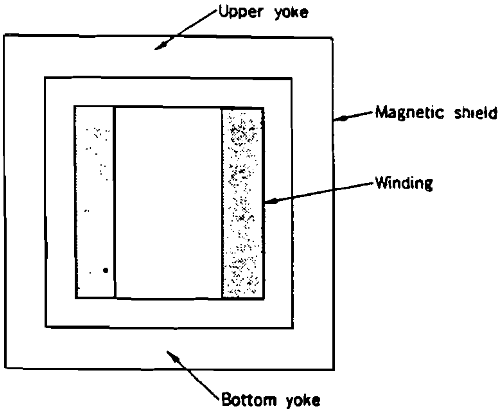
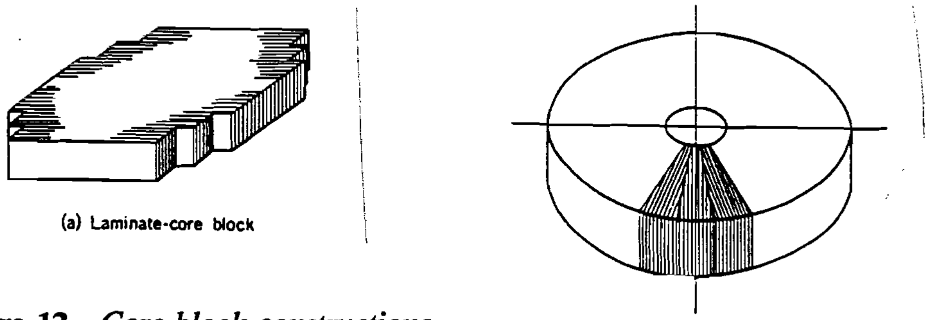


**Figure 11** - *Cross-sectional view of single-phase air-core reactor with magnetic shield.*

In tables 1 and 2 of [3.16] some of the basic electrical characteristics (Rated voltage, rated 3-phase power, power frequency, rated current, inductance, capacitance and natural frequency) are given. Medium voltage reactors are either oil-filled units with three-legged gapped cores and layer windings or more recently air-cored dry coil units. At 765 kV shunt reactors are exclusively banks of single-phase units.

The capacitance values are dependent on the design and construction of the reactors. For oil-filled units the capacitance is composed of:

1. Bushing capacitance.
2. Winding series capacitance.
3. Winding capacitances to ground or to shields.



(a) Laminate-core block

(b) Radial-core block

**Figure 12** - *Core block constructions.*

The bushing capacitances vary from 300 to 800 pF. The winding capacitances vary from about 1200 pF up to about 3500 pF. Layer windings have the lowest capacitance values and interleaved disc windings the highest values.

The gapped-core type shunt reactor has a winding that surrounds a core formed by alternately layered air gaps and core blocks. The gapped-core type is further classified by shape into laminate-core block and radial-core block. The capacity of a shunt reactor is expressed by the magnetic energy stored in its air gap. The gapped-core shunt reactor is capable of storing a large amount of energy even with its small gaps. This is due to the use of the highly permeable silicon steel for the core blocks which make a high density magnetic flux possible. However the magnetic flux in the core block expands in a gap component and a radial component. Due to this a fringing flux is produced which can cause local overheating in the core block. This is a complicated process and reference is made to [3.12] and [3.15]. The air-core reactor with a magnetic shield has an air-core inside the winding. In this construction, the air-core is too large for a gap to increase the magnetic flux density, but the capacity of the reactor can be increased by enlarging the gap volume. An increase in the laminated thickness of the magnetic shield solves the problem of local overheating. Simple construction and easily controlled manufacturing processes have made this type popular in the manufacturing sense of the word.

However due to the larger winding used to obtain the necessary magnetic energy despite the low flux density in the gap, the air-core reactor with a magnetic shield becomes very heavy and bulky (the so-called "copper-machine"). Therefore it will have higher losses than gapped-core reactors.

As it has been explained in chapter 1 the balancing of reactive power in a large interconnected system is a complex problem. There is a need for a base load of reactive power as well as a supplementary load which must be available on supervisory control. Shunt reactors are operated at virtually 100 % load whenever they are connected to transmission lines. Therefore their losses greatly affect the total loss in the power system. If the reactor is connected to the tertiary winding, its power has to be transformed. These losses in a normally dimensioned system transformer will be higher then the reactor's own losses. A tertiary connected reactor is also bound to and dependent on the transformer, whereas the shunt reactor is independent. The tertiary connected reactor operates at medium voltages and the shunt reactor at high system voltages. This also has its impact on the circuit breaker. The loss evaluation of a shunt reactor is a problem of its own. Within utilities there has been an increasing demand that losses in shunt reactors had to be minimized. This resulted into the development of radial-core shunt reactors.

# *Appendix 5*

## *Measuring Equipment used during the Field Tests*

***ESKOM's Mobile Transient Measuring Facility (Situation at July 1993):***

**Measuring Instrument Specifications:**

1. Nicolet Multipro 502
   Multipro digitizers, Types 140 (12 bits) and 160 (8 bits).

2. Multipro 200 Advanced Trigger Board

**Interfacing Equipment:**

1. Haefely high voltage RC dividers, 6 stacked elements each providing a step-down ratio of 1000 : 1.
   Bandwidth: DC to 5 MHz.
   Risetime: 70 ns.

2. Tektronix voltage probes.
   Attenuation ratio: 1000 : 1 (variable by about 9%).
   Maximum input: 13 kV (DC or RMS), 18 kV peak.
   Bandwidth: DC to 75 MHz.
   Risetime: 4,67 ns.

3. Pearson current transformers.
   Maximum peak current: 50 kA.
   Nominal current: 400 A RMS at 50 Hz.
   Bandwidth: 5 Hz to 2 MHz.
   Risetime: 200 μs.
   Transducer: 10 mV equals 1 A.
   Internal diameter: 85 mm.

4. Nicolet Isobe 3000 (Fibre optic system).
   Bandwidth: 15 MHz.
   Risetime: 25 ns.
   Input impedance: 1 MΩ, 50 pF.
   Output impedance: 50 Ω.
   Voltage: 2 V peak-to-peak (50 Ω load).

Operating temperature: $0^{0}$C to $45^{0}$C
10 channels, 3 x 100 m and 1 x 50 m fibre optic cable available.

5. Interposing current transformers.

***KEMA-equipment used in the various field tests:***

**Measuring Instrument Specifications:**

| | | |
|---|---|---|
| 1. | KRENZ digitizers. | (Borssele) |
| 2. | IO-Tech ADC488-digitizer. | (Borssele) |
| 3. | KEMA Transient Recorder (Type Damstra). | (Doetinchem) |

This newly developed special transient recorder was trial tested during field tests at Doetinchem Substation. Sample frequency 50 MHz, ADC 10 bit/50 MHz, combination of digital and analog electronics, digitized measuring data and control signal transfer by optic fibre, general array logic, 6 channels, 32 k memory / channel (slow channels), 16 x 2 k memory (fast channels), all 6 parameters are recorded and displayed simultaneously.

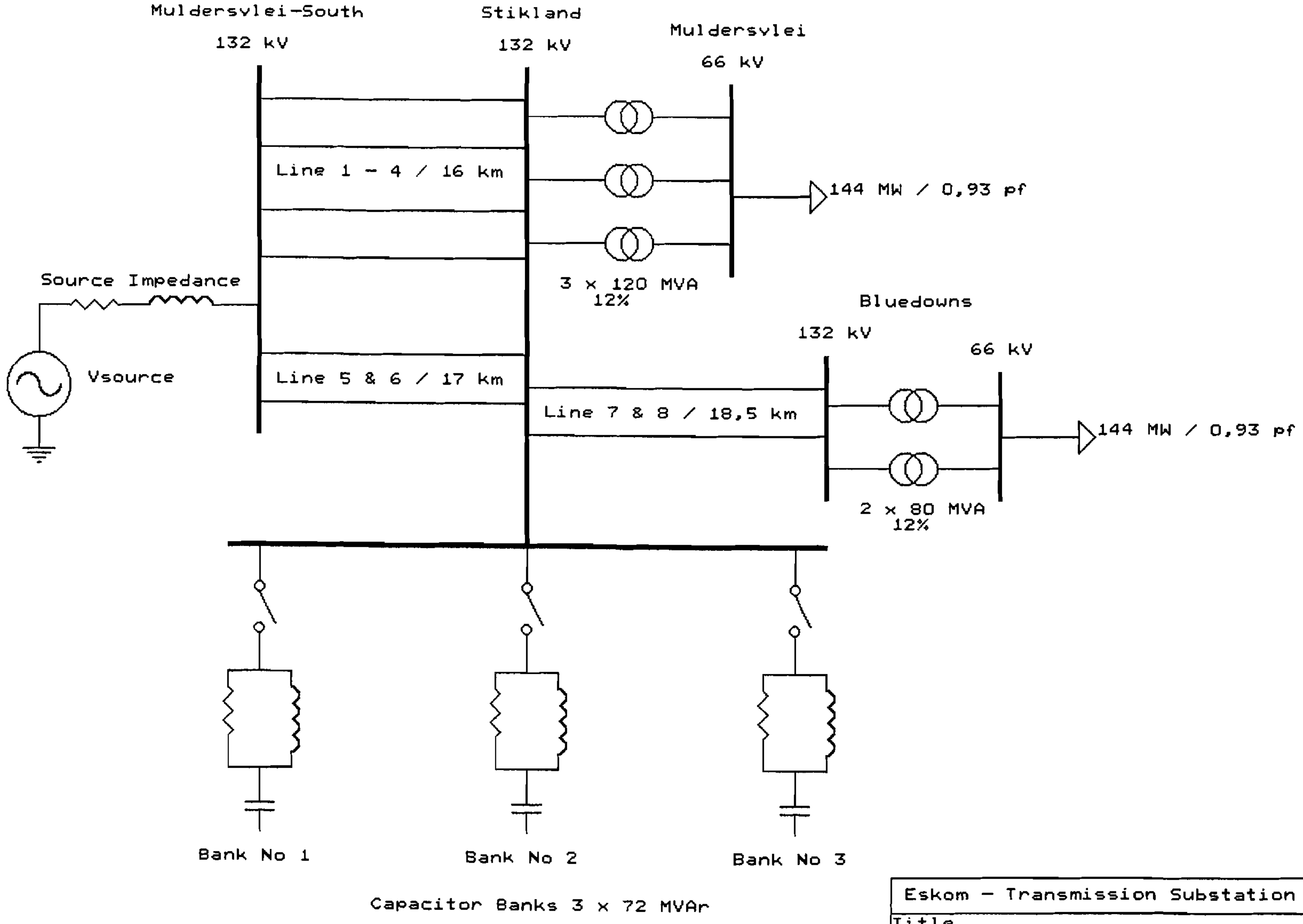
**Interfacing Equipment:**

| | | |
|---|---|---|
| 1. | Haefely high voltage dividers. | (Borssele) |
| 2. | KEMA, in-house made RC voltage dividers. | (Doetinchem) |
| 3. | Pearson current transformers. | (Doetinchem) |
| 4. | KEMA, in-house made fibre-optic system. | (Borssele and Doetinchem) |

# *Appendix 6*

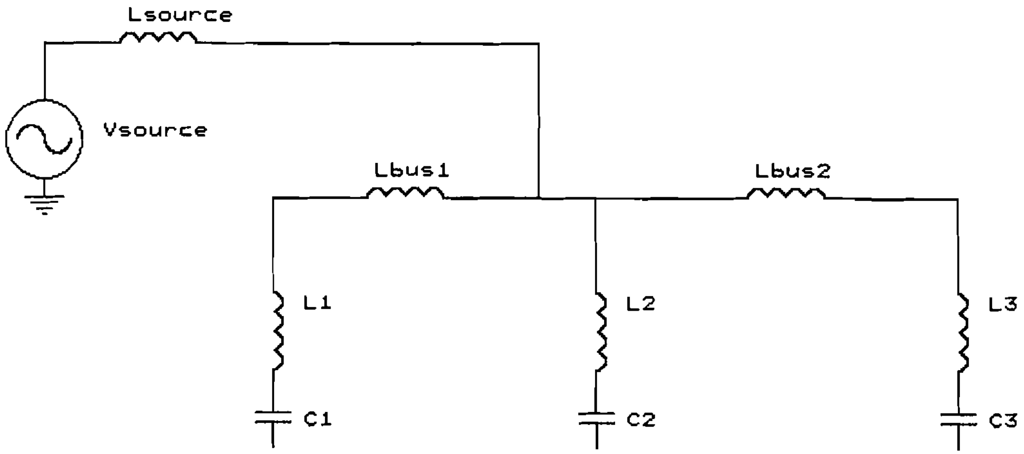
## *Stikland Substation*

## *Shunt Capacitor Bank Measurements*



Eskom - Transmission Substation Technology

| | | |
|---|---|---|
| Title<br>Power System around Stikland Substation | | |
| Size<br>A | Document Number<br>SCHEMATIC DIAGRAM | REV |
| Date: December 13, 1993 | Sheet 1 of 2 | |



Vsource = 108 kV

Lsource = 13 mH (Short Circuit Impedance)

Bus reactance = 1 Micro Henry / Meter

Lbus1 = 90 Micro Henry; Lbus2 = 80 Micro Henry

L1 = L2 = L3 = 300 Micro Henry / Phase

C1 = C2 = C3 = 13,1 Micro Farad / Phase

Eskom - Transmission Substation Technology

Title
Equivalent scheme Stikland Substation

| | | |
|---|---|---|
| Size | Document Number | REV |
| A | SCHEMATIC DIAGRAM | |

# *Appendix 7*

## *Apollo Substation*

## *Filter Bank Measurements*

Legenda on the overview of the measurements:
The data set numbers are the numbers under which the files are stored on ESKOM's Power Network Technologies data storage media. The data set date and time are the date and time that the measurements were carried out.

SS = Steady State
C = Closing operation of the circuit breaker
O = Opening operation of the circuit breaker

The test sequence indicates single or back-to-back switching:
1 = Single filter bank switching.
2 = Back-to-back switching with 150 MVAr shunt capacitor bank.
3 = Back-to-back switching with 300 MVAr shunt capacitor bank.

The page number indicates the page of the additional confidential report in which all the data-files have been printed out.

Legenda on the overview of the maximum values of voltages and currents on energizing: For the data set number and test sequence the same information as for the previous table is valid. For the currents and voltages the absolute maximum values have been given. No distinction was made if the maximum was of positive or negative polarity. The maximum inrush currents are given in kA. The maximum busbar voltages are given in per unit. The one per unit value was based on a 275 kV steady state voltage. Normally the voltage is higher than 275 kV. It is also possible to relate the overvoltage to the steady state momentary phase-to-ground voltage. However because of the long measurements period this would be a tedious job. It can be said that the overvoltages in pu as they were calculated are then a bit too high if the stated reasoning is used. However the equipment specifications are based on a nominal voltage of 275 kV, so it is acceptable to relate the one per unit value on this.

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | Page Number |
|---|---|---|---|---|---|
| 1 - RF1 | 26 May 1993 | 12:36 | SS | 1 | 1 |
| 2 - FB1 | | 12:50 | O | | 5 |
| 3 - FB2 | | 14:17 | O | | 9 |
| 4 - FB3 | | 15:09 | C | | 13 |
| 5 - FB4 | | 15:18 | O | | 19 |
| 6 - FB5 | | 15:27 | C | | 23 |
| 7 - FB6 | | 15:34 | O | | 27 |
| 8 - FB9 | | 17:11 | C | 2 | 31 |
| 9 - FC1 | | 17:15 | O | | 35 |
| 10 - FB7 | | 17:35 | C | | 39 |
| 11 - FB8 | | 17:39 | O | | 43 |
| 12 - FC2 | | 17:58 | C | 3 | 47 |
| 13 - FC3 | | 18:10 | O | | 51 |
| 14 - FC4 | | 18:33 | C | | 55 |
| 15 - FC5 | | 18:38 | O | | 59 |
| 16 - FD3 | 28 May 1993 | 12:21 | C | 1 | 63 |
| 17 - FD4 | | 12:39 | O | | 67 |
| 18 - FD5 | | 12:45 | C | | 71 |
| 19 - FD6 | | 12:49 | O | | 75 |
| 20 - FD7 | | 12:55 | C | | 79 |
| 21 - FD9 | | 12:58 | O | | 83 |
| 22 - FE1 | | 13:05 | C | | 87 |
| 23 - FE2 | | 13:13 | C | | 91 |
| 24 - FE3 | | 13:26 | O | | 95 |
| 25 - FE4 | 1 June 1993 | 12:20 | C | 1 & F1 E | 99 |
| 26 - FE5 | | 12:41 | O | | 103 |
| 27 - FE6 | | 13:02 | C | | 107 |
| 28 - FE7 | | 13:15 | O | | 111 |

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | Page Number |
|---|---|---|---|---|---|
| 29 - FE8 | 1 June 1993 | 13:33 | C | 2 | 115 |
| 30 - FE9 | | 13:42 | O | | 119 |
| 31 - FF1 | | 13:47 | C | | 123 |
| 32 - FF2 | | 13:57 | O | | 127 |
| 33 - FF3 | | 14:03 | C-O-C | | 131 |
| 34 - FF4 | | 14:07 | O | | 145 |
| 35 - FF5 | | 14:14 | C | | 149 |
| 36 - FF6 | | 14:23 | O | | 153 |
| 37 - FF7 | | 14:32 | C | | 157 |
| 38 - FF8 | | 14:42 | O | | 161 |
| 39 - FF9 | | 15:04 | C | 3 | 165 |
| 40 - FG1 | | 15:11 | O | | 169 |
| 41 - FG2 | | 15:16 | C | | 173 |
| 42 - FG3 | | 15:21 | O | | 177 |
| 43 - FG4 | | 15:25 | C | | 181 |
| 44 - FG5 | | 15:30 | O | | 185 |
| 45 - FG6 | | 15:36 | C | | 189 |
| 46 - FG7 | | 15:48 | O | | 193 |
| 47 - FG8 | | 15:52 | C | | 197 |
| 48 - FG9 | | 15:58 | O | | 201 |

| Data-Set Number | Test Sequence | Absolute Maximum Inrush Current | | | Absolute Maximum Busbar Voltage | | |
|---|---|---|---|---|---|---|---|
| | | $I_{Red}$ (kA) | $I_{White}$ (kA) | $I_{Blue}$ (kA) | $V_{Red}$ (kV) | $V_{White}$ (kV) | $V_{Blue}$ (kV) |
| 4/ FB3 | 1 | 2,2 | 1,0 | 2,8 | 1,16 | 1,05 | 1,31 |
| 6/ FB5 | | | ☹ | ☹ | 1,31 | 1,27 | 1,07 |
| 8/ FB9 | 2 | 1,8 | 2,7 | 2,6 | 1,11 | 1,29 | 1,16 |
| 10/ FB7 | | 7.3<br>☹ | 6.0<br>☹ | 4.6<br>☹ | 1,11 | 1,05 | 1,27 |
| 12/ FC2 | 3 | 1.0 | 1.4 | 3.0 | 1,05 | 1,16 | 1,31 |
| 14/ FC4 | | 0.8 | 3.0 | 3.0 | 1,05 | 1,16 | 1,20 |
| 16/ FD3 | 1 | 2.3 | 2.3 | 1.1 | 1,33 | 1,29 | 1,11 |
| 18/ FD5 | | 1.0 | 1.9 | 3.0 | 1,07 | 1,16 | 1,25 |
| 20/ FD7 | | 1.0 | 1.0 | 2.5 | 1,07 | 1,11 | 1,29 |
| 22/ FE1 | | 2.1 | 1.2 | 2.1 | 1,29 | 1,07 | 1,20 |
| 23/ FE2 | | 2.6 | ☹ | 1.5 | 1,29 | 1,20 | 1,07 |
| 25/ FE4 | 1 & F1 E | 1.1 | 2.0 | 3.0 | 1,09 | 1,20 | 1,20 |
| 27/ FE6 | | 1.6 | 3.0 | 3.0 | 1,16 | 1,25 | 1,20 |
| 29/ FE8 | 2 | 1.1 | 1.8 | 3.0 | 1,11 | 1,20 | 1,20 |
| 31/ FF1 | | 1.2 | 2.2 | 2.6 | 1,11 | 1,15 | 1,20 |
| 33/ FF3 | | 2.7 | 15.0<br>☹ | 1.5 | 1,34 | 1,16 | 1,07 |
| 35/ FF5 | | 0.8 | 1.3 | 3.0 | 1,07 | 1,11 | 1,29 |
| 37/ FF7 | | 1.3 | 2.0 | ☹ | 1,11 | 1,15 | 1,18 |
| 39/ FF9 | 3 | 1.7 | 2.4 | 1.9 | 1,14 | 1,25 | 1,16 |
| 41/ FG2 | | 1.5 | 0.9 | 2.2 | 1,15 | 1,09 | 1,20 |
| 43/ FG4 | | 2.2 | 2.4 | 0.9 | 1,20 | 1,34 | 1,11 |
| 45/ FG6 | | 1.8 | 1.2 | 2.2 | 1,16 | 1,11 | 1,16 |
| 47/ FG8 | | 1.6 | 2.4 | 2.2 | 1,16 | 1,25 | 1,20 |

During some of the tests National Control needed the MVAr-Support of Filter Bank No 1. In that case Filter 1 was energized, indicated as F1 E.

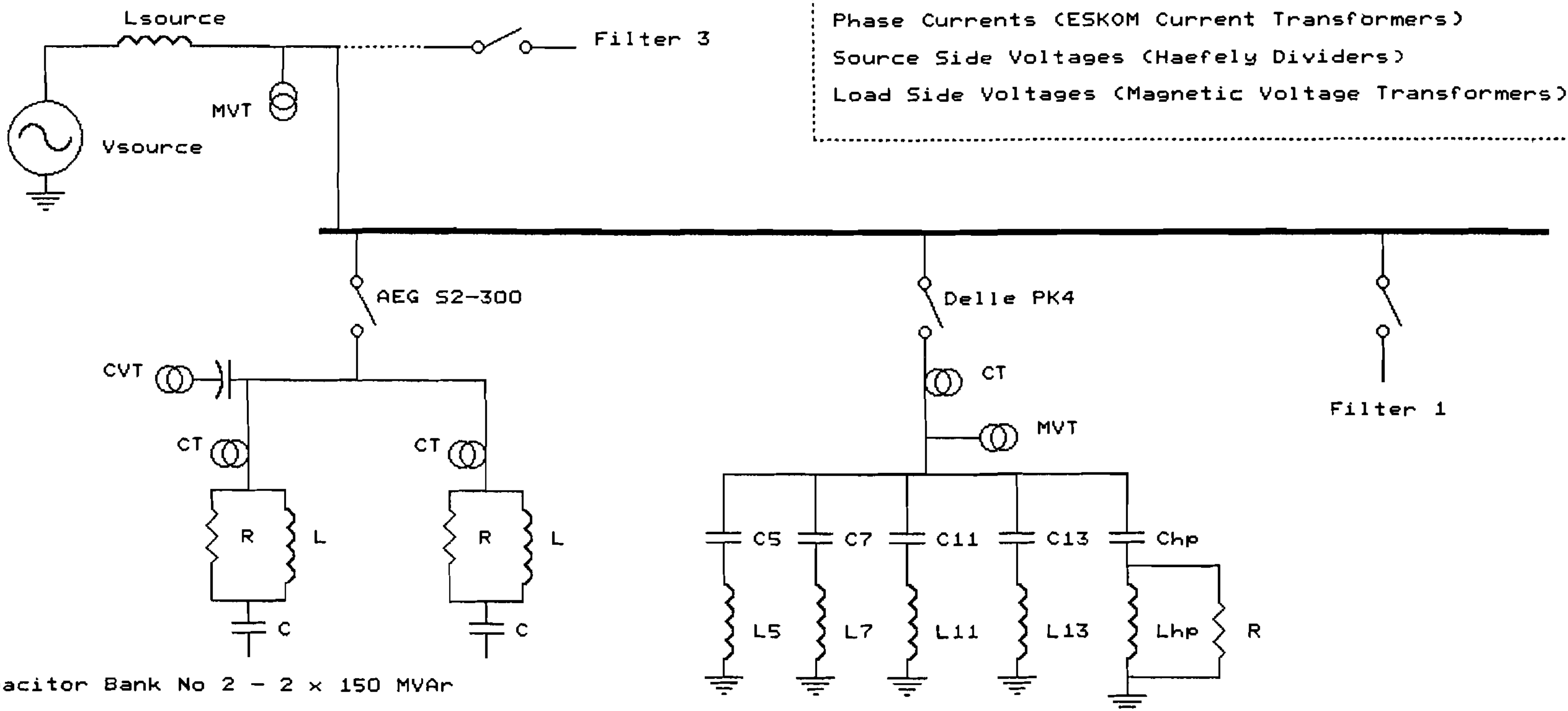
In appendix 7, the wave-forms are presented for a closing and an opening operation of the circuit breaker.

**Discussion of Results** - General overview of the recorded events:

| | |
|---|---|
| Total Number of Switchings | 55 |
| Not Measured | |
| Not Triggering or Triggering not in time | 7 |
| Loose connection in measuring circuit | 3 |
| Impossible wave-form | |
| Due to faulty AC/DC Coupling | 2 |
| Number of completely Recorded Switchings | 43 |

System Voltage = 275 kV - 50 Hz

Lsource =      mH (Short Circuit Impedance)



MEASURING POINTS FILTER BANK:

Phase Currents (ESKOM Current Transformers)

Source Side Voltages (Haefely Dividers)

Load Side Voltages (Magnetic Voltage Transformers)

Capacitor Bank No 2 - 2 x 150 MVAr

Damping Network: R = 20 Ohm / L = 400 Micro Henry

C = 6,31 Micro Farad / Phase (150 MVAr)

Filter Bank No 2 - 200 MVAr

C5 = 1,96 Micro Farad / L5 = 226 mH / Q = 100

C7 = 0,96 Micro Farad / L7 = 216 mH / Q = 100

C11 = 1,26 Micro Farad / L11 = 66 mH / Q = 100

C15 = 0,89 Micro Farad / L15 = 67,9 mH / Q = 100

Chp = 1,99 Micro Farad / Lhp = 8,8 mH / Rhp = 94,2 Ohm

5th, 7th, 11th and 13th harmonic filters and high pass

MEASURING POINTS CAPACITOR BANK:

Phase Currents (ESKOM Current Transformers)

Source Side Voltages (Magnetic Voltage Transformers)

Load Side Voltages Red & Blue Phase (Haefely Dividers)

Load Side Voltages White & Blue Phase (CVT)

Neutral Voltage, Unbalance Current and Earth Current

Eskom - Transmission Substation Technology

Title
Experimental Set-Up Apollo Substation

| Size | Document Number | REV |
|---|---|---|
| A | SCHEMATIC DIAGRAM | |

Date: December 14, 1993 Sheet 1 of 2

# *Appendix 8*

# *Apollo Substation*

## *Shunt Capacitor Bank Measurements*

Legenda on the tables with the measurement results:
The data set numbers are the numbers under which the files are stored on ESKOM's Power Network Technologies data storage media. The data set date and time are the date and time that the measurements were carried out.

For the events the following abbreviations are valid:
SS = Steady State
C = Closing operation of the circuit breaker
O = Opening operation of the circuit breaker

The following test sequences have been carried out:

1 = Single 150 MVAr bank.
2 = 150 MVAr bank back-to-back with 200 MVAr filter.
3 = 150 MVAr bank back-to-back with filters 2 (1) and 3.
4 = 150 MVAr bank back-to-back with filters 1, 2 and 3.

5 = 150 MVAr, Neutral earthed and back-to-back with filters 2 and 3

6 = 300 MVAr bank back-to-back with 200 MVAr filter.
7 = 300 MVAr bank back-to-back with filter 2 and 3.
8 = 300 MVAr bank back-to-back with filter 1, 2 and 3.

The addition R or C indicates Random or Controlled Switching respectively.

The First Pole to Clear indicates which pole is interrupted the first after an opening order is given. The page number indicates the page of the additional report in which all the data-files have been printed out. This report is strictly for use within ESKOM !

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | First Pole to Clear | Page N° |
|---|---|---|---|---|---|---|
| 1 - CBB | 4 June 1993 | 16:18 | C | 1R | / | 1 |
| 2 - CB2 | | 16:44 | C | | / | 7 |
| 3 - CB3 | | 16:58 | O | | R | 13 |
| 4 - CC1 | 7 June 1993 | 11:40 | C | 2R | / | 19 |
| 5 - CC2 | | 12:37 | O | | W | 27 |
| 6 - CC4 | | 14:12 | C | | / | 33 |
| 7 - CC3 | | 15:07 | C | 1R | / | 39 |
| 8 - CC5 | | 15:41 | O | | B | 45 |
| 9 - CC6 | | 16:34 | C | | / | 51 |
| 10 - CC7 | | 16:58 | O | | B | 57 |
| 11 - CC8 | 8 June 1993 | 14:26 | C | 3R | / | 63 |
| 12 - CC9 | | 16:37 | C | | / | 69 |
| 13 - CD1 | | 16:52 | O | | W | 75 |
| 14 - CD2 | 9 June 1993 | 10:25 | C | | / | 81 |
| 15 - CD3 | | 10:46 | O | | W | 87 |
| 16 - CD4 | | 11:33 | C | | / | 93 |
| 17 - CD5 | | 11:49 | O | | W | 99 |
| 18 - CD6 | | 12:10 | C | | / | 105 |
| 19 - CD7 | | 12:31 | O | | B | 111 |
| 20 - CD8 | | 13:29 | C | 4R | / | 117 |
| 21 - CD9 | | 13:55 | O | | W | 123 |
| 22 - CE1 | | 14:08 | C | | / | 129 |
| 23 - CE2 | | 14:31 | O | | W | 135 |
| 24 - CE3 | 10 June 1993 | 11:15 | C | 6R | / | 141 |
| 25 - CE4 | | 11:43 | O | | / | 147 |

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | First Pole to Clear | Page N° |
|---|---|---|---|---|---|---|
| 26 - CE5 | 29 June 1993 | 13:12 | C | 5R | / | 155 |
| 27 - CE6 | | 13:58 | SS | | / | 161 |
| 28 - CE7 | | 14:29 | O | | | 165 |
| 29 - CE8 | | 15:53 | C | | / | 171 |
| 30 - CE9 | | 16:26 | O | | ⊗ | 179 |
| 31 - CF1 | 30 June 1993 | 12:50 | C | | / | 187 |
| 32 - CF2 | | 13:39 | C | | / | 193 |
| 33 - CF4 | | 14:11 | C | | / | 199 |
| 34 - CF5 | | 14:22 | SS | | / | 205 |
| 35 - CF6 | | 14:26 | SS | | / | 211 |
| 36 - CF7 | | 14:31 | O | | | 215 |
| 37 - CF8 | | 14:53 | C | | / | 221 |
| 38 - CF9 | | 15:06 | O | | | 227 |
| 39 - CG1 | | 15:32 | C | | / | 233 |
| 40 - CG2 | | 15:48 | O | | | 239 |
| 41 - CG3 | | 16:33 | C | | / | 245 |
| 42 - CG4 | | 17:05 | O | | | 251 |
| 43 - CG5 | | 17:37 | C | | / | 259 |
| 44 - CG6 | | 18:14 | O | | | 265 |
| 45 - CH1 | 6 July 1993 | 12:09 | C | 7R | / | 273 |
| 46 - CH2 | | 13:32 | C-O | | / | 279 |
| 47 - CH3 | | 16:11 | C | | / | 285 |
| 48 - BA1 | 7 July 1993 | 11:48 | C | 2CC | / | 291 |
| 49 - BA2 | | 12:34 | C | | / | 299 |
| 50 - BA3 | | 12:58 | C | | / | 305 |

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | First Pole to Clear | Page N° |
|---|---|---|---|---|---|---|
| 51 - BA4 | 7 July 1993 | 13:28 | C | 2CC | / | 311 |
| 52 - BA5 | | 13:59 | C | | / | 317 |
| 53 - BA6 | | 14:26 | C | | / | 323 |
| 54 - BA7 | | 14:39 | C | | / | 329 |
| 55 - BA8 | | 15:20 | C | | / | 337 |
| 56 - BA9 | | 15:41 | C | | / | 345 |
| 57 - BB1 | | 16:26 | C | | / | 353 |
| 58 - BB2 | | 16:42 | C | | / | 361 |
| 59 - BB3 | | 16:54 | C | | / | 369 |
| 60 - BB4 | | 17:20 | C | | / | 375 |
| 61 - BB5 | 8 July 1993 | 11:00 | C | 3CC | / | 381 |
| 62 - BB6 | | 11:34 | C | | / | 389 |
| 63 - BB7 | | 11:59 | C | | / | 397 |
| 64 - BB8 | | 12:17 | C | | / | 405 |
| 65 - BB9 | | 12:35 | C | | / | 413 |
| 66 - BC1 | | 12:55 | C | | / | 423 |
| 67 - BC2 | | 15:21 | C | 4CO | / | 431 |
| 68 - BC3 | | 15:34 | O | | B | 437 |
| 69 - BC4 | | 15:43 | C | | / | 445 |
| 70 - BC5 | | 15:55 | O | | W | 451 |
| 71 - BC6 | | 16:08 | C | | / | 459 |
| 72 - BC7 | | 16:16 | O | | R | 465 |
| 73 - BC8 | | 16:49 | C | | / | 475 |
| 74 - BC9 | | 17:03 | O | | W | 481 |

| Data Set Number | Data Set Date | Data Set Time | Event | Test Sequence | First Pole to Clear | Page N° |
|---|---|---|---|---|---|---|
| 75 - CH4 | 12 July 1993 | 11:00 | C | 8R | / | 491 |
| 76 - CH5 | | 11:08 | O | | B | 497 |
| 77 - CH6 | | 11:39 | C | | / | 503 |
| 78 - CH7 | | 11:52 | O | | B | 509 |
| 79 - CH8 | | 12:33 | C | | / | 515 |
| 80 - CH9 | | 12:43 | O | | B | 523 |
| 81 - CI1 | | 14:03 | C | | / | 529 |
| 82 - CI2 | | 14:14 | O | | B | 537 |
| 83 - CI3 | | 16:59 | C | 7R | / | 543 |
| 84 - CI4 | | 17:08 | O | | B | 549 |
| 85 - CI5 | | 17:29 | C | | / | 557 |
| 86 - CI6 | | 17:38 | O | | R | 563 |

| Data Set Number | Test Sequence | Absolute Maximum Inrush Currents (kA) | | | Absolute Maximum Busbar Voltages (kV) | | | Pre-arcing times (ms) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_{Red}$ | $I_{White}$ | $I_{Blue}$ | $V_{Red}$ | $V_{White}$ | $V_{Blue}$ | $t_{Red}$ | $t_{White}$ | $t_{Blue}$ |
| 1 CBB | 1R | 1.3 | 1.7 | 1.8 | 1.29 | / | / | 5.3 | 4.0 | 3.8 |
| 2 CB2 | | 2.0 | 2.2 | 2.2 | 1.56 | / | / | 4.0 | 3.33 | 7.9 |
| 4 CC1 | 2R | 3.6 | 3.1 | 3.1 | 1.25 | 1.20 | 1.20 | 7.1 | 12.5 | 7.5 |
| 6 CC4 | | 3.5 | 3.4 | ⊗ | 1.20 | 1.16 | 1.13 | 11.8 | 8.2 | ⊗ |
| 7 CC3 | 1R | 2.7 | 1.3 | 1.5 | 1.51 | 1.02 | 1.25 | 11.9 | 7.7 | 6.2 |
| 9 CC6 | | 1.5 | 2.0 | 2.0 | 1.11 | 1.20 | 1.34 | 7.1 | 5.2 | 8.1 |
| 11 CC8 | 3R | 4.5 | 4.2 | 2.1 | 1.34 | 1.11 | 1.16 | 9.3 | 7.1 | 14.2 |
| 12 CC9 | | 3.6 | 4.4 | 4.4 | 1.16 | 1.18 | 1.16 | 5.7 | 8.3 | 9.1 |
| 14 CD2 | | 3.6 | ⊗ | 2.8 | 1.29 | 1.24 | 1.24 | 10.0 | ⊗ | 10.0 |
| 16 CD4 | | 3.1 | 3.2 | 3.1 | 1.36 | 1.31 | 1.07 | 8.1 | 7.6 | 9.5 |
| 18 CD6 | | 3.4 | 3.2 | 3.2 | 1.31 | 1.16 | 1.18 | 8.1 | 7.6 | 8.6 |
| 20 CD8 | 4R | 3.5 | 2.5 | 3.0 | 1.34 | 1.25 | 1.16 | 8.1 | 8.6 | 8.1 |
| 22 CE1 | | 2.6 | 3.3 | 3.0 | 1.25 | 1.25 | 1.20 | 7.8 | 8.8 | 8.3 |
| 24 CE3 | 6R | 1.6 | 0.7 | 1.6 | 1.36 | 1.09 | 1.34 | 9.5 | / | 5.2 |
| 26 CE5 | 5R | 2.6 | 2.6 | 1.5 | 1.38 | 1.40 | 1.25 | 8.2 | 9.5 | 5.7 |
| 29 CE8 | | 2.6 | 2.4 | 1.4 | 1.51 | 1.47 | 1.07 | 7.6 | 6.7 | 6.7 |
| 31 CF1 | | 2.0 | 2.4 | 2.9 | 1.47 | 1.43 | 1.56 | 6.0 | 8.3 | 7.6 |
| 32 CF2 | | 1.2 | 1.3 | 2.4 | 1.25 | 1.25 | 1.51 | 6.7 | 5.7 | 6.7 |

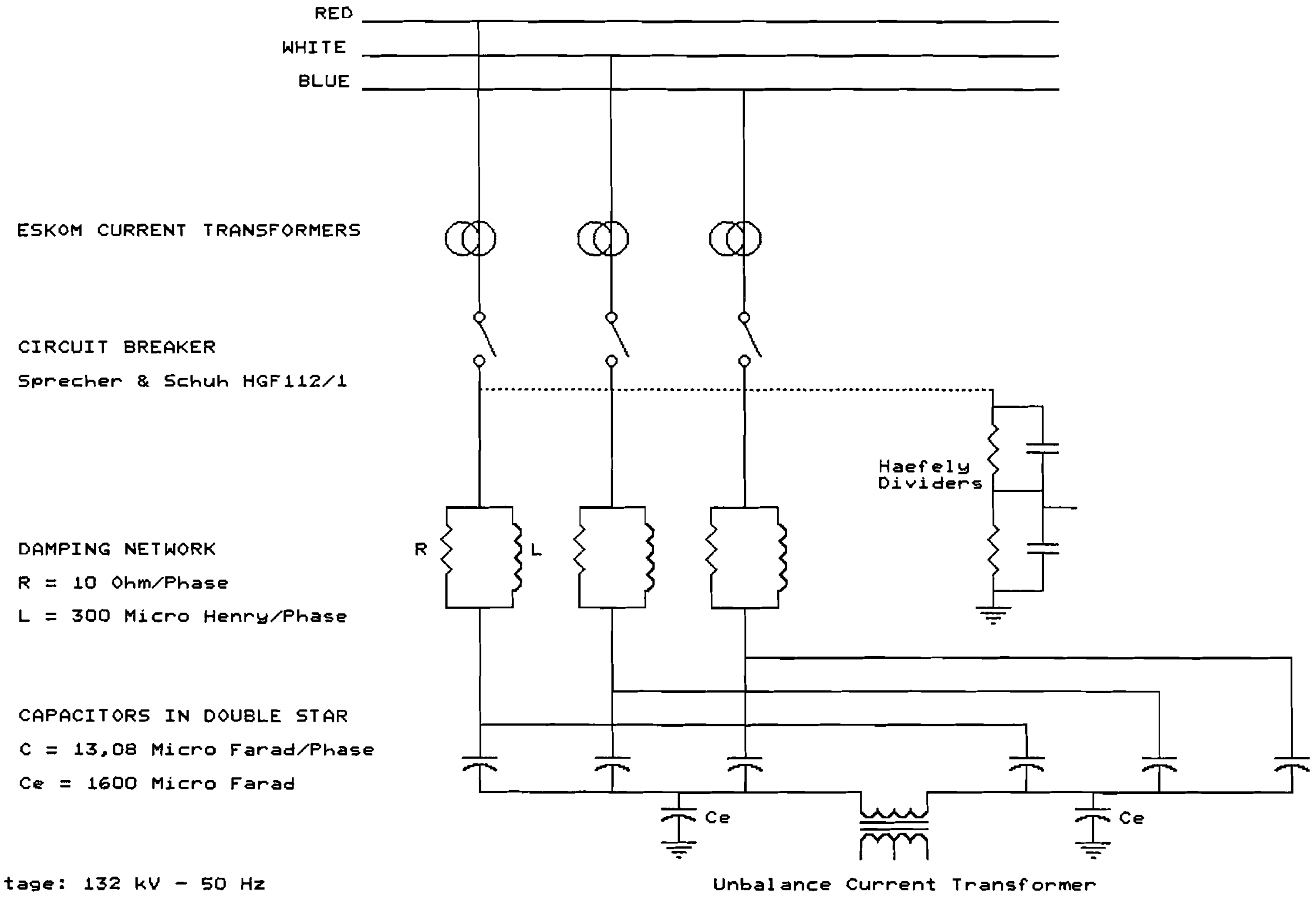
APPENDIX 8

APPENDIX 8

| Data Set Number | Test Sequence | Absolute Maximum Inrush Currents (kA) | | | Absolute Maximum Busbar Voltages (kV) | | | Pre-arcing times (ms) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_{Red}$ | $I_{White}$ | $I_{Blue}$ | $V_{Red}$ | $V_{White}$ | $V_{Blue}$ | $t_{Red}$ | $t_{White}$ | $t_{Blue}$ |
| 34 CF4 | 5R | 1.9 | 2.0 | 3.0 | 1.29 | 1.31 | 1.60 | 6.0 | 8.3 | 5.0 |
| 38 CF8 | | 1.6 | 1.7 | 3.0 | 1.25 | 1.29 | 1.60 | 6.4 | 8.6 | 7.1 |
| 40 CG1 | | 2.4 | 2.6 | 2.8 | 1.65 | 1.56 | 1.43 | 5.0 | 6.4 | 9.1 |
| 42 CG3 | | 2.7 | 2.7 | 1.3 | 1.74 | 1.74 | 1.25 | 9.0 | 3.3 | 4.8 |
| 44 CG5 | | 1.7 | 1.0 | 2.6 | 1.25 | 1.25 | 1.56 | 7.6 | 9.5 | 6.7 |
| 46 CH1 | 7R | 0.9 | 1.5 | 1.5 | 1.20 | 1.34 | 1.60 | 6.0 | 5.2 | 5.2 |
| 47 CH2 | | 1.6 | 1.6 | 1.6 | 1.51 | 1.60 | 1.34 | 5.5 | 4.8 | 5.5 |
| 48 CH3 | | 1.7 | 1.6 | 1.6 | 1.60 | 1.65 | 1.25 | 5.5 | 9.5 | 7.6 |
| 49 BA1 | 2CC | 1.4 | 2.1 | 3.0 | 1.34 | 1.34 | 1.78 | 7.0 | 6.3 | 8.3 |
| 50 BA2 | | 1.0 | 2.4 | 3.0 | 1.25 | 1.51 | 1.60 | 7.5 | 11.0 | 12.5 |
| 51 BA3 | | 1.3 | 1.8 | 3.0 | 1.31 | 1.29 | 1.78 | 7.1 | 7.1 | 8.6 |
| 52 BA4 | | 1.5 | 1.4 | 2.4 | 1.29 | 1.38 | 1.69 | 4.8 | 4.5 | 8.1 |
| 53 BA5 | | 1.5 | 1.4 | 2.0 | 1.29 | 1.34 | 1.34 | 7.8 | 6.8 | 6.8 |
| 54 BA6 | | 2.1 | 2.1 | 1.4 | 1.34 | 1.56 | 1.29 | 4.7 | 8.4 | 6.6 |
| 55 BA7 | | 1.4 | 1.4 | 1.0 | 1.29 | 1.34 | 1.29 | 6.8 | 6.8 | 5.2 |
| 56 BA8 | | 0.9 | 1.1 | 1.5 | 1.25 | 1.38 | 1.29 | 6.8 | 6.8 | 7.8 |
| 57 BA9 | | 2.5 | 2.5 | 1.1 | 1.70 | 1.34 | 1.29 | 9.2 | 11.6 | 5.3 |
| 58 BB1 | | 1.2 | 1.1 | 1.4 | 1.25 | 1.25 | 1.34 | 7.1 | 8.7 | 6.8 |

| Data Set Number | Test Sequence | Absolute Maximum Inrush Currents (kA) | | | Absolute Maximum Busbar Voltages (kV) | | | Pre-arcing times (ms) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $I_{Red}$ | $I_{White}$ | $I_{Blue}$ | $V_{Red}$ | $V_{White}$ | $V_{Blue}$ | $t_{Red}$ | $t_{White}$ | $t_{Blue}$ |
| 59 BB2 | 2CC | 1.5 | 1.2 | 1.1 | 1.25 | 1.34 | 1.34 | 8.4 | 5.1 | 5.3 |
| 60 BB3 | | 1.3 | 1.3 | 0.7 | 1.29 | 1.34 | 1.20 | 6.7 | 6.2 | 6.2 |
| 61 BB4 | | 1.4 | 1.5 | 2.9 | 1.25 | 1.38 | 1.60 | 5.2 | 5.2 | 9.5 |
| 62 BB5 | 3CC | 2.8 | 2.8 | 3.7 | 1.42 | 1.38 | 1.43 | 8.2 | 7.4 | 9.5 |
| 63 BB6 | | 1.2 | 1.2 | 1.3 | 1.29 | 1.25 | 1.34 | 6.1 | 11.0 | 4.5 |
| 64 BB7 | | 1.3 | 1.8 | 2.9 | 1.29 | 1.34 | 1.29 | 8.2 | 7.3 | 9.5 |
| 65 BB8 | | 1.1 | 2.2 | 3.4 | 1.29 | 1.45 | 1.45 | 9.5 | 6.3 | 9.3 |
| 66 BB9 | | 0.8 | 1.5 | 2.2 | 1.25 | 1.16 | 1.43 | 9.5 | 6.3 | 6.3 |
| 67 BC1 | | 2.0 | 2.0 | 1.4 | 1.29 | 1.25 | 1.34 | 8.7 | 9.5 | 5.3 |
| 68 BC2 | 4CO | 0.9 | 1.0 | 1.0 | 1.34 | 1.25 | 1.34 | 6.6 | 8.0 | 6.6 |
| 70 BC4 | | 1.8 | 1.7 | 1.7 | 1.43 | 1.34 | 1.60 | 7.9 | 7.9 | 9.2 |
| 72 BC6 | | 1.1 | 1.3 | 1.3 | 1.25 | 1.29 | 1.38 | 7.1 | 5.8 | 3.9 |
| 74 BC8 | | 1.1 | ⊗ | 1.2 | 1.38 | 1.25 | 1.43 | 7.1 | ⊗ | 6.2 |
| 76 CH4 | 8R | 1.8 | 1.2 | ⊗ | 1.56 | 1.34 | 1.34 | 9.5 | 7.6 | ⊗ |
| 78 CH6 | | 1.4 | 1.6 | 1.6 | 1.56 | 1.63 | 1.38 | 8.4 | 5.8 | 6.1 |
| 80 CH8 | | 1.9 | 1.0 | 1.7 | 1.60 | 1.25 | 1.56 | 10.0 | 9.7 | 8.7 |
| 82 CI1 | | 1.8 | 1.2 | 1.8 | 1.60 | 1.43 | 1.60 | 9.5 | 9.2 | 3.6 |
| 84 CI3 | 7R | 1.7 | 1.7 | 1.7 | 1.65 | 1.78 | 1.25 | / | / | / |
| 86 CI5 | | 0.9 | 0.9 | 0.9 | 1.34 | 1.25 | 1.56 | / | / | / |

APPENDIX 8



System Voltage: 132 kV - 50 Hz

Capacitor Bank: 72 MVAr - Fuseless

Measuring Points on Capacitor Bank No 1:

1) Eskom Current Transformers (Three Phases)

2) Haefely Dividers for load-side voltage (Three Phases)

3) Neutral Voltage, Earth Current and Unbalance Current

| Eskom - Transmission Substation Technology | | |
|---|---|---|
| Title<br>Experimental Set-Up Stikland Substation | | |
| Size<br>A | Document Number<br>SCHEMATIC DIAGRAM | REV |

# *Appendix 9*

## *Doetinchem Substation*

## *Shunt Reactor Measurements*

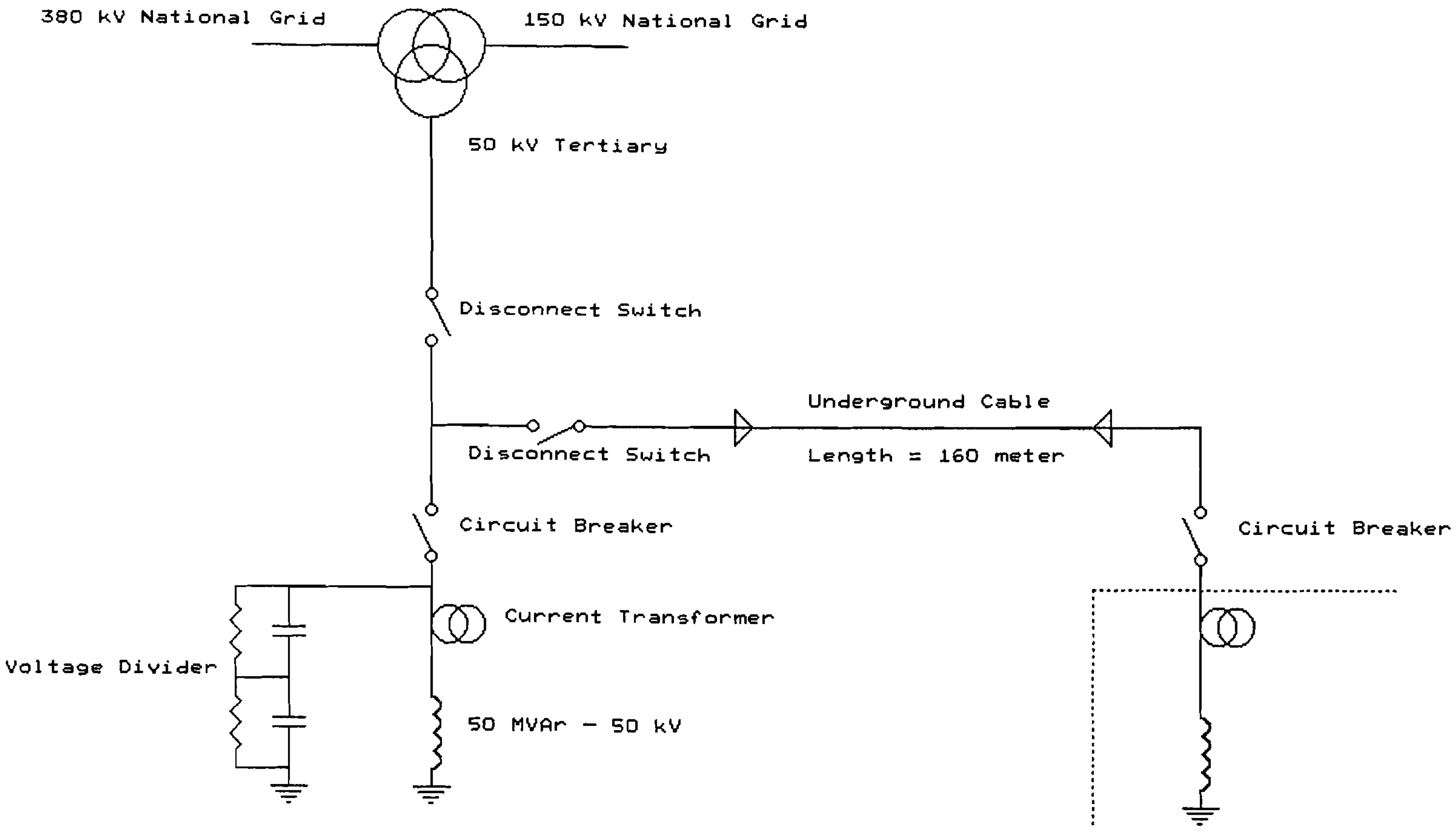
Results of Field Tests at Doetinchem Substation on 22 September 1993:

| Test Set Number | Test Set Time | Clock Time (ms) | Maximum Phase-to-ground Voltages | | | |
|---|---|---|---|---|---|---|
| | | | Red Phase | White Phase | | Blue Phase |
| | | | Voltage | Event | Voltage | Voltage |
| 1 | 11:36 | / | / | SS | / | / |
| 2 | 11:41 | / | 1.42 | None | 1.02 | 1.17 |
| 3 | 11:54 | / | 1.50 | Single | 2.00 | 1.50 |
| 4 | 12:01 | / | 1.25 | None | 1.08 | 1.08 |
| 5 | 12:06 | 10.6 | 1.33 | None | 1.08 | 1.08 |
| 6 | 12:11 | 10.7 | 1.33 | None | 1.08 | 1.08 |
| 7 | 12:17 | 10.9 | 1.25 | None | 1.08 | 1.17 |
| 8 | 12:22 | 11.1 | 1.50 | Single | 1.92 | 1.42 |
| 9 | 12:30 | 11.3 | 1.25 | Single | 1.83 | 1.25 |
| 10 | 12:36 | 11.5 | 1.25 | Single | 1.83 | 1.17 |
| 11 | 12:40 | 11.7 | 1.17 | Single | 1.42 | 1.33 |
| 12 | 12:46 | 11.7 | 1.50 | Single | 1.33 | 1.42 |
| 13 | 12:50 | 11.5 | 1.42 | Single | 1.92 | 1.17 |
| 14 | 12:54 | 11.3 | 1.33 | Single | 1.50 | 1.33 |
| 15 | 12:58 | 11.1 | 1.33 | None | 1.08 | 1.17 |
| 16 | 13:06 | 11.1 | 1.50 | Single | 2.00 | 1.50 |
| 17 | 13:10 | 10.9 | 1.25 | None | 1.08 | 1.08 |
| 18 | 13:14 | 11.1 | 1.25 | None | 1.08 | 1.17 |
| 19 | 13:18 | 11.3 | 1.50 | Single | 1.58 | 1.33 |
| 20 | 13:21 | 11.5 | 1.50 | Single | 1.67 | 1.33 |
| 21 | 13:25 | 11.7 | 1.08 | Single | 1.08 | 1.33 |

**Legenda:**

1. Test Numbers 1,2,3 and 4 were random shots.
2. Test Numbers 8, 9, 10 and 11 were done with an extra capacity on the supply side.
3. The Shunt Reactor Circuit Breaker was equipped with a single operating mechanism with mechanical coupling between the three poles. Therefore it was only possible to do controlled opening tests on just one phase, the S Phase was chosen.
4. Average Opening Time 21 ms.

The wave forms can be found in a separate appendix.



Title

Shunt Reactor De-Energizing

| Size | Document Number | REV |
|---|---|---|
| A | Doetinchem Substation | |

Date: December 15, 1993 Sheet of

# *Appendix 10*

## *Borssele Substation*

## *Shunt Capacitor Bank Measurements*

***Results of Field Tests at Borssele Substation on 29 October 1993:***

***Shunt Capacitor Bank connected to National Grid***

***Measured Overvoltages in Per Unit***

$$1\ pu = 150\ kV \cdot \sqrt{\frac{2}{3}} = 122{,}5 kV$$

| Test Set N° | Test Set Time | Edge | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Pos. Peak | Neg. Peak | Pos. Peak | Neg. Peak | Pos. Peak | Neg. Peak |
| 1 | 11:04 | DUU | 1.57 | 1.47 | 1.43 | 1.18 | 1.52 | 1.41 |
| 2 | 11:26 | UDD | 1.36 | 1.39 | 1.16 | 1.34 | 1.33 | 1.38 |
| 3 | 11:38 | DUU | 1.23 | 1.43 | 1.44 | 1.29 | 1.53 | 1.54 |
| 4 | 11:49 | UDD | 1.25 | 1.34 | 1.28 | 1.28 | 1.41 | 1.54 |
| 5 | 11:59 | UDD | 1.28 | 1.31 | 1.20 | 1.25 | 1.36 | 1.43 |
| 6 | 12:10 | DUU | 1.28 | 1.28 | 1.22 | 1.17 | 1.35 | 1.31 |
| 7 | 12:22 | DUU | 1.26 | 1.27 | 1.20 | 1.15 | 1.30 | 1.28 |

*Shunt Capacitor Bank connected to Local Grid*

*Measured Overvoltages in Per Unit*

$$1\ pu = 150\ kV \cdot \sqrt{\frac{2}{3}} = 122{,}5kV$$

| Test Set N° | Test Set Time | Edge | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Pos. Peak | Neg. Peak | Pos. Peak | Neg. Peak | Pos. Peak | Neg. Peak |
| 1 | 14:16 | DUU | 1.01 | 1.09 | 1.01 | 1.02 | 1.03 | 1.03 |
| 2 | 14:28 | DUU | 1.01 | 1.09 | 1.01 | 1.02 | 1.03 | 1.03 |
| 3 | 14:37 | UDD | 1.08 | 1.01 | 1.02 | 1.02 | 1.02 | 1.03 |
| 4 | 14:44 | DUU | 1.02 | 1.08 | 1.01 | 1.02 | 1.02 | 1.02 |
| 5 | 14:54 | DUU | 1.02 | 1.07 | 1.02 | 1.02 | 1.02 | 1.02 |

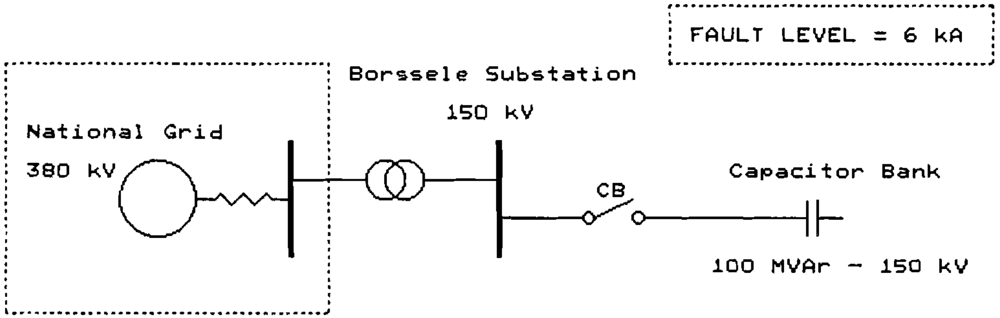
**Legenda:**

Edge = In this column it is indicated if the capacitor is energized on the up or down going edge of the respective phase voltage (R, S and T respectively). It can be concluded that the highest overvoltage is not necessarily on the positive peak if the energization takes place on an up going edge or vice versa.

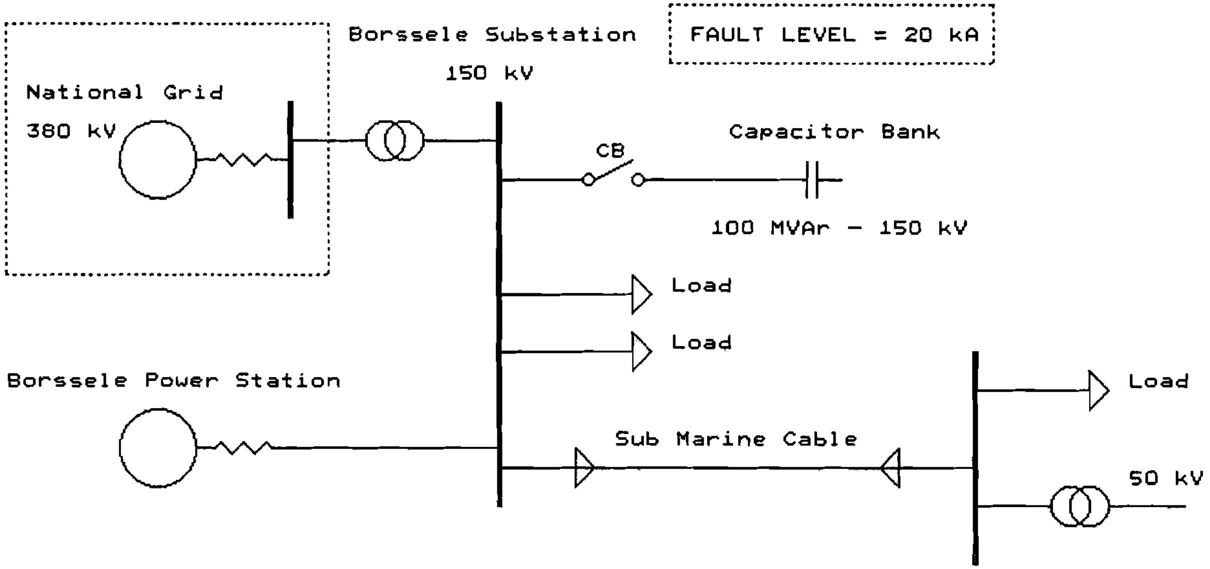
Time Deviation = In this column the time difference is given between the actual point-on-wave and the aimed (ideal) point-on-wave

During field tests at Borssele Substation, the enormous influence of system loading was measured. The field tests consisted of two parts. During the first part of the tests, the capacitor bank was connected to the National Grid through a transformer (380 kV - 150 kV). This situation was used to bring the controlled switching device to the optimum timing for each phase.

SITUATION 1 – CAPACITOR BANK CONNECTED TO NATIONAL GRID



SITUATION 2 – CAPACITOR BANK CONNECTED TO LOCAL GRID



TOTAL LOAD PARALLEL TO CAPACITOR BANK IS
APPROXIMATELY 500 MW – 0,9 pf
(IN SITUATION 2 ONLY = NORMAL SITUATION)
FAULT LEVELS REFER TO 150 kV BORSSELE CAPACITOR BANK BUSBAR

| Title | | |
|---|---|---|
| Shunt Capacitor Controlled Closing | | |
| Size | Document Number | REV |
| A | Borssele Substation | |