THE PROTECTION OF
HIGH-VOLTAGE SHUNT CAPACITOR BANKS

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Synopsis

The use of shunt capacitor bank equipment is essential if a utility wishes to control the flow of reactive power effectively. The most significant results stemming from this will be lower losses on the system and an increased power transfer capability. Thus it is important that the methods used to protect a shunt capacitor bank will ensure that the bank is available when required.

While the more common shunt capacitor problems are related to capacitor unit failures, conditions such as bank overcurrents, surge voltages and harmonics can cause extended undesired conditions. Today's protection methods are able to remove a shunt capacitor bank from service before extensive damage is done, although the location of the faulty capacitor units will not be known (if this was in fact the reason for the protection tripping the bank). This thesis explores the subject of improving the protection of high-voltage shunt capacitor banks, specifically with respect to the detection of unhealthy fuseless capacitor units.

An extensive literature search was carried out on the theory pertaining to the protection of shunt capacitor banks, and a model of a fuseless shunt capacitor bank was built in the laboratory to better understand the failing process of an element within a capacitor unit. The changes in the capacitor unit's current and voltage profiles, as well as those of the remaining healthy capacitor units, were monitored as an element failure was simulated (whereby the element forms a solid weld, or short circuit).

Stemming from these experiments, it was found that where a bank consists of strings of units with no interconnection between the units of different strings, an element failure in a capacitor unit would cause a significant decrease in voltage across the affected unit. This voltage change could be used to identify when elements are failing in capacitor units, and the location of the unhealthy unit could also be determined. One potential method would be to have capacitor units with built-in voltage transformers attached across each element section in the unit. As element failures occur either send this information to ground level, where it can be read by a microprocessor relay device, or have a display on the outside of the capacitor unit. In the case of the change in unit current, it was found to be very small and thus had no function for detecting unhealthy capacitor units.

Further experiments were done in the laboratory whereby the voltage across a capacitor was increased until the capacitor failed. During this process the temperature and the

current harmonics of the capacitor were monitored. As expected, the temperature increased with the voltage, and as the capacitor failed there was a sudden change in temperature. It was also noticed that a certain current harmonic was not behaving as expected while the capacitor was under overvoltage strain. This phenomenon could be useful for unhealthy capacitor unit detection. However, this could be an isolated case in terms of the conditions in the laboratory, which indicates the need for further testing of this idea (and that of temperature monitoring) on a high-voltage capacitor unit.

A computer model was used to simulate element failures on a 3-phase shunt capacitor bank. The effect of a capacitor bank's unit arrangement on the reaction of capacitor units to element failures was observed. A capacitor arrangement different to those used in the laboratory, whereby each string consisted of sections with two units in parallel per section, was modelled. With respect to the change in unit current after an element failure, the increase in current was large enough to detect for protection purposes (although it was not as substantial as the change in voltage across each unit).

Thus a current detection technique could be used to pick up successive element failures, whereby the string current gradually increases after each failure. However, this is no more effective than existing protection methods using a current transformer on each phase. The element failure is detected but there is no way of locating which units suffered element failures (although the phase could be detected). Effectively locating the unhealthy units is the primary difference between current and voltage detection.

Subsequent model simulations showed that using this different arrangement could allow for a bank to be kept in service longer. This is possible as more element failures could be tolerated before recommended overvoltage limits on the remaining healthy units are violated. However, the simulations showed this to be the case only if the element failures were spread throughout the string. A complete unit failure in this arrangement would have similar results to the laboratory experiments, where the overvoltage levels across the remaining units would increase dramatically.

By detecting various signs of a capacitor unit in an unhealthy condition, the protection of fuseless shunt capacitor banks can be improved. As mentioned above, the arrangement of units plays an important role in determining how effective the protection can be.

Implementing any such method must be cost-effective to an electrical utility, while keeping the reliability factor at a suitable level. It would not be practical to use a highly accurate and reliable method if the costs involved caused a utility to actually lose money. This could happen if the protection costs were higher than the costs incurred before the method was implemented (consisting of the cost of losses and the cost of the existing protection method). A more favourable approach would be to use a method that, while not as accurate, results in the utility reducing the costs incurred.

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Explanation of Key Terms

1. **Capacitor element:** capacitor film with interleaving tissues of paper (dielectric material), wound up to form a single cylindrical roll. Used within a **capacitor unit**.

2. **Capacitor unit:** refers to a single container, made of steel or stainless steel, with two terminals brought outside. Inside is an assembly of **capacitor elements** in a parallel/series configuration. Used to form a **capacitor bank**.

3. **Capacitor bank:** a number of **capacitor units** connected in a series/parallel configuration. The bank can be constructed for a specific voltage and capacitance rating as required.

4. **Element section:** a group of **elements** connected in parallel within the **capacitor unit**.

5. **Unit section:** a group of **units** connected in parallel.

6. **Internally fused capacitor unit:** a **unit** where a fuse is connected in series with each capacitor **element**.

7. **Externally fused capacitor unit:** a **unit** connected in series with a single fuse mounted between the **unit** and the **capacitor bank** fuse bus.

8. **Fuseless capacitor unit:** a **unit** applied to a circuit without fuses.

9. **String:** a string of series connected fuseless **units** in a **capacitor bank** phase.

1. Introduction

1.1 Background

For an electric power system to operate reliably and economically, it is important that reactive power is controlled in an effective manner. Very simply, this follows the basis that the smaller the amount of reactive power flow, the smaller amount of losses on a system.

The application of high-voltage (HV) shunt capacitors at the load end of a system supplying a load of lagging power factor will have several effects. Below is a short summary of these effects (covered extensively in Chapter 2), one or more of which may be the reason the capacitors are being applied (Westinghouse, 1964:233):

- Reduction in line current.
- Increase in voltage level at the load.
- Improvement of voltage regulation if the capacitors are appropriately switched.
- Reduction in power losses in the system because of the reduction in current.
- Increases in power factors of the source generators.
- Decrease in reactive power loading to relieve an overloaded condition or to release capacity for additional load growth.

The protection of HV shunt capacitor banks requires an understanding of the limitations and capabilities of capacitors and their switching devices (EPRI, 1998:9-1). This is essential for determining when a bank should be taken out of service (depending on the amount and type of stresses being put on the bank). Thus a reliable protection method is needed to ensure minimal damage to the bank.

The different types of fault conditions or impending fault conditions on a shunt capacitor bank can be categorised into two groups. Firstly, there are those incidents that occur due to undesired external or system influences, and secondly, there are those internal incidents (such as a capacitor unit failing). Studying these conditions and the protection methods used to counter them (with more focus on capacitor unit failures) forms a substantial part of this thesis work (see Chapter 3). The failings and disadvantages of existing protection methods will constitute the basis of this investigation, by looking at new or improved ways of protecting a shunt capacitor bank.

Briefly, the main shunt capacitor bank problems associated with undesired external or system conditions, and their respective protection methods, are:

1. Bank Overcurrents

Bank overcurrents, in the form of line-to-line faults (between different phases of the capacitor bank) or line-to-ground faults, will generally require some form of external protection for the capacitor bank. This is achieved using a circuit breaker with time-overcurrent relays. Inrush currents, on the other hand, can be limited by a fixed reactor in series with the capacitor bank.

2. Surge Voltages

Transient surge voltages, caused by either lightning or capacitor bank switching, may be curtailed with standard overvoltage protection such as surge arresters. Depending on the capacitor bank arrangement, the placement of surge arresters at one or more strategic points within the bank can fully eliminate the generation of severe transient overvoltages (Pretorius, 1998:13). In the case of a grounded bank, the bank provides a low impedance path to ground for lightning surge currents and gives some protection from surge voltages (EPRI, 1998:9-4).

The switching of shunt capacitor banks is known to cause transient overvoltages on equipment, such as transformers, connected at remote locations. Synchronised switching and 'tuning reactors' in series with the bank are two of the more common solutions used to eradicate the transients.

3. Harmonics

The principal cause of harmonic voltages and currents in capacitors is the magnetising requirements of transformers (Westinghouse, 1964:253). Other sources of harmonics include system voltage dips. These harmonics can cause conditions severe enough for a capacitor bank to trip. A careful study and design approach could result in a trouble-free solution, although the cost implications may present limitations.

As mentioned earlier, the effect of an unhealthy or failed capacitor unit on a capacitor bank will be looked at in detail in this report. The two main capacitor unit ratings as specified by the IEEE (1990:8) are that capacitor units should operate at up to 110 % of rated rms voltage and up to 180 % of rated rms current. Depending on the bank arrangement and the type of fusing used, the failure of a unit will cause varying degrees of overcurrents and overvoltages on adjacent units.

Unbalance relaying is the most common scheme for detecting these stresses on the bank as a whole. There are two methods of unbalance relaying: current unbalance detection and voltage unbalance detection. The current unbalance method calls for two star-connected groups with the star points connected. Any unbalance in the capacitances will cause current to flow in the star connection, where a current transformer can detect this current. The voltage unbalance method compares the voltage across a known low-voltage capacitor with the voltage across the rest of the bank. Any difference in these values indicates that capacitor failure has occurred. For both the current and voltage methods, system unbalance must be considered. There are other various unbalance schemes, with most working on the same principles but with slight differences in application.

In HV shunt capacitor banks, the fuseless capacitor unit is preferred over internally and externally fused units. The main reason for this is the arrangement of the capacitor units. Strings, consisting of a number of units in series, are placed in parallel (there is no interconnection between units in different strings). When a unit fails, voltages across the remaining units in the string will increase, and the string current will increase. These will not necessarily reach levels that will cause the bank to trip out.

At present, HV banks incorporating fuseless units use unbalance methods as the main form of protection. The main disadvantages are that the protection methods cannot detect whether a specific unit is under severe stress and close to failing, and in the case where a unit has failed, where the unit is exactly located on the bank.

The aim of this thesis is to investigate possible improvements to existing protection methods, and thus make suitable conclusions on how the protection of shunt capacitor banks could be made more effective.

1.2 Research on Which This Thesis is Based

Research was done using a host of different information sources. This allowed a balanced investigative procedure, and ensured a high level of accuracy with respect to information that was drawn into the thesis. Below is a summary of the main types of research undertaken:

1. Literature Survey

This included a thorough search of all available texts pertaining to the thesis at the University of Cape Town Library and the Eskom Library (Megawatt Park, Gauteng). For journal papers the INSPEC search program was consulted at the University of Cape Town. Additionally, leading South African companies who deal with shunt capacitors and the protection of shunt capacitors were contacted and relevant information was obtained from them. Engineers at Eskom's offices in Simmerpan, Gauteng and Bellville, Western Cape were able to supply specific literature relating to Eskom equipment currently in operation. Finally, a search of the Electric Power Research Institute (EPRI) information database on the Internet yielded some helpful reports and papers.

2. Field Visits and Visits to Suppliers

Before this area of research was decided upon, I spent two months gaining practical experience with the Test Department at the Eskom office in Brackenfell, Western Cape. Most of this training involved testing protection relays for different types of equipment at distribution stations.

Once the subject of the thesis was narrowed down to the protection of shunt capacitors, I visited the 132 kV, 72 MVAR shunt capacitor bank at Muldersvlei substation in the Western Cape. Here I gained a practical sense of the general operation of the bank. I also visited ABB Powertech (Gauteng), one of the main suppliers of reactive power compensation equipment to Eskom. Consultations with ABB engineers helped considerably with the understanding of how shunt capacitor banks operate.

3. Laboratory Models

I assembled two models in the laboratory to experiment on for this thesis. The first model was built to represent a single phase of a shunt capacitor bank, consisting of a number of capacitors. I carried out tests on the bank at 200 V. The aim of these was to gain further understanding of a failed capacitor unit on the capacitor bank. Using these results, existing protection methods could be examined and the improvement of these methods looked into, and new methods investigated.

The second model was built to test the limitations of a single capacitor unit and to identify any form of signature, when the unit failed, that would be detectable by an existing or new protection device. The capacitor unit had a continuous overvoltage applied across its terminals, which was stepped up at intervals until the capacitor failed.

4. Computer Model

I developed a computer model of the operation of a fuseless shunt capacitor bank. The main purpose of the model was to determine how the voltage, current and reactive power profiles of the capacitor bank would react to element failures within capacitor units. Test cases were run using various bank arrangements and element failure simulations with the aim of investigating how this would effect protection procedures.

1.3 Scope and Organisation of Thesis

The focus of this thesis is on HV shunt capacitor banks and the protection thereof. Shunt capacitor banks are an integral component of a power system, and it is important that any adverse effects imposed on them, by the system or other influences, will have as few as possible negative implications.

The aim of this research is to review existing protection methods and to investigate improvements of these methods and other methods of detecting an unhealthy capacitor unit, bearing in mind the different application considerations involved. The following basic questions will be addressed:

- Can an unhealthy capacitor unit be detected accurately?
- If so, is the method used appropriate to the level of protection required, and what are the implications?

This thesis is divided into six chapters. Chapter 2 provides the first part of the literature survey, introducing the fundamentals of capacitors. The development of capacitor units and shunt capacitor banks is traced, and the benefit of shunt capacitors described. Finally, different bank configurations are covered. This chapter lays down a foundation of the terminology and concepts that will be used throughout the thesis.

Continuing with the literature survey, Chapter 3 is a comprehensive review on the subject of shunt capacitor bank protection. This includes a discussion on the limitations of capacitor units and their operation. Unbalance detection, the principal protection method, is covered with respect to the three different capacitor unit fusing applications, namely: internally fused, externally fused, and fuseless units. Examples are then given of stresses that a bank may suffer (and the protection methods used against these).

Detecting unhealthy fuseless capacitor units is focussed on in Chapter 4. Results of tests done in the laboratory are presented and discussed. The main areas of investigation include looking at the effects on voltage and current profiles at different locations on a bank as an element within a capacitor unit fails, and also looking for lesser known signs that an element has failed. The possibilities of using these signature changes as alarms in protection devices are considered, from a logistical and economical stance.

The effect of element failures, using a computer model of a fuseless shunt capacitor bank, is investigated in Chapter 5. An analysis of the results of this investigation is made, pertaining to how the arrangement of capacitor units in a bank affects the accuracy of detecting an unhealthy unit or bank. Finally, in Chapter 6, conclusions are drawn and presented within a summary of the main results of the thesis project.

2. The Application of High-Voltage Shunt Capacitors

2.1 An Introduction to Capacitors and Capacitor Types

2.1.1 Fundamentals

The equations and derivations stated in this section are taken mainly from The Art of Electronics (Horowitz and Hill, 1993:21,22).

A capacitor of C farads with V volts across its terminals and Q coulombs of stored charge on one plate, and –Q on the other (Figure 1), has the property

$$Q = CV \tag{2.1}$$

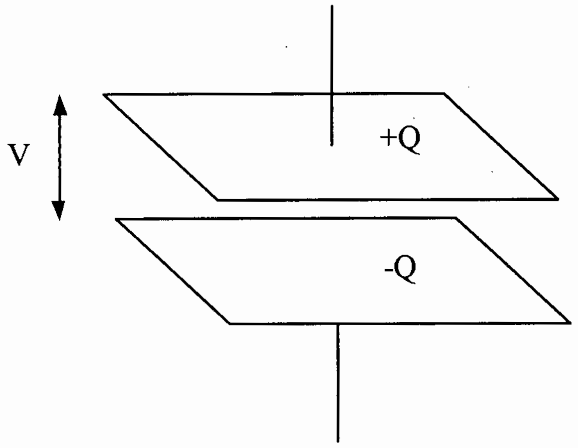


Figure 1. General depiction of a capacitor with voltage V across its terminals

The derivative of Equation 2.1 gives

$$I = C\frac{dV}{dt} \tag{2.2}$$

Unlike a resistor, the current is not proportional to the voltage, but rather to the change of voltage. By changing the voltage across a 1-farad (F) capacitor by 1 volt (V) per second, an amp (A) will be supplied. Conversely, if 1 A is supplied, the voltage will change by 1 V per second.

Usually capacitors are rated in microfarads (uF) or picofarads (pF), as a farad is very large. For instance, if a current of 1 mA is supplied to 1 uF the voltage will rise at 1000 V per second. A 10 ms pulse of this current will increase the voltage across the capacitor by 10 V (Figure 2). This has a charging effect on the capacitor, and the power associated with the capacitive current is not turned into heat, but is stored as energy in the capacitors internal electric field. All of this energy is released when the capacitor is discharged (capacitors cannot dissipate power, even though current can flow through them, because the voltage and current are 90° out of phase). The power properties of a capacitor are looked at in more detail in the next section.

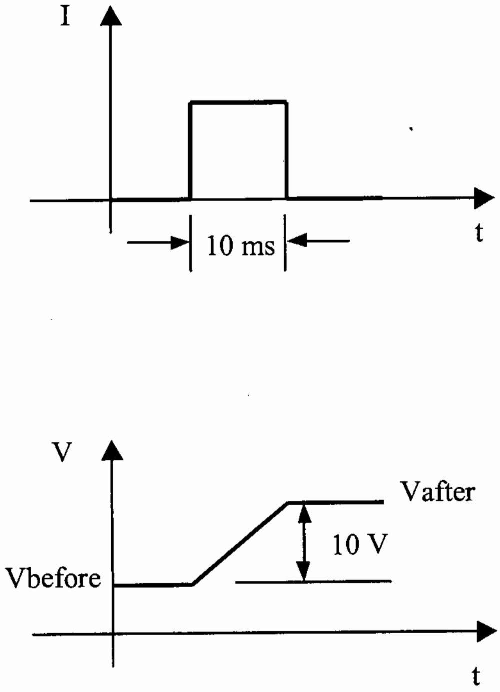


Figure 2. The voltage change across a capacitor when a current flows through it (Horowitz and Hill, 1993:21)

The capacitance of several capacitors in parallel is the sum of their individual capacitances. If a voltage V is put across the parallel combination, then

$$\begin{aligned} C_{total}V = Q_{total} &= Q_1 + Q_2 + Q_3 + \ldots \\ &= C_1V + C_2V + C_3V + \ldots \\ &= (C_1 + C_2 + C_3 + \ldots)V \end{aligned}$$

or

$$C_{total} = C_1 + C_2 + C_3 + \ldots \qquad (2.3)$$

For capacitors in series, the formula is like that for resistors in parallel:

$$C_{\text{total}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots} \tag{2.4}$$

2.1.2 Capacitor Types

There are a large variety of capacitors with different shapes and sizes. The basic construction is simply two conductors near each other (but not touching), as shown in Figure 1. For greater capacitance, more area is needed as well as closer spacing. The general approach is to attach some conductor onto a thin insulating material (known as a dielectric). For example, aluminised Mylar (polyester) film rolled onto a thin dielectric. Other popular types include metalled mica, metal foils with oxide insulators (electrolytics), and thin ceramic wafers (disc ceramics) (Horowitz and Hill, 1993:21). Each of these types has unique properties; for a brief and somewhat subjective guide see Table 1 (Horowitz and Hill, 1993:22).

2.1.3 Reactance

Consider a single-phase capacitive load that has a voltage across it of:

$$\begin{aligned} v(t) &= V_{\max}\cos(wt) \\ &= \mathrm{Re}[V_{\max}e^{jwt}] \end{aligned} \tag{2.5}$$

Using (2.2), the current through the capacitor is

$$\begin{aligned} i(t) &= -CV_{\max}w\sin(wt) \\ &= \mathrm{Re}[\frac{V_{\max}e^{jwt}}{-j/wC}] \end{aligned} \tag{2.6}$$

Applying a complex form of Ohm's law, the reactance X_C of the capacitor at a frequency w (remember $w = 2\pi f$) is defined as (Horowitz and Hill, 1993:32)

$$X_C = -j/wC \tag{2.7}$$

A circuit containing only capacitors and inductors has a purely imaginary impedance, meaning that the voltage and current are always 90° out of phase – it is purely reactive

(Horowitz and Hill, 1993:32). In the case of capacitors, the current will lead the voltage by 90°. When the circuit contains resistors, there is also a real part to the impedance. The term ‘reactance’ refers only to the imaginary part.

Type	**Capacitance Range**	**Maximum Voltage**	**Accuracy**	**Temperature Stability**	**Leakage**	**Comments**
Mica	1pF-0.01uF	100-600	Good		Good	Excellent (RF)
Tubular ceramic	0.5pF-100pF	100-600		Selectable		Several temperature coefficients
Ceramic	10pF-1uF	50-30000	Poor	Poor	Moderate	Small, cheap, very popular
Polyester (Mylar)	0.001uF-50uF	50-600	Good	Poor	Good	Cheap, good, popular
Polystyrene	10pF-2.7uF	100-600	Excellent	Good	Excellent	High quality, large; filters
Polycarbonate	100pF-30uF	50-800	Excellent	Excellent	Good	High quality, small
Polypropylene	100pF-50uF	100-800	Excellent	Good	Excellent	High quality, low dielectric absorption
Teflon	1000pF-2uF	50-200	Excellent	Best	Best	High quality, lowest dielectric absorption
Glass	10pF-1000pF	100-600	Good		Excellent	Long-term stability
Porcelain	100pF-0.1uF	50-400	Good	Good	Good	Good long-term stability
Tantalum	0.1uF-500uF	6-100	Poor	Poor		High C; low L; small, polarised
Electrolytic	0.1uF-1.6F	3-600	Very poor	Very poor	Very poor	Power-supply filters; polarised; short life
Double layer	0.1F-10F	1.5-6	Poor	Poor	Good	Memory backup; high series resistance
Oil	0.1uF-20uF	200-10000			Good	HV filters; large, long life
Vacuum	1pF-5000pF	2000-36000			Excellent	Transmitters

Table 1. Capacitor types (Horowitz and Hill, 1993:22)

2.1.4 Reactive Power

Glover and Sarma's "Power System Analysis and Design" (1994:18-24) was examined for this section, and thus the material below is taken largely from their work.

The instantaneous power absorbed by the reactive part of a load is a double-frequency sinusoid with zero average value and with amplitude Q given by

$$Q = VI_x = VI\ \sin(\delta - \beta) \tag{2.8}$$

where δ = phase angle of the voltage

β = phase angle of the current

$(\delta - \beta)$ = angle between the voltage and current, called the power factor angle (commonly referred to as ϕ)

The term Q is given the name reactive power. Although it has the same units as real power, units of reactive power are usually referred to as volt-amperes reactive, or VAR (Glover, J D and M Sarma, 1994:18). In the case of a capacitor, the reactive power absorbed can also be calculated using

$$Q_C = -\frac{V^2}{X_C} \tag{2.9}$$

Note that the reactive power absorbed is negative. This follows from what was initially discussed in the previous section: due to the 90° phase difference between voltage and current, the capacitor does not dissipate energy, but rather alternates between storing and discharging energy. It is more useful to say that a capacitor delivers positive reactive power (the opposite of an inductive load, which absorbs positive reactive power). The reactive power delivered by a capacitor is

$$Q_C = +\frac{V^2}{X_C} \tag{2.10}$$

In Figure 3, a complex power triangle is used to indicate how reactive power Q (in volt-amperes reactive), apparent power S (in volt-amperes) and real power P (in watts) are related, in terms of the three sides of the triangle (Glover, J D and M Sarma, 1994:23). The power factor angle $(\delta - \beta)$ is also shown, from which the power factor (pf) is calculated. The following expressions are obtained from the power triangle:

$$S = \sqrt{P^2 + Q^2} \tag{2.11}$$

$$(\delta - \beta) = \tan^{-1}(Q/P) \tag{2.12}$$
$$Q = P\tan(\delta - \beta) \tag{2.13}$$

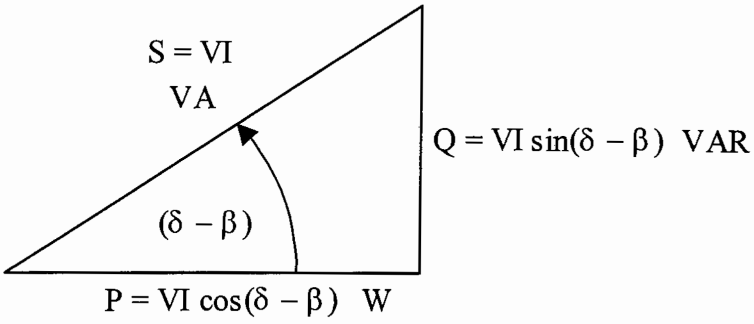


Figure 3. Power Triangle (Glover, J D and M Sarma, 1994:23)

$$\text{p.f.} = \cos(\delta - \beta) = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{2.14}$$

The power associated with a single-phase circuit is very easily converted to a three-phase format. Consider the a-phase voltage $\mathbf{V}_{an}$ and current $\mathbf{I}_a$ (both vectors) represented here in their phasor form of a scalar line-to-neutral voltage V_{LN} and line current I_L, with their respective angles δ and β :

$$\mathbf{V}_{an} = V_{LN}\angle\delta \tag{2.15}$$
$$\mathbf{I}_a = I_L\angle\beta \tag{2.16}$$

The complex power $\mathbf{S}_a$ delivered (for a capacitor) by the a-phase is

$$\begin{aligned}\mathbf{S}_a &= \mathbf{S}_{an}\mathbf{I}_a^* = V_{LN}I_L\angle(\delta - \beta)\\ &= V_{LN}I_L\cos(\delta - \beta) + jV_{LN}I_L\sin(\delta - \beta)\end{aligned} \tag{2.17}$$

Under balanced operating conditions, the complex powers delivered by phases b and c are identical to $\mathbf{S}_a$, and the total three-phase complex power $\mathbf{S}_{3\phi}$ is

$$\begin{aligned}\mathbf{S}_{3\phi} &= \mathbf{S}_a + \mathbf{S}_b + \mathbf{S}_c = 3\mathbf{S}_a\\ &= 3V_{LN}I_L\cos(\delta - \beta) + j3V_{LN}I_L\sin(\delta - \beta)\end{aligned} \tag{2.18}$$

In terms of real and reactive powers,

$$S_{3\phi} = P_{3\phi} + jQ_{3\phi} \tag{2.19}$$

In the case of a capacitor, the reactive power $Q_{3\phi}$ is

$$\begin{aligned} Q_{3\phi} &= \text{Im}(S_{3\phi}) = 3V_{LN}I_L \sin(\delta - \beta) \\ &= \sqrt{3}V_{LL}I_L \sin(\delta - \beta) \text{ VAR} \end{aligned} \tag{2.20}$$

Here V_{LL} is the line-to-line voltage. The total apparent power (in magnitude) is

$$S_{3\phi} = |S_{3\phi}| = 3V_{LN}I_L = \sqrt{3}V_{LL}I_L \text{ VA} \tag{2.21}$$

2.2 Power Capacitor Units

2.2.1 History of Capacitor Development

Capacitors that are utilised on high-voltage equipment, or ‘power capacitors’, have been in use on power systems for over 50 years. In this period there have been numerous advances that have made power capacitors highly effective electrical components (Miller, 1975).

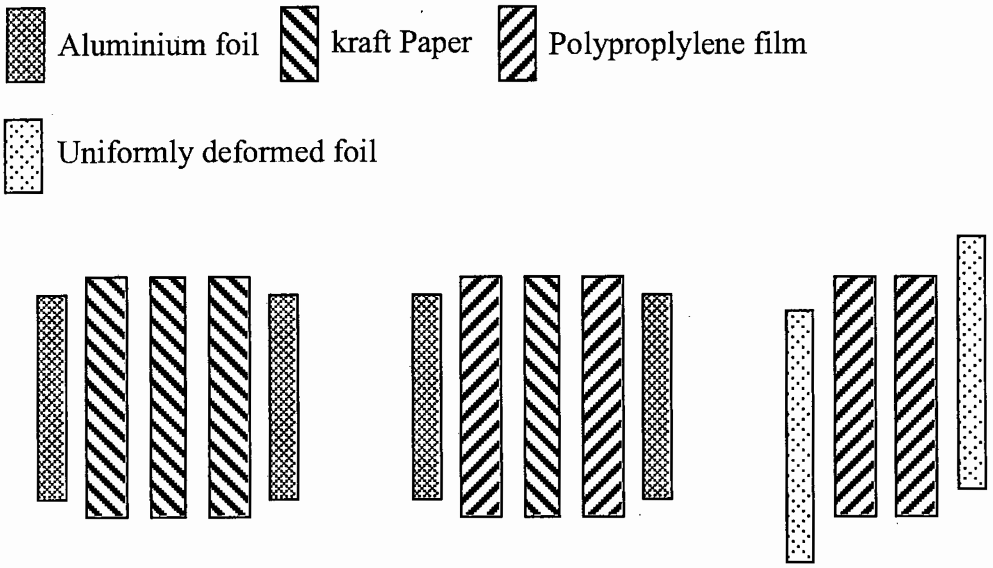
Before 1968, kraft paper (a strong, usually brown paper processed from wood pulp, used chiefly for bags and as wrapping paper) was used as the principal dielectric with aluminium foil electrodes. The liquid impregnant commonly used was polychlorinated biphenyl (PCB), sold under the name of Askaral. These capacitors are commonly referred to as all-paper capacitors. In the event of a dielectric failure the paper would char (keeping the electrodes separated), and the resulting arc would lead to gassing. An essential requirement was prompt disconnection of failed capacitors by fuses, as this would keep the probability of case rupture low (Constable, 1992:28).

Through improvement in materials and design skills, unit sizes progressed from a 10-kVAR size at almost 3 kg per kVAR to a 100-kVAR size at 0.5 kg per kVAR (Sangamd, 1993). In 1968 a plastic film called polypropylene was developed, bringing with it the introduction of a 150-kVAR unit at 0.3 kg per kVAR (Stone). The unit employed a dielectric that was composed of a combination of kraft paper and film, known as a paper/film design. Askaral was, at this stage, still the industry standard liquid impregnant (Allis-Chalmers, 1960).

Liquid dielectrics that are used as impregnants provide insulation by ensuring all moisture, products of oxidation and other contaminants are excluded within a capacitor unit. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength considerably (Wadhwa, 1994:20).

The main consideration in the selection of a liquid dielectric is its chemical stability. Other considerations include cost, the saving in space, and susceptibility to environmental influences. The use of Aroclar fluid (another type of PCB) presented some problems that were realised in the late 1960's. This was due to the fact that the fluid was non-biodegradable and thus had a negative effect on the environment. In 1975 the Environmental Protection Agency (EPA) in the United States indicated that PCBs would eventually be banned from all uses. As a result, all capacitor manufacturers now use a non-PCB, mineral-based impregnant that is biodegradable (Constable, 1992:28).

Another significant development in dielectric design was the introduction of the all-film capacitor in 1971, which dramatically improved the electrical operating characteristics of capacitors. The all-film capacitor eliminates the use of kraft paper in the active dielectric. This provides the user with several benefits. These include: lower operating costs due to reduced operating losses, increased safety due to reduced case rupture hazards, and increased reliability due to lower operating temperatures. Figure 4 illustrates the three basic dielectric systems.



(a)
All-paper
dielectric

(b)
Paper-film
dielectric

(c)
All-film
dielectric

Figure 4. The three basic capacitor dielectric systems (Tzou, 1990)

Today capacitor units can achieve terminal voltage ratings of 25 kV (rms), unit outputs of over 400 kVAR with dielectric strengths of up to 80 kV per mm and losses of around 0.06 W/kVAR. The cost per kVAR installed varies little over a wide range of capacity (Constable, 1992:28).

2.2.2 Capacitor Unit Design

The material in this section is taken largely from Tzou (1990).

High-voltage capacitor units are made up internally of smaller capacitors called elements. These elements, with discrete voltage and kVAR ratings, are interconnected to obtain the desired voltage and kVAR rating of the capacitor unit itself. Figure 5 shows schematic representations of the three typical capacitor units, namely, fuseless, externally fused and internally fused (adapted from diagrams used by Francocci, 1992 and 1995). These capacitors are discussed in more detail in Section 3.2. Figure 6 illustrates how the various layers of film and foil are wound up to form an element.

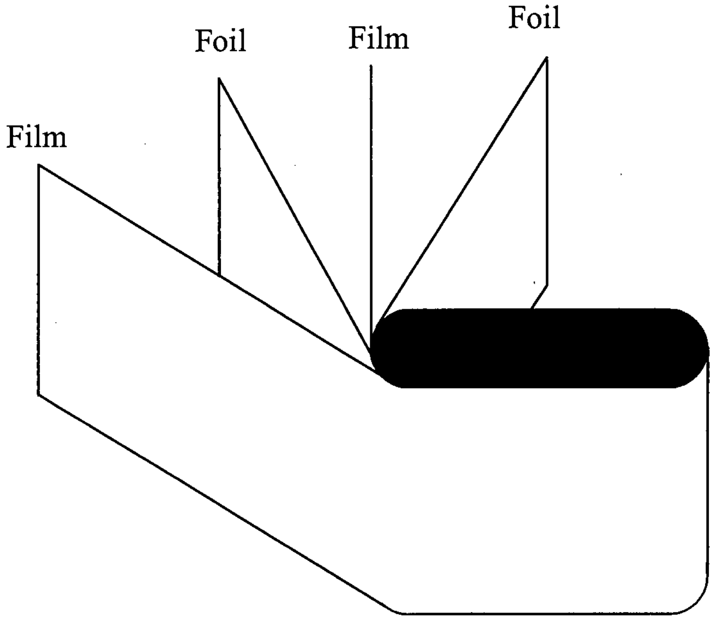


Figure 6. Capacitor element construction (Tzou, 1990)

The following equations outline the basic calculations used in capacitor design, and are listed in their final form. When a dielectric is placed between two flat metallic plates, as illustrated in Figure 7, the capacitance is calculated as

$$C = \varepsilon \frac{A}{t} \qquad (2.22)$$

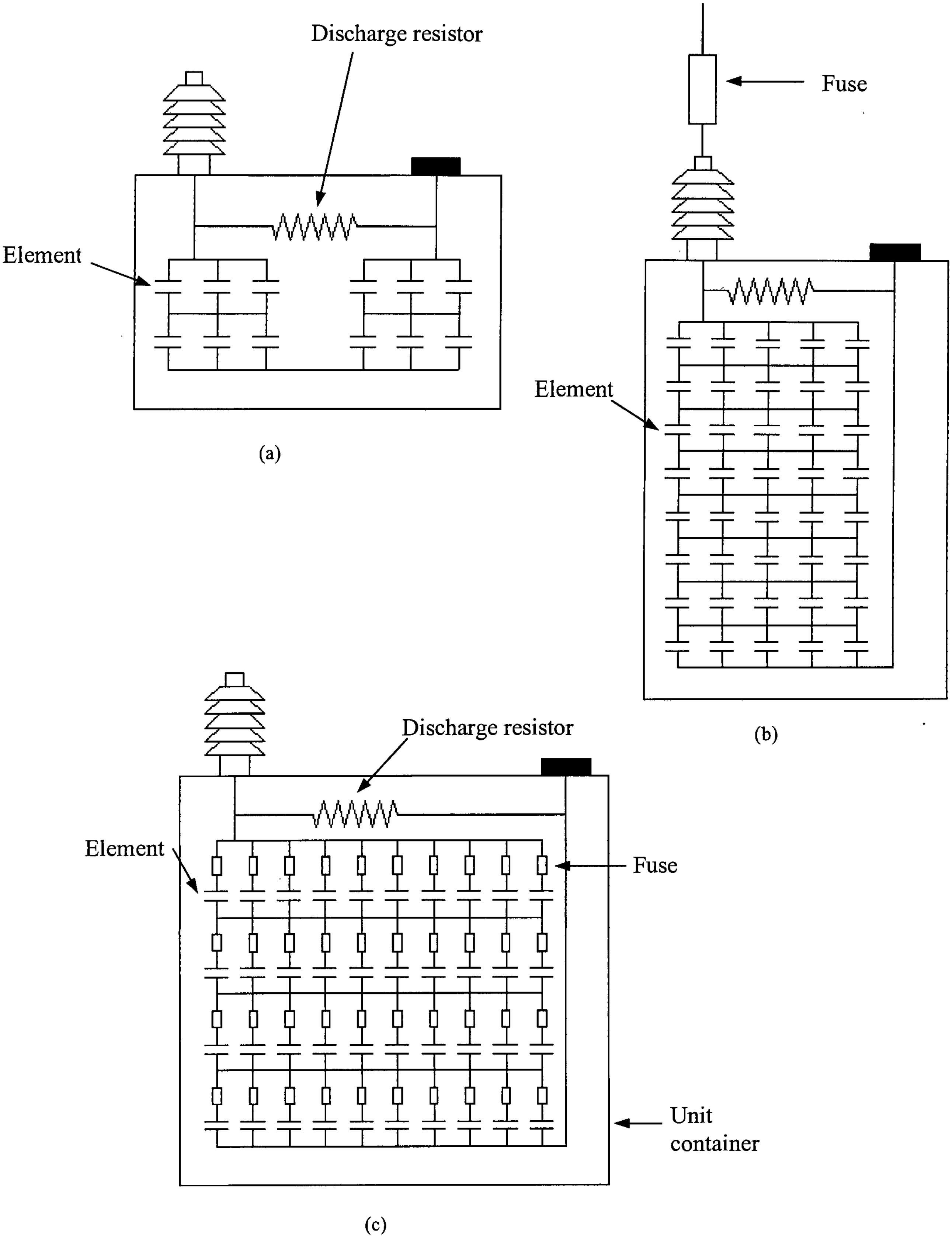


Figure 5. Fuseless, externally fused and internally fused capacitor units

where ε = relative permittivity constant

A = plate area (in m^2)

t = distance between plates (in m).

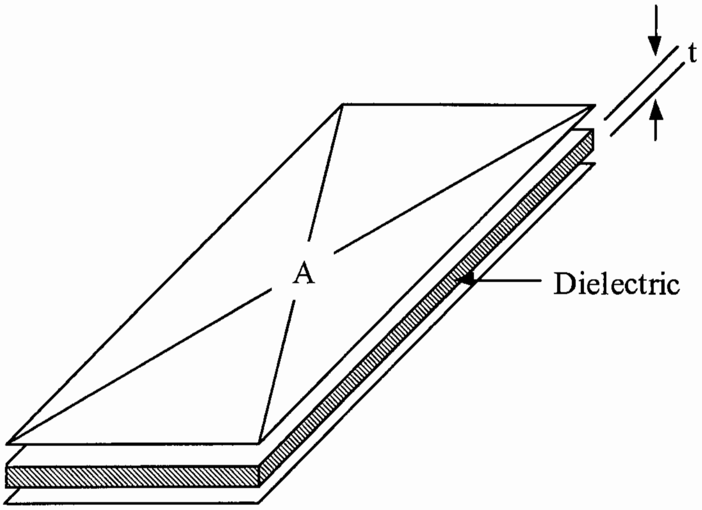


Figure 7. Cross-sectional view of a capacitor (Tzou, 1990)

If two different dielectrics are used, as in the case of a paper/film capacitor (Figure 8), and with relative dielectric constants K_1 and K_2, the composite relative dielectric constant is calculated using

$$K_C = \frac{K_1 K_2 t}{K_1 t_2 + K_2 t_1} \tag{2.23}$$

where t = distance between plates ($t_1 + t_2$)

t_1 = thickness of dielectric 1

t_2 = thickness of dielectric 2.

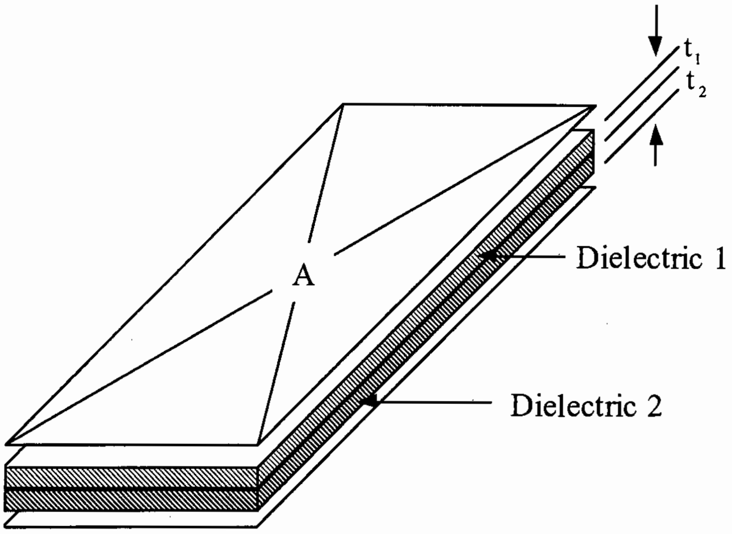


Figure 8. Capacitor with two dielectrics (Tzou, 1990)

The actual capacitance for a desired capacitor unit with a rating of Q VAR can be calculated as follows:

$$C = \frac{Q}{2\pi f V_R^2} \tag{2.24}$$

where f = frequency

V_R = capacitor unit rated voltage

Q = capacitor unit reactive power rating.

When capacitors are operated at voltages other than nameplate voltages, the reactive power generated changes by the square of the ratio of applied voltage to nameplate voltage:

$$Q_O = Q_R \left(\frac{V_O}{V_R} \right)^2 \tag{2.25}$$

where Q_O = operating power

Q_R = rated power

V_O = operating voltage

V_R = rated voltage.

Similarly, the reactive power changes directly as the frequency changes:

$$Q_O = Q_R \left(\frac{f_O}{f_R} \right) \tag{2.26}$$

where f_O = operating frequency

f_R = rated frequency.

The electrical stress distribution on different dielectrics in the dielectric system, typically given in volts per mm of dielectric thickness, is calculated using

$$\frac{E_1}{E_2} = \frac{K_2}{K_1} \tag{2.27}$$

where E_1 = electrical stress on dielectric 1 (V/mm)

E_2 = electrical stress on dielectric 2 (V/mm).

The number of internal sections connected in series within a capacitor unit, where a section consists of a group of elements in parallel, is determined by the capacitor's rated voltage and dielectric thickness. The voltage across each section is calculated using

$$V_S = \frac{V_R}{S} \tag{2.28}$$

$$V_S = E_1 t_1 + E_2 t_2 \text{ (if two dielectrics are used)} \tag{2.29}$$

where V_S = voltage of an internal series group

V_R = rated voltage of the capacitor unit

S = number of series groups

E_1, E_2 = as defined in (2.27)

t_1, t_2 = as defined in (2.23).

Using the results of these calculations, the design procedure for a whole shunt capacitor bank can be developed (Tzou, 1990:2-13).

2.2.3 Testing of Capacitors

ANSI (1968) and IEEE (1977, 1980) define industry standards for power capacitors. The main areas covered by these standards are service conditions, ratings, testing and the application of power capacitors. This section summarises the standards for capacitor testing according to design, routine and field tests.

<u>Design Tests</u>

The design tests listed below have to be performed by the manufacturer on a sufficient number of capacitor units to prove that the design of the capacitor complies with design requirements (Wadwha, 1994:153). These tests do not have to be repeated unless there is a design change that would cause a difference in a unit's performance characteristics.

1. Dielectric Strength Test

A terminal-to-terminal DC withstand test.

2. Dielectric Loss Angle Test (pf Test)

A high-voltage Schering Bridge is used to measure the dielectric power factor. The value of loss angle tan δ should not be more than the value agreed to between the manufacturer and the purchaser. It should not exceed 0.0035 for mineral oil impregnants and 0.005 for chlorinated impregnants.

3. Impulse Withstand Test

This is a case insulation test performed on two-bushing units only. Five impulses of either polarity are applied between the terminals (joined together) and the case. This voltage should be withstood without causing any flashover.

4. Thermal Stability Test

The capacitor is placed in an enclosure and monitored while the temperature is maintained at ± 2 °C above the maximum working temperature for 48 hours.

5. Radio Influence Voltage Test

Tests are done to ensure that radio influence does not exceed a predetermined level while operating within its design limits.

6. Voltage Decay Test

The effectiveness of the discharge resistor is checked. The residual capacitor voltage after the supply voltage is switched off should drop to 50 V in less than one minute for capacitors rated up to 650 V, and in 5 minutes for capacitors rated greater than 650 V.

Routine Tests

Routine tests are carried out on all capacitors by the manufacturer to ensure they comply with industry standards.

1. Short-Time Overvoltage Test

This is a terminal-to-terminal withstand test. The manufacturer can perform this test with either an AC or DC voltage. An additional terminal-to-case test is also performed on two-bushing units.

2. Capacitance Test

The capacitance is measured to ensure that the kVAR rating of the capacitor unit does not differ by more than –5 to +10 % of the specified value, at 25°C ± 5°C ambient temperature.

3. Discharge Resistor Test

Resistance measurements are taken to ensure they are within predetermined limits.

4. Leak Test

A test to determine whether the capacitor unit is free from leaks.

Field Tests

The most common way of determining the health of a capacitor unit in the field is to measure the capacitance. A capacitance meter or low-voltage bridge can be used to determine whether an all-film unit has partially failed. The voltage needed in this test is only a few volts. A failure in an all-film unit has a very low impedance even to those low voltages so, as a result, partial failures can be easily identified. This same method can also be used to identify partially failed paper/film units with reasonably good results.

2.3 Shunt Capacitors in a Power System

2.3.1 Introduction and History

Although an unloaded transmission line is capacitive in character, a fully loaded line has inherent inductive and resistive characteristics. On main transmission lines operating at near unity power factor, the power that can be transmitted is determined largely by the system stability limit. Provided the phase angle between the voltages at the sending and receiving ends does not exceed a certain critical value, the system will remain stable. On distribution networks the inductive reactance makes a major contribution to the voltage drop, especially on networks operating at low power factors. It is these voltage drop considerations that frequently dictate the amount of power that can be distributed. Series inductance in a power network can cause (Dolby, 1995):

- A phase shift between the different parts of the network tending towards instability at an undesirably low power level.
- Excessive voltage drops between ends of feeders.
- Unequal sharing of the load between parallel feeders, thus limiting the total power which can be transmitted.

It is possible to postpone expensive system reinforcement by installing reactive power compensation equipment. In order for improvements to be made, means have to be introduced that will reduce the system reactance or the phase angle between the system current and voltage. Installing static plant, such as series or shunt capacitors to generate reactive power, or reactors to absorb reactive power, can achieve this. Rotating plant, in the form of large synchronous machines, can also be used. Depending on the system requirements at the time, these machines are operated as capacitors (overexcited) during periods of heavy active load transfer, and as reactors (underexcited) during periods of light load transfer.

When a shunt capacitor is applied reactive power is generated and the phase angle between the voltage and current is reduced, which has the effect of:

- Reducing the transmission line current to a value less than the current in the load.
- Improving the power factor of the transmitted power.
- Reducing the voltage drop uniformly along the length of the line (Figure 9).

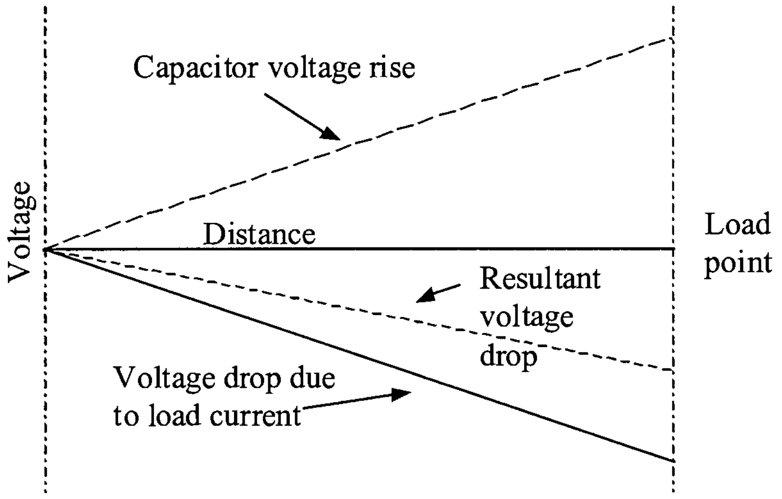


Figure 9. Line voltage drop with distance and the effect of a shunt capacitor (Dolby,1995)

This last effect of the voltage drop being reduced uniformly along the line is more favourable when compared to the effects of a series capacitor bank. The reduction in voltage drop due to a series capacitor is concentrated mainly at the location of the capacitor itself (Figure 10).

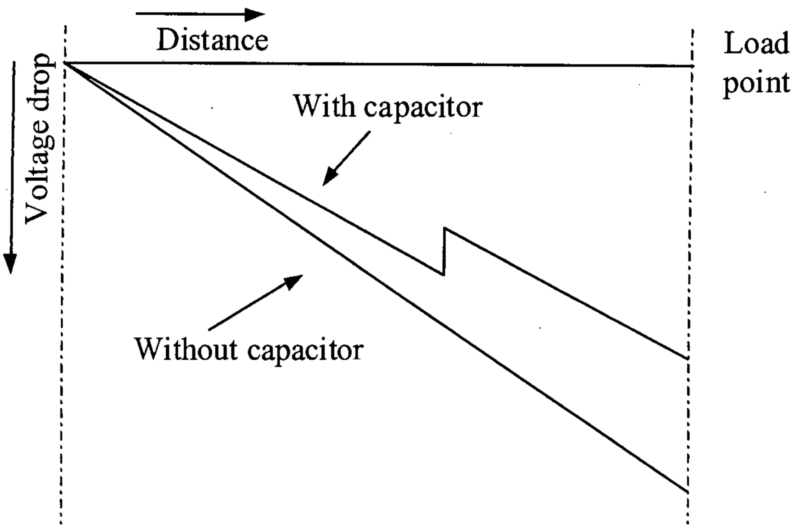


Figure 10. Line voltage drop with distance and the effect of a series capacitor (Dolby, 1995)

Shunt capacitors have an effect on all electrical equipment and circuits on the source side of where they are installed. According to Westinghouse (1964:233), if the capacitor kVAR is small (say 10% of the circuit rating) it is usually sufficient to make an analysis only on the circuit where the capacitor bank exists. Where the capacitor bank is large, however, the effect it has on each part of the system back to and including the source should be considered.

One of the benefits of shunt capacitors mentioned above is that line voltage drops are reduced, leaving the load end of a network at a higher voltage. In determining the amount of kVAR required for a shunt capacitor application, it must be recognised that the voltage increase will cause a rise in the lagging (or absorbing) kVAR in the exciting current of transformers and motors. Thus, some additional kVAR may have to be installed, above the kVAR based on initial conditions without capacitors, to achieve the desired correction (Westinghouse, 1964).

History

Shunt capacitors were first applied for power factor correction about 1914 in the USA (Westinghouse, 1964). Due to the high cost per kVAR, a capacitor's large size and weight, their use was limited for the next twenty years. Before 1937 practically all capacitors were installed indoors in industrial plants. Extensive utility use started after the outdoor unit arrived (which eliminated the need for steel housings and other accessories). By 1939 capacitor costs had been reduced almost proportionately with weight and their ability had been proved in the field. Manufacturing costs have steadily reduced over the years, and increased capacitor usage has also been mainly due to the following:

- Improved design and manufacturing methods resulting in smaller size banks.
- Reduction in failures.
- Better understanding of system benefits that accrue from their use, including economic benefits.

2.3.2 Benefits of Shunt Capacitors

Shunt capacitors provide many important benefits to power systems. A relatively small investment in a low maintenance capacitor installation can often provide savings many times greater than the initial cost of the capacitors (Tzou, 1990:3-1).

A shunt capacitor bank supplies reactive power to a system where it is needed. Loads on the early power systems were predominantly lighting loads, which are resistive, and thus they did not impose many kVAR demands on the system. However, the characteristics of loads have changed over the years, with loads being much larger and consisting more of motor-type devices that place greater kVAR demands upon electrical systems. The correct application of a shunt capacitor bank can supply the system with the capacitive kVAR necessary to counteract the inductive kVAR required by these modern day loads.

System Current and System Voltage Improvements

The effects of capacitors on an electrical system can best be explained in terms of current and reactive power. Figure 11 shows an AC system with a load that is both resistive and inductive, where the inductive part of the load could be a motor, for example (Tzou, 1990). The motor requires an out-of-phase current when operating, which is 90° out-of-phase from the voltage at the load. This current lags the voltage by 90°; hence it is a lagging power factor load. Below the circuit is a phasor diagram depicting this situation. The system generator at the sending end has to supply the reactive power in addition to the normal real power drawn by the resistive load. This reactive power must be supplied by the system, and thus larger conductors and related equipment will be needed.

If a capacitor is properly applied, it will supply a sufficient amount of reactive power that will counteract the reactive power required by the load. This will relieve the generator from supplying the reactive power, and will relieve the system from carrying it. Increasing the capacitance will lessen the reactive power carried by the system, up to the ultimate point where the capacitor will supply all of the kVAR required by the load, and the system will supply only the kW component. Figure 12 shows the equivalent circuit diagram with a capacitor included and the phasor diagram relevant to this.

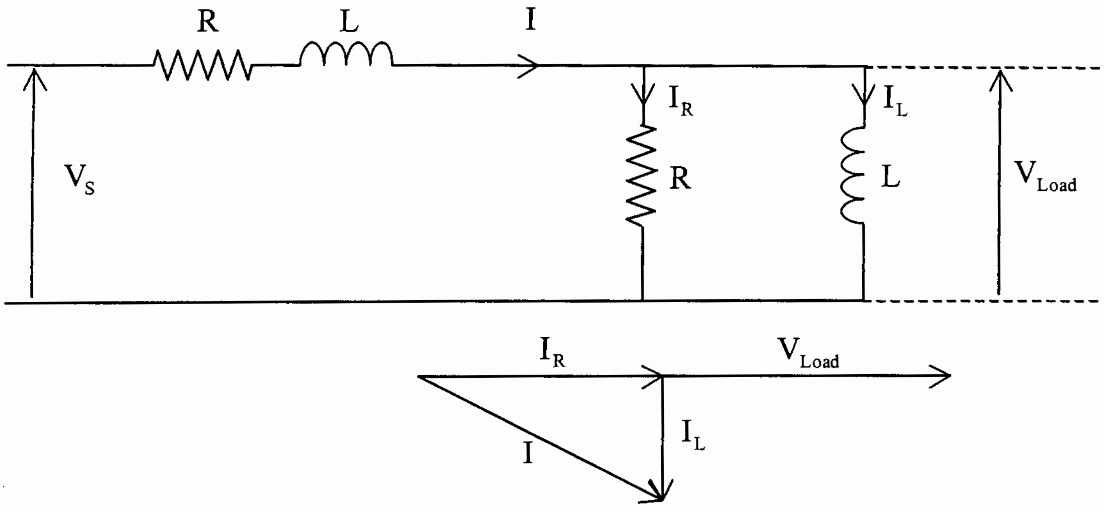


Figure 11. A lagging power factor load (Tzou, 1990)

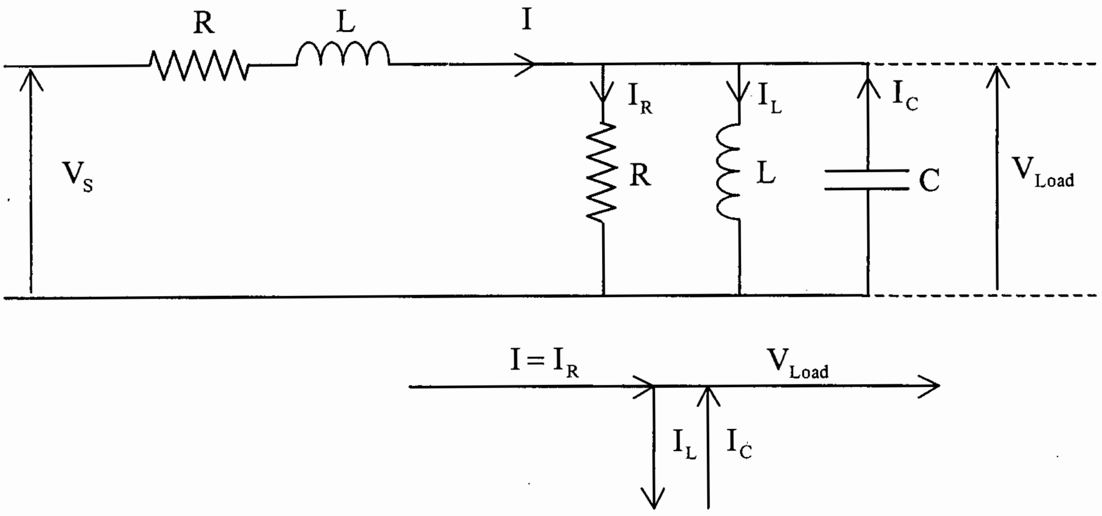


Figure 12. Adding a power-factor-correction capacitor (Tzou, 1990)

Adding various amounts of capacitors allows the useful load to be increased. In a case where equipment may be loaded to its full thermal capability, even to the point of being overloaded, the reduced power demand due to a shunt capacitor will relieve the overload conditions on the equipment. Consequently, the life of the existing equipment is prolonged.

A full phasor diagram showing the effect of a shunt capacitor in a circuit with a load is illustrated in Figure 13.

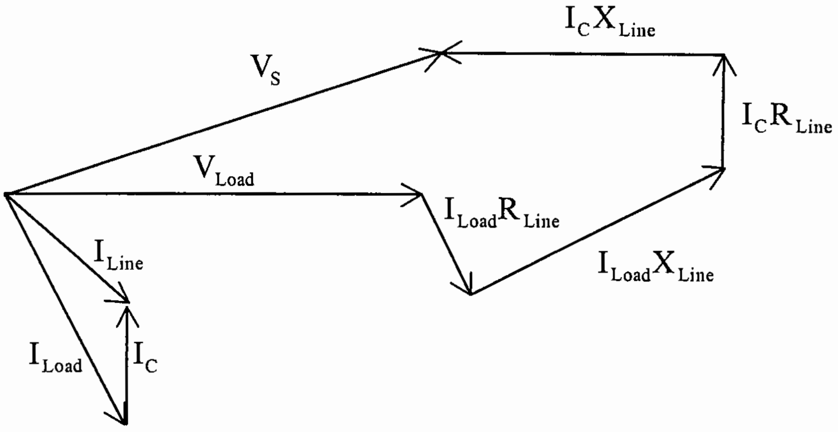


Figure 13. Phasor diagram of shunt capacitor circuit with a resistive load (not to scale)

The system current decreases (shown as the line current in the Figure 13), since the capacitor current draws a leading current to counter the effect of the lagging current drawn by the inductive part of the load. Thus there is a rise in voltage from the point of installation all the way back to the voltage source. This includes every transformer, where the voltage rise is independent of the load or the power factor of the system.

Power Factor Improvements

Most utilities will correct to at least 0.95 power factor (pf) using shunt capacitor banks (Tzou, 1990). Many have economically justified going to unity power factor. If a system has a constant 24-hour load at a given power factor, it is not difficult to attain unity power factor. In reality, however, a load curve will vary, which makes power factor correction more difficult. If unity power factor is achieved during the peak demand period, then during the light demand periods there will be an excess of kVAR being supplied by the capacitor bank. This will result in a leading power factor, causing line losses to increase and excessive voltages to occur at the capacitor bus. In the process equipment may be damaged. Therefore, a leading power factor is of no more use than one that is lagging.

A more effective way of using shunt capacitors is to switch the banks in sections, so as to match the variation in load. This approach will require additional auxiliary equipment.

An example of how the new power factor is calculated after a capacitor bank is added:

Consider a plant that has a load of 70 kW at 0.7 pf. A 42 kVAR capacitor bank is added. What is the resulting power factor of the plant?

Using Equations 2.11-2.14, the apparent and reactive power drawn by the load is

$$S = \frac{70 \times 10^3}{0.7} = 100 \text{ kVA}$$

$$Q = \sqrt{(100 \times 10^3)^2 - (70 \times 10^3)^2} = 71.4 \text{ kVAR}$$

Since 42 kVAR of reactive power is supplied, the new reactive power drawn by the load will be

$$Q = 29.4 \text{ kVAR}$$

This brings the power factor up to

$$\text{pf} = \frac{70 \times 10^3}{\sqrt{\left(70 \times 10^3\right)^2 + \left(29.4 \times 10^3\right)^2}} \approx 0.9$$

2.3.3 The Design of a Bank

This section covers the different types of shunt capacitor bank configurations used in South Africa as well as internationally. Topics closely related to a bank's configuration, such as earthing and protection issues, are looked at more extensively in Chapter 3, which covers all aspects of the protection of shunt capacitor banks.

Bank Configurations

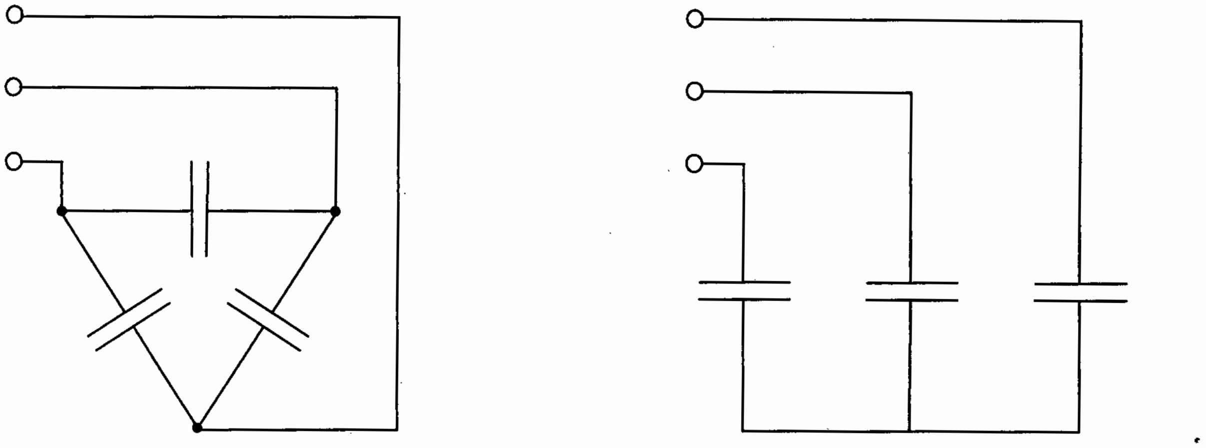
Shunt capacitor banks can be connected to a transmission or a distribution system in either star (wye) or delta configuration, much the same as a transformer (Francocci, 1998:8). The choice of configuration used depends on factors such as:

- The voltage level of the system.
- The size of the bank (in VAR).
- The voltage rating of the capacitor units.
- The available earthing at the site of the bank.
- The protection scheme used.

Delta-connected banks (Figure 14a) are generally used at the lowest system voltages (11 kV to 33 kV) with a single series group of capacitors rated for line-to-line voltage (Francocci, 1998:8). According to the IEEE (1991:12), the lowest capacitor voltage rating of units used in delta-connected banks is 2.4 kV. At 2.4kV capacitor units for star connection are not available as a standard unit size, as star-connected banks are used at much higher voltages (IEEE, 1991:12).

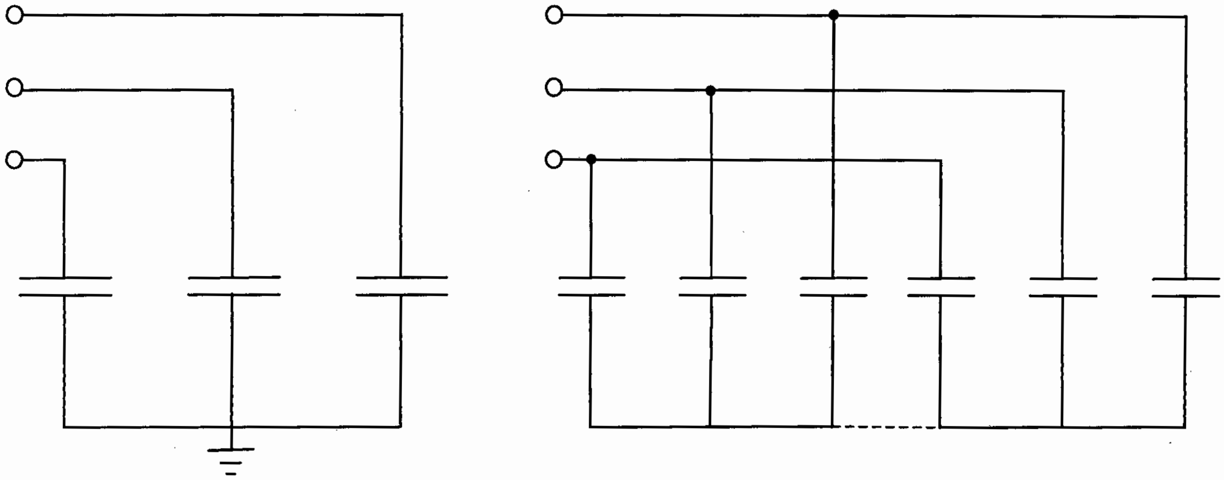
As delta-connected banks require either two-bushing capacitors with a grounded rack or single-bushing units with an insulated rack, star-connected banks are less complicated and more economical. Figures 14b and 14c show unearthed and earthed single star configurations respectively. Depending on the capacitor MVAR size and the protection scheme used, star configurations consisting of two sections of equal size can be used (Figures 14d and 14e). This method is used when the bank becomes too large to ensure adequate operation of fuses. In America the IEEE (1990:9) recommends, for 60 Hz systems, a maximum limit of 4650 kVAR per series group to ensure fuse operation.

Like star-connected banks, H-bridge banks can be either earthed (as shown in Figure 14f) or unearthed. According to Francocci (1990:8), H-bridge configuration is preferred when the capacitor banks are very large and a higher sensitivity of protection is needed, as in the case of internally fused capacitor units. A higher sensitivity is achieved by using the bridge for measurement purposes, as any difference in capacitance between the parallel legs can be detected.



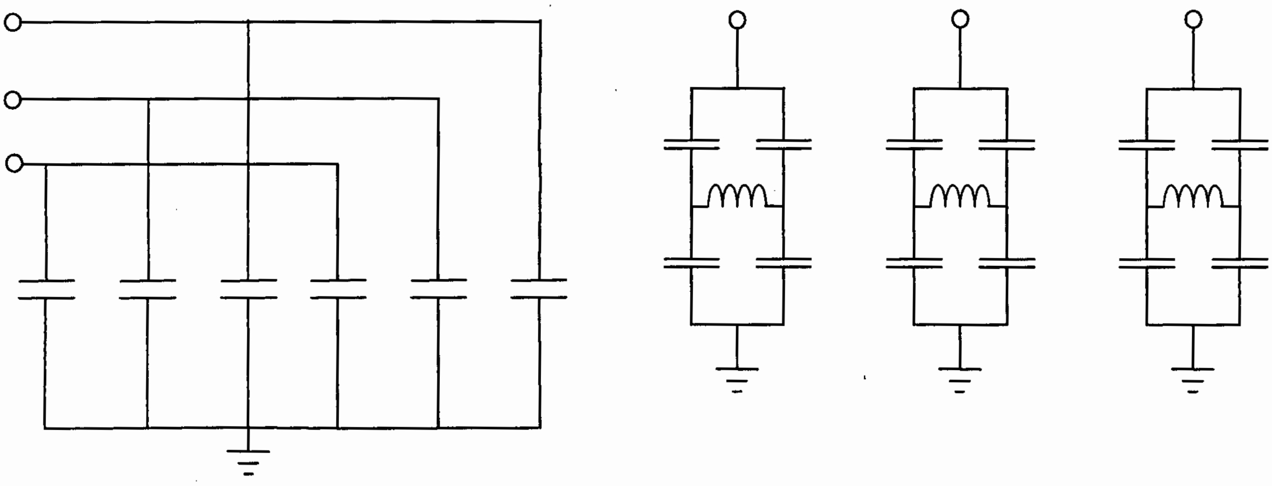
(a) Delta

(b) Unearthed single star



(c) Earthed single star

(d) Unearthed double star



(e) Earthed double star

(f) Earthed H-bridge

Figure 14. Different shunt bank configurations (Francocci, 1998:8)

In the past Eskom in South Africa used the configuration of two star sections of equal size (double-star) as a standard for all system voltage ratings. Moreover, two standard sizes of capacitor banks were decided upon to cope with the shunt compensation requirement of each system voltage. Since 1992, however, neutral-earthed capacitor banks in single-star, double-star and even in H-bridge configurations were commissioned for operation on 132 kV, 275 kV and 400 kV Eskom substation buses.

After intensive studies conducted by computer simulations and analysing and monitoring of transient phenomena in several Eskom networks, it was concluded by Eskom that shunt capacitor banks applied to effectively earthed systems of 132 kV and above perform better and are thus more reliable than unearthed systems (Francocci, 1998:8).

A practical example

The Eskom distribution stations of Muldersvlei, Acacia and Plattekloof, situated in the Western Cape, South Africa, all use the same type of fuseless shunt capacitor bank. Figure 15 shows the configuration of the bank. It has a double-star earthed arrangement (2 legs per phase) with 12 sections per leg. Each section consists of 2 capacitor units in parallel.

The output of this bank is 72 MVAR at a nominal system voltage of 132 kV, while the rated bank voltage is 145 kV (or about 84 kV per phase). At 50 Hz the capacitance per phase is 13.2 uF. The voltage across each capacitor unit at rated bank voltage is about 7 kV, with each unit being rated at 604 kVAR. In terms of bank protection a current transformer (CT) is used in each phase for unit-failure detection (see Chapter 3 for more details on the use of CTs), while reactors at 0.6 mH per phase prevent high frequency overcurrents from causing damage.

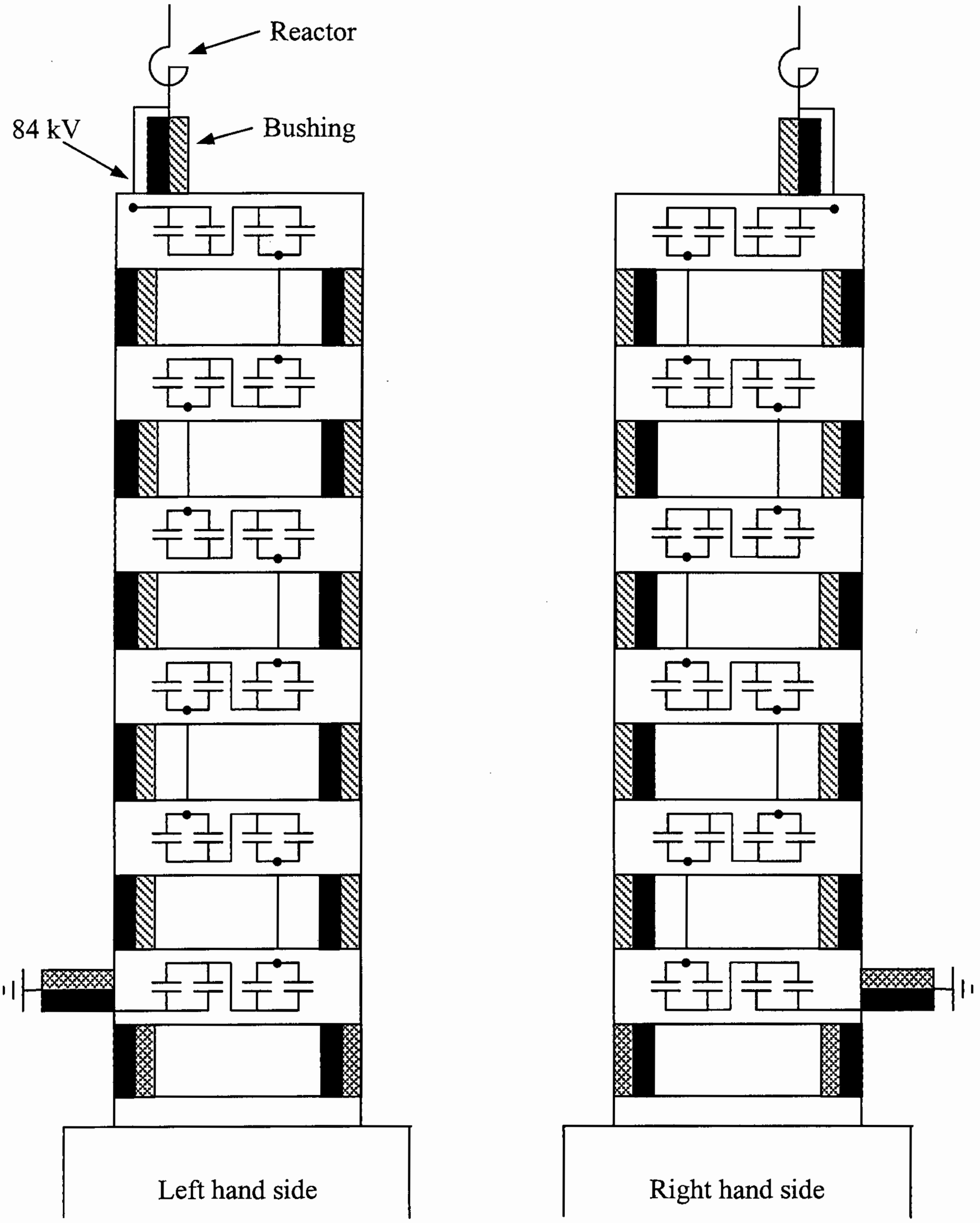


Figure 15. Eskom132 kV shunt capacitor bank

3. Existing Techniques in Shunt Capacitor Bank Protection

This chapter looks at various stresses that a capacitor bank may suffer and the respective protection methods used to ensure these stresses have as little as possible negative affects on a bank. Protection against capacitor unit stresses related to overcurrents and overvoltages is covered in detail, which includes the application of fused and fuseless capacitor units.

3.1 Introduction and Overview of the Protection Philosophy

Before a capacitor bank suffers damage after a failure of some elements or units, the bank should be removed from the system. Similarly, a capacitor unit that has failed should be removed from the circuit so that as few as possible negative effects are transferred to adjacent units. Achieving these objectives, and thus minimising damage to the bank, means having an effective and reliable protection method. This in turn requires an understanding of the limitations and capabilities of capacitors, including their associated switching devices (EPRI, 1998:9-1).

With regard to the limitations and capabilities of capacitor units in a shunt capacitor bank, there are some significant ratings as specified by the IEEE (1980: 8) that should be noted:

- Capacitors must be capable of continuous operation at up to 110% of rated rms voltage, including harmonics, and up to 180% of rated rms current, including fundamental and harmonic currents.
- Capacitors should give not less than 100% and not more than 115% rated reactive power at rated sinusoidal voltage and frequency, measured at a uniform case and internal temperature of 25 °C.
- Capacitors mounted in multiple rows and tiers should be designed for continuous operation for a normal annual temperature of 25 °C and for a 24 hour average temperature of 40°C.
- Capacitors should be able to operate continuously at up to 135% of rated reactive power caused by the combined effects of:
    - Voltage in excess of nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.
    - Harmonic voltages superimposed on the fundamental frequency.
    - Reactive power manufacturing tolerance of up to 115% of rated reactive power.

This chapter explains the attributes of different shunt capacitor bank designs. Depending on the capacitor unit arrangements, the type of capacitor unit fusing used and whether the bank is earthed or not, the protection methods can vary. All protection methods should reflect consideration of the influence of the following basic undesired conditions (IEEE, 1990:16):

- Overcurrents due to capacitor bank bus faults.
- System surge voltages.
- Overcurrents due to individual capacitor unit failure.
- Continuous capacitor unit overvoltages.
- Discharge current from parallel capacitor units.
- Inrush current due to switching.
- Arc-over within the capacitor rack.

Table 2 summarises the conditions that may arise, and the types of protection methods employed to detect and counter these conditions on standard shunt capacitors (IEEE, 1990:16). The more significant of these are examined in this chapter, along with other specific undesired conditions and the methods used to protect against them.

Condition	Type of Protection & Preventative Measures	Remarks
Capacitor bank bus faults	1. Breaker with overcurrent relays 2. Power fuses	Conventional methods apply
System surge voltages	Surge arresters	Grounded capacitor banks partially reduce surge voltages
Overcurrents due to individual capacitor unit failures	1. Individual unit fuses (expulsion or current limiting types) 2. Capacitor bank configuration and internal design (fuseless banks)	Co-ordination normally provided by capacitor manufacturer
Continuous capacitor unit overvoltages	1. Unbalance sensing with current or voltage relays 2. Periodic visual fuse inspection 3. Phase voltage relays	Various schemes have some limitations and suitability depends on bank arrangement and rating
Discharge current from parallel capacitor units	1. Current limiting fuses for each capacitor unit 2. Proper bank design	Co-ordination normally provided by capacitor manufacturer
Inrush current	Switched or fixed impedance in series with capacitor bank	May not be necessary with single bank
Rack Faults	1. Unbalance relaying	Prompt relay action necessary to limit fault damage

Table 2. Summary of shunt capacitor protection methods (IEEE, 1990:16)

3.2 Capacitor Unit Overcurrent and Overvoltage Protection

When capacitor units within a capacitor bank experience overcurrents or overvoltages, unbalance sensing and the arrangement and design of capacitor units are the most effective forms of protection for the bank. Whereas the arrangement and design of units will determine to what extent the stresses on one unit will affect surrounding units, unbalance sensing can trip the bank out when these stresses go beyond certain limits. Included in this section are explanations of these two protection methods, and the relationship between them.

3.2.1 Unbalance Protection

The diagrams of capacitor bank arrangements in this section are based on those found in Francocci (1992 and 1997) and IEEE (1990).

Shunt capacitor banks are generally configured using one or more series groups of parallel-connected capacitor units per phase. Figure 16 shows a capacitor bank using internally fused capacitor units, where a fused link is connected in series with each capacitor element. Each capacitor unit consists of a large number of elements connected in parallel, and with only a few series element sections. The opposite is found in externally fused capacitor units, as shown in Figure 17. Here, a large number of series element sections are used, while there are fewer elements connected in parallel (the reason for the difference in configuration is covered later in this chapter). Recent developments in capacitor technology have shown that in high-voltage (HV) capacitor banks fuses may be dispensed with altogether (Constable, 1992:28). Figure 18 shows a fuseless capacitor bank configuration.

As mentioned in Section 2.2, modern capacitor units have all-film dielectrics. The voltage stress levels that the dielectrics operate at are far higher than those experienced in other electrical equipment (Constable, 1992:28). This is in order to achieve acceptable electrical performance and thus it is not surprising that dielectric breakdown is the most common cause of failure.

When the film dielectric of an element inside a capacitor unit is punctured (due to stresses) the element 'fails', and a short circuit occurs. Today's polypropylene film dielectric tends to 'draw back' from the site of the initial puncture and allows good contact of the foil electrodes, whereas earlier paper dielectrics would promote arcing across the electrodes. With this short circuit the stored energy of any remaining elements in the same element group as well as a portion of the energy in other element groups and adjacent capacitor units will discharge through the shorted element. Even though using polypropylene film reduces the total energy liberated at the site of the puncture, it may still be sufficiently severe as to rupture the metal case of the capacitor unit. This is an extreme case of a unit failing, which often results in the impregnating fluid catching fire, and it indicates a type of scenario that should be avoided at all costs (Constable, 1992:29).

The most common scheme for detection of capacitor overvoltages due to failed capacitor units is unbalance relaying. At present, for a large capacitor bank the protective system used is generally sensitive enough to detect the loss of a single failed capacitor unit, without being affected by variable system voltage. In the case of a fuseless bank the loss of a single element should be detectable (this is elaborated on in Section 3.2.4). In Chapter 4 the accuracy of detecting the failure of a single element within a unit is investigated.

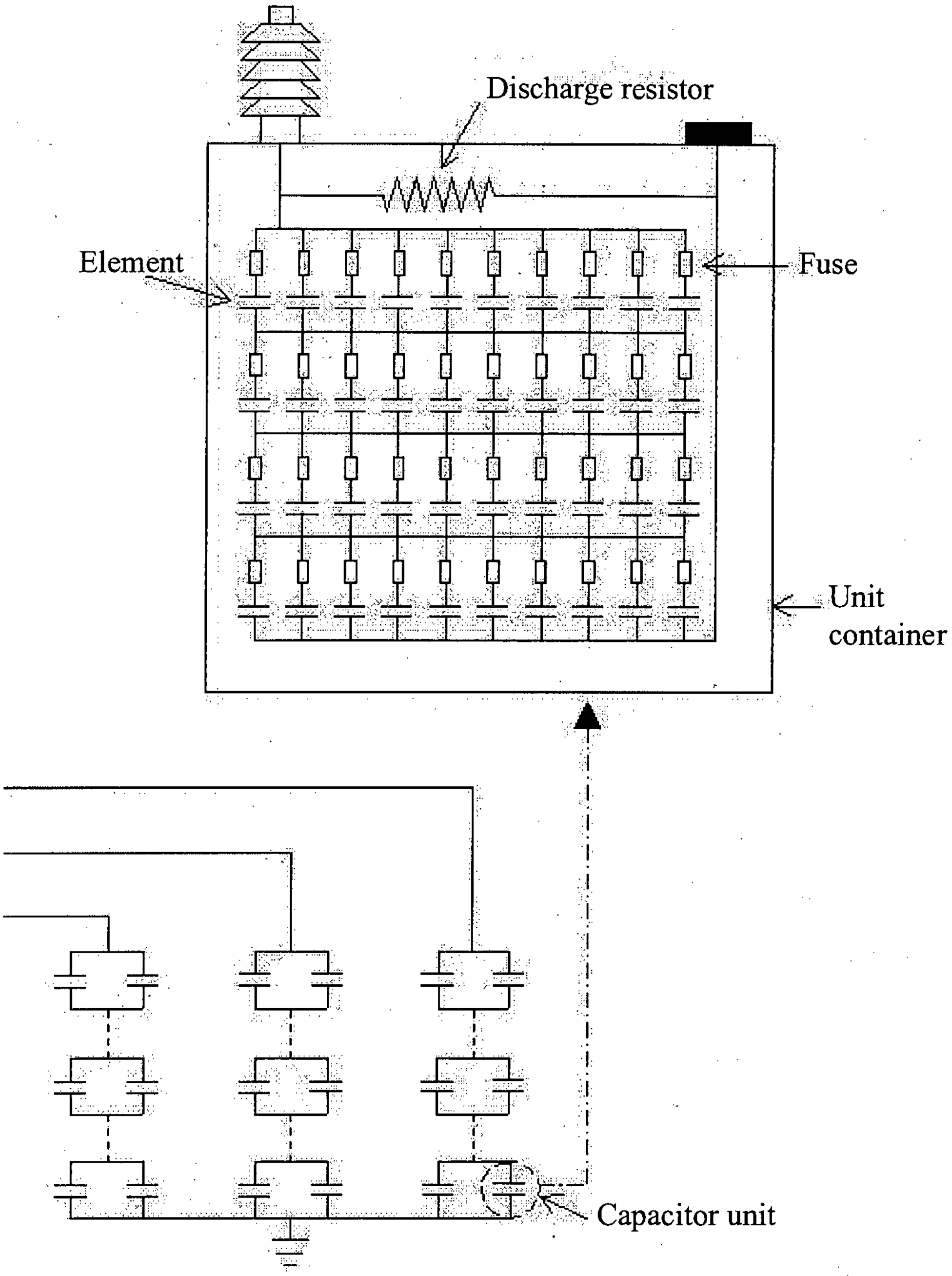


Figure 16. Y-Connected capacitor bank: internally fused capacitor units

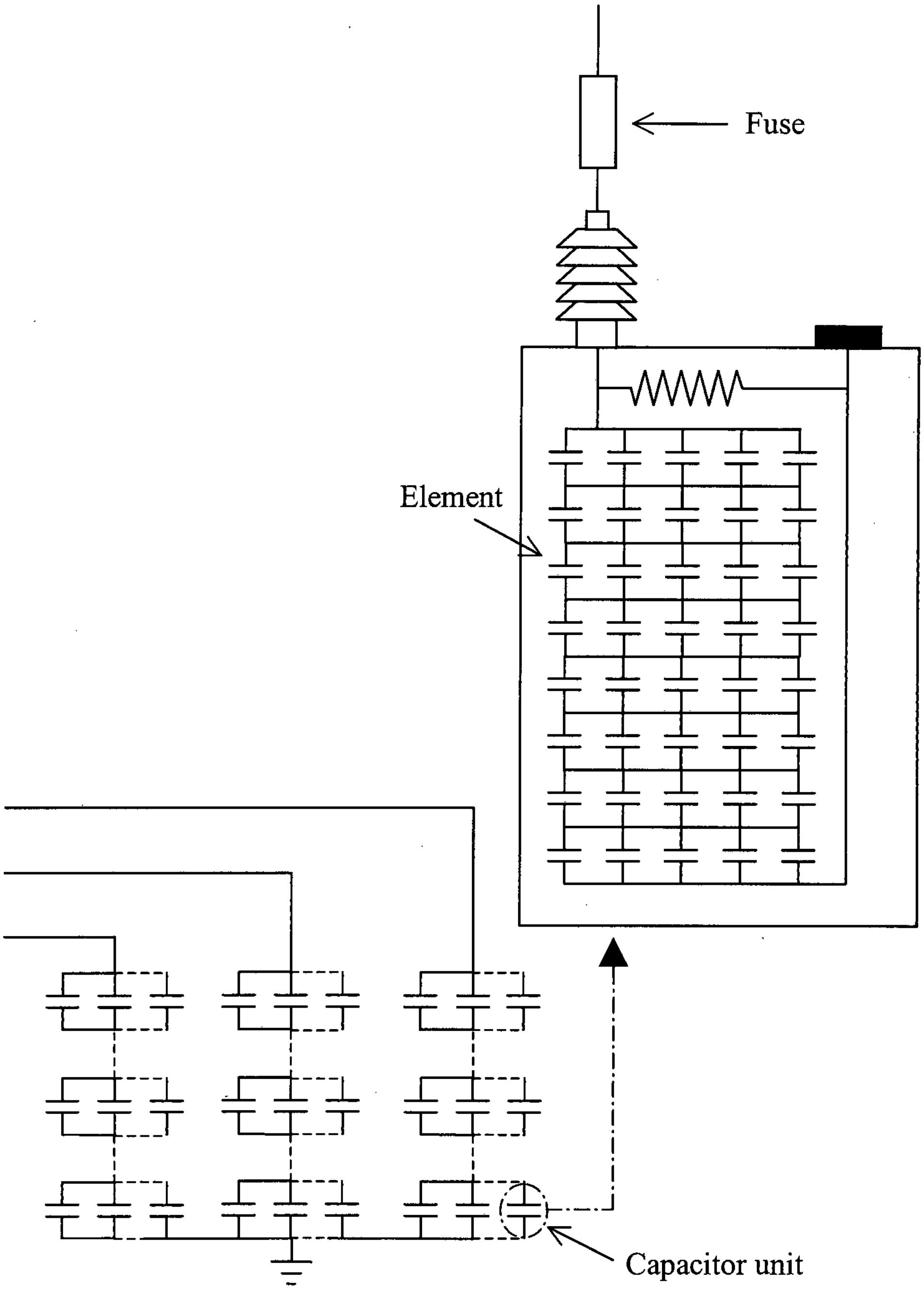


Figure 17. Y-connected shunt capacitor bank:externally fused units

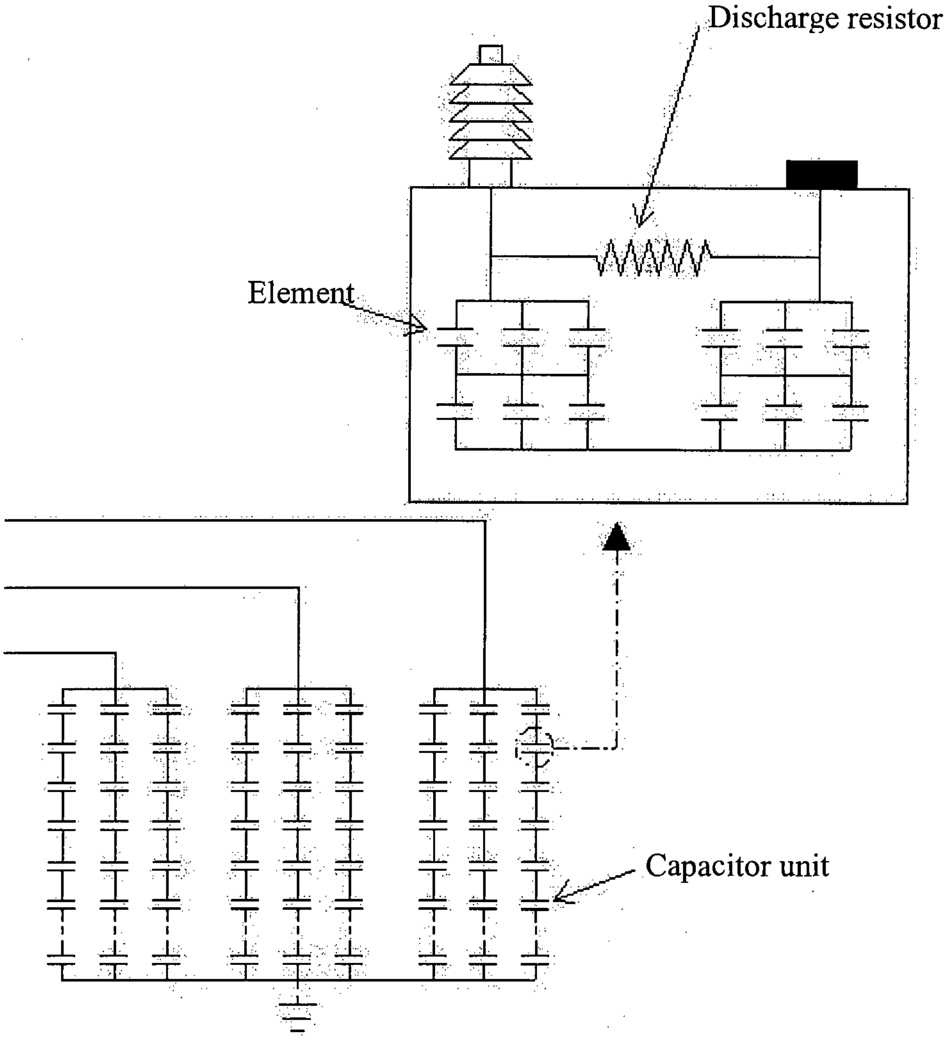


Figure 18. Y-connected capacitor bank: fuseless capacitor arrangement

The protection schemes that will be focused on here are those associated with HV grounded wye banks (expanded on in Section 3.3).

The voltage differential scheme shown in Figure 19 is the most commonly used and effective method of capacitor unbalance detection (IEEE, 1990:23). Here the capacitor bank tap voltage is compared to the bus voltage (typically already available) through a differential relay (device 60V) for each phase. Initially, the bus and tap voltages are scaled and adjusted so that assuming that all capacitor units are in working order and none are 'failed', the voltage difference signal is zero. Thus capacitor tolerance is compensated for by this initial calibration (EPRI, 1998:9-9). If the voltage difference signal varies by more than a certain limit, the relay will operate to alarm or it will take the bank out of service. The effect of system voltage unbalance does not matter in this case, as each phase has a differential relay.

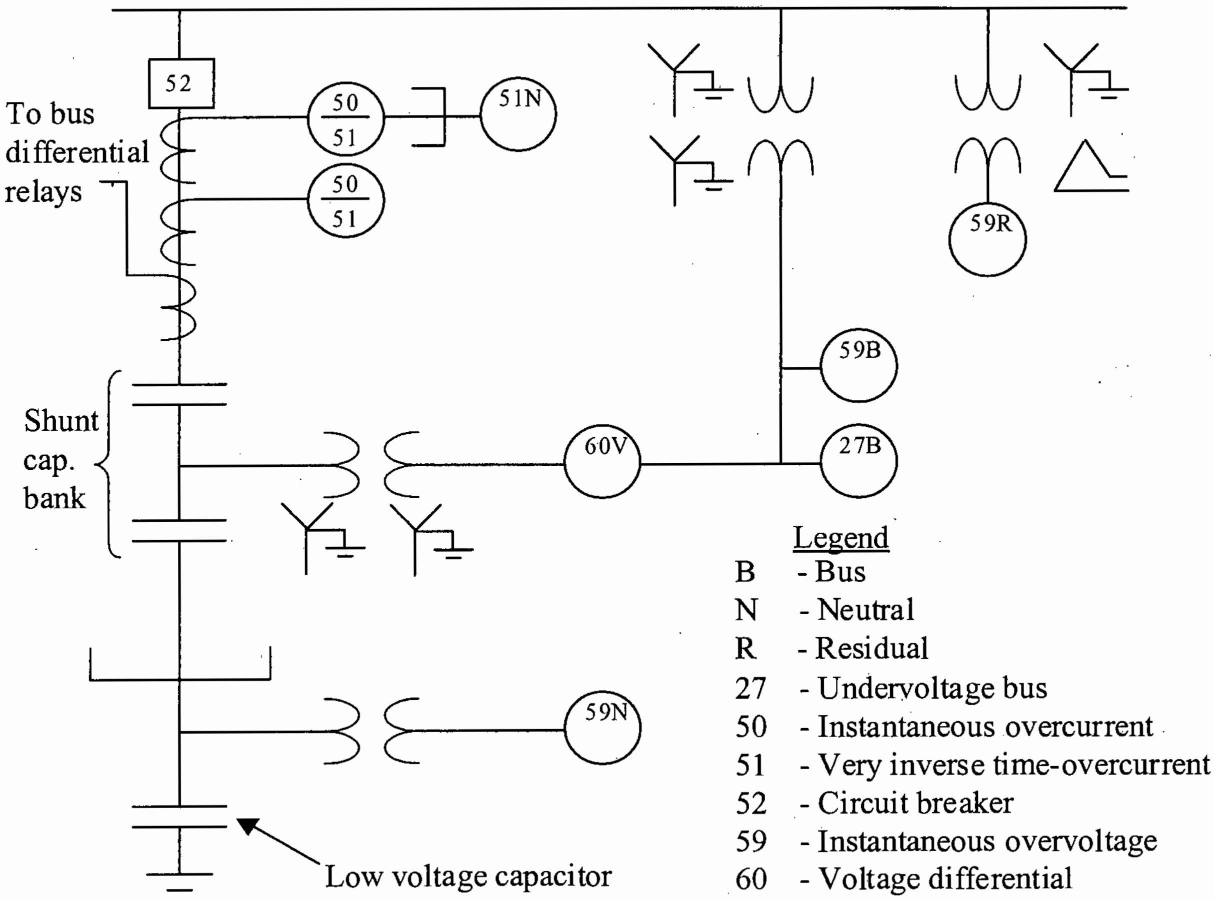


Figure 19. Protection scheme for large shunt capacitor banks (IEEE, 1990:23)

There are various unbalance detection schemes using voltage differentials in terms of where a tap voltage is connected. Tapping can occur anywhere between the mid-point all the way down to the low voltage end of the bank. Figure 20 shows three common unbalance protection schemes (EPRI, 1998:9-10). The mid-point tap method is shown in Figure 20a, while Figure 20c shows a scheme that compares bus voltage with a scaled voltage across the bottom group of the capacitor bank. Bonneville Power Administration (BPA) in the U.S.A has used this second scheme for many years.

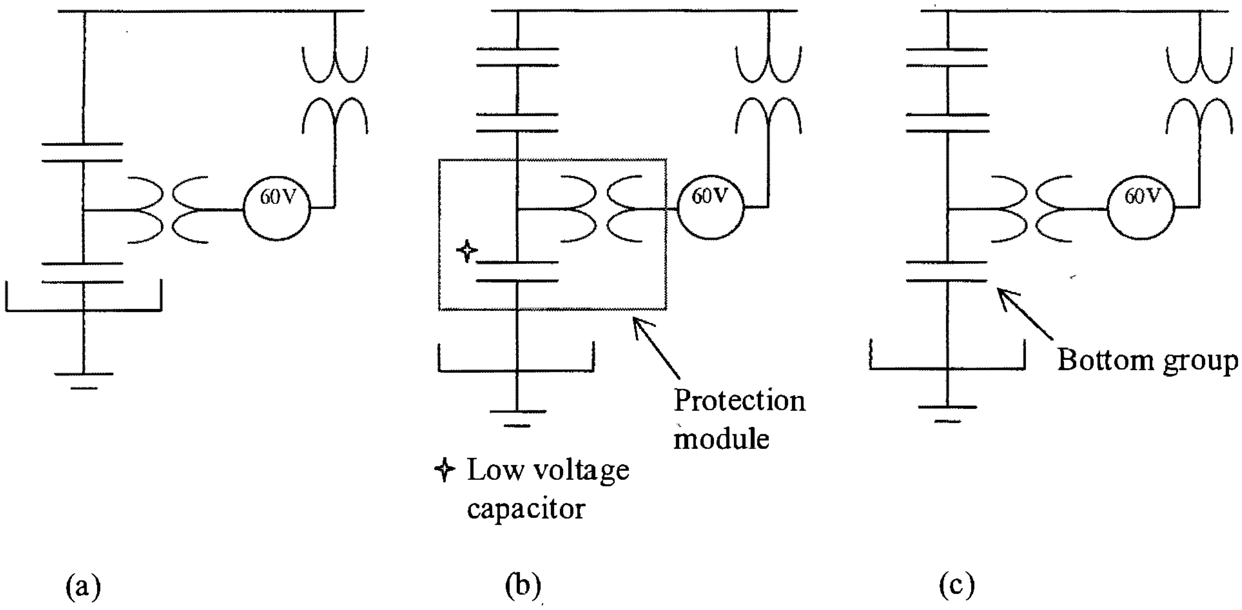


Figure 20. Common unbalance schemes for capacitor banks (EPRI, 1998:9-10):

(a) Mid-point tap
(b) Protection module
(c) BPA scheme

Another scheme that is utilised by Eskom is to use a separate protection module that is connected between the neutral and the low end of the bank, as shown in Figure 20b. This protection module makes use of a low-voltage capacitor unit that is connected to an isolating potential transformer. The voltage across the low voltage capacitor, which develops as a result of normal phase current in the bank, is compared to the bus voltage. If a capacitor fails, causing the phase current to increase, a differential voltage will result when compared to the bus voltage. In the case of fuseless banks this scheme is more attractive than it is to fused banks, as fuseless banks do not have a point for a Common Connection Voltage Transformer (CCVT) to mid-point connection.

There are typically two alarm levels for this type of unbalance protection. The first alarm level is selected to respond to the failure of a single capacitor unit (or capacitor section in the case of fuseless banks). The second alarm, accompanied by a time-delayed trip after several hours will warn the system operator of an impending trip and lockout, allowing an orderly de-energisation of the bank (EPRI, 1998).

3.2.2 Internal Fusing

For fused banks (either internally or externally fused), the first line of protection for a capacitor bank is the individual capacitor fuse (EPRI, 1998:9-5). For internally fused banks, each capacitor unit has each of its capacitor elements fused (as shown in Figure 16). The fuse is used to prevent a situation where the failure of a single element can lead to a unit's case rupture and damage (by way of the discharge of 'parallel energy' from parallel elements in the same section). A proper fuse operation is desirable in order to minimise the chance of cascading failure of additional capacitor elements and units that may, in turn, lead to a major bus fault (IEEE, 1990:16).

When a capacitor element fails, other elements in the same group will contain some amount of charge. This charge will then drain off as high-frequency current that flows through the faulted element and its fuse. This high-frequency transient current or discharge energy is limited by the individual element fuse, which operates to isolate the faulty element. The capacitor unit will continue to operate after the fault is cleared, although with different voltage and current distribution over the remaining healthy elements.

If the discharge current is too low, the resulting increased steady state current through the shorted element will be far too low to ensure fuse operation. Thus, bank configuration plays an important role in determining whether an individual capacitor fuse will operate correctly. A minimum number of parallel elements per series group are needed in order to obtain rapid fuse operation i.e. the discharge current must be large enough to isolate the faulty capacitor element as soon as possible.

When faulty elements in a section are disconnected, the remainder of the healthy elements of the group can withstand an increasing overvoltage up to a certain limit (10% of the element rated voltage). The current through these elements will also increase, and there is a general change in the voltage and current distribution of the elements and units of the affected phase. The unbalance protection should intervene to warn of the occurrence of unbalance before the voltage limit is exceeded and to trip the bank when that limit is reached.

One of the major problems with internally fused capacitors is that in large HV banks there is inadequate sensitivity for the unbalance protection (Constable, 1992:30). Francocci (1992:8) states that experience with Eskom's HV large internally fused capacitor banks has shown that imbalances due to several element failures in a unit section will remain undetected by unbalance protection. Conditions of undetected element failures can lead fairly quickly to cascading failures within the affected unit, which will result in the case rupturing. This is likely to be accompanied by severe damage to surrounding units and capacitor bank equipment.

Due to the lack of co-ordination between the unbalance protection and fuse operations on HV capacitor banks, the use of internally fused capacitor units is thus preferred in banks of medium voltage (MV), in the region 44–66 kV, and HV banks of small output (Francocci, 1992:8).

3.2.3 External Fusing

Francocci (1992:6,7) was examined at large for this section, and so the main points of his work are included.

For externally fused capacitors each unit is connected in series with a fusible link (shown in Figure 17). As with internally fused capacitors, bank configuration and size plays an important role in ensuring that fuses are cleared properly. Fuses must be rated to operate as a result of the available current from the system and of high frequency currents discharging into faulty units from the remainder of the parallel capacitor units. Fuses must also be capable of operating without exploding on fault currents, and their link characteristics must co-ordinate with case rupture curves to prevent surplus energy from entering faulty capacitor units (Francocci, 1992:6).

These requirements are met by connecting a defined number of units, according to a minimum limit, in parallel. This will allow for rapid fault clearing. Below this minimum, when elements fail in the unit, the fault current will not be large enough to cause fast fuse clearing.

A faulty unit is isolated from the rest of the bank by the unit fuse operation, usually after several elements within the unit have failed and short-circuited. Thus with a unit isolated the remainder of the units in the affected section will then experience severe overvoltage conditions. Other units will eventually fail due to the voltage stress until unbalance protection isolates the entire bank from the system (Francocci, 1992:4). After a fuse operation the resulting overvoltage (per unit of unit normal voltage) across the remaining externally fused units of the affected group is given as (Francocci, 1992):

$$\mathrm{Vpu} = \frac{3\mathrm{PS}}{3\mathrm{S}(\mathrm{P}-\mathrm{F})+2\mathrm{F}} \tag{3.1}$$

where P = number of units per section/group
S = number of sections/groups
F = number of units removed by fuse operation.

From the graphs in Figure 21 it can be seen how, after a fuse operation, the voltage increases substantially across the few remaining units of the series group and as the number of series groups increases it will increase even more. The unbalance protection must be set to give an alarm when a few elements fail within the faulty unit and to trip the bank as soon as it operates. This will ensure that intolerable voltage stress on the few remaining units of the affected groups and further unit failures in rapid succession are avoided. However, this is very difficult to achieve, since the failure process within the faulty unit is unpredictable and the unbalance protection scheme has a limited selectivity capacity. It is more likely that the unbalance protection will operate too early or too late, and will thus have a negative effect on the bank performance.

One way of overcoming this problem on MV banks and smaller HV banks (power-wise) is to use many smaller externally fused units in each series section. Due to the high costs involved, however, for these applications it is preferable to use internal fusing on MV banks and fuseless capacitors on HV banks (see Section 3.2.4).

On the other hand, there is also a maximum limit as to the number of capacitor units that can be installed in parallel in a group. This limitation depends on the maximum energy, which, when stored in the healthy units of the affected group, can discharge into the faulty unit without causing unit case rupture and explosion of the fuse assembly. The IEEE (1991:9) recommends that the total energy stored in parallel-connected group of capacitors not exceed 15kJ (for all-film capacitor units) at maximum peak voltage.

The damage caused by high frequency currents (induced by energy discharge) can be prevented by using current-limiting fuses instead of expulsion type fuses. The high cost of these fuses, however, has led to capacitor banks of large output being split into two star (wye) sections, called a double star configuration. This practice allows for the phase section kVAR capacity to be limited, and it also allows for unbalance to be detected more easily as a result of the bank symmetry. There are cases where current limiting fuses have been used in extremely large double star capacitor banks, although not in South Africa by Eskom.

From the above considerations, it is clear that the size and the type of fuse used depends largely on the selection of bank configuration and size, besides other important factors such as switching transients and the maximum permissible energy discharging into a faulty unit.

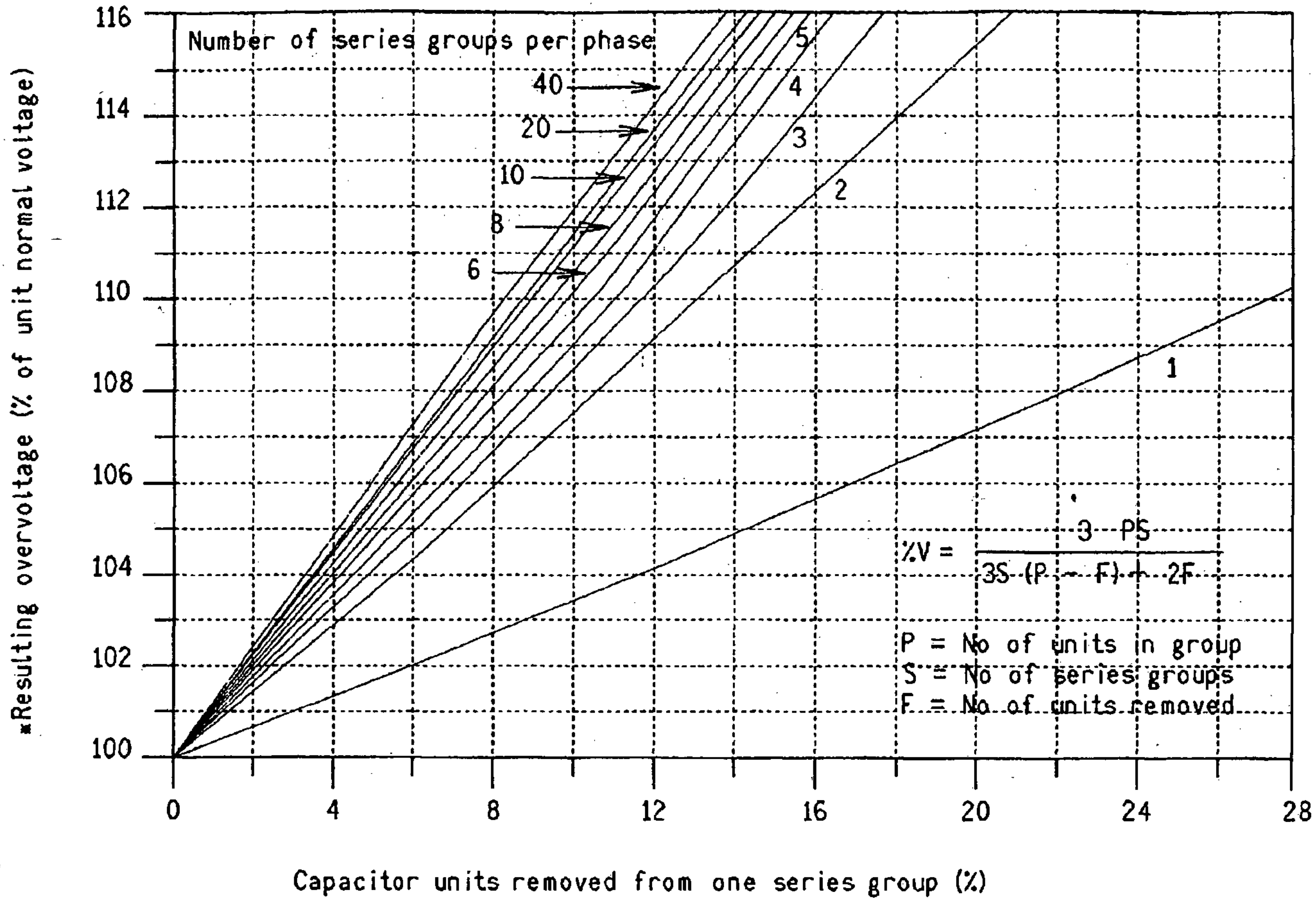


Figure 21. Resulting overvoltage across the remaining externally fused units of an affected series section (Francocci, 1992:6)

Two important advantages of using externally mounted fuses are that they are very effective in protecting the bank against internal faults (such as phase to rack faults), and the identification of faulty units in large capacitor banks is simplified.

Finally, when considering small capacitor banks, using externally mounted fuses can have serious disadvantages. If an element fails and its unit fuse blows, the voltage across the remaining units in the group can increase to a value that cannot be tolerated for long and thus the bank must be tripped. The failure of one element could therefore mean the loss of an entire capacitor bank.

3.2.4 Fuseless Capacitors

A fuseless capacitor unit is generally made up of a few element sections in series, where each section is made up of a number of elements in parallel.

For fuseless banks, protection from unit overcurrents is provided through the capacitor arrangement and internal design of the individual capacitor units. A robust capacitor design and reducing parallel discharge energy can eliminate the chances of case rupture (Constable, 1992:31). Parallel discharge energy can be significantly reduced by getting rid of the 'cross bonding' between parallel units in each series group (found in fused capacitor arrangements). Because there are no units in parallel, discharge energy from adjacent units does not exist. Each phase would then consist of a number of independent 'strings' of capacitor units in series, as shown in Figure 18.

Since modern all-film capacitors produce a solid short circuit when they fail (that will carry a considerable load current without arcing or gassing) and considering as well there is no discharge energy from adjacent units, means that the use of fuses is no longer required. In addition, the large number of sections in series provides enough impedance so that the shorting of one section does not cause significant increase of the current in the faulty string, and therefore does not impose significant stresses on the other units in the same string (EPRI, 1998:9-7).

In typical designs, a capacitor bank can continue normal service with several sections shorted. The resulting overvoltage (pu of unit normal voltage) on each remaining string unit, after a complete unit failure, is given as (Francocci, 1992).

$$\mathrm{Vpu} = \frac{3\mathrm{SN}}{3\mathrm{SN} - \mathrm{n}(3\mathrm{S} - 1)} \qquad (3.2)$$

where S = number of parallel strings of units per phase

N = total number of units in series in each string

n = number of complete capacitor units short-circuited in one string.

Note that fuseless capacitor applications are more appealing at higher voltages (66kV upward). At these voltages, the failure of a few unit sections is unlikely to cause complete unit failure as the overvoltages resulting from the failure are uniformly distributed across the remaining sections of the affected string. At lower voltages, there would be fewer sections per string, thus causing higher overvoltages across the remaining sections. This is true only if the capacitor units used are of the same rating as those used in HV applications)

As the voltage rating of the capacitor bank decreases the permissible overvoltage limit would be reached for a lesser number of section failures. The use of fuseless capacitor units for capacitor banks of voltage ratings less than 44kV is not advisable, as a few section failures in a string lead to overstressing of the remaining sections, which may in turn fail in cascading fashion, causing a line-to-neutral fault (Francocci, 1992:9).

Consider a bank with 3 strings per phase, as in Figure 18, each string being made up of 12 series-connected units. If each unit consists of 4 element sections in series, then the string will consist of 48 sections in series. Using (3.2), only after five sections have been short-circuited (due to element failures) will the resulting overvoltage on each remaining string unit be above the limit of 10%:

$$\text{Vpu} = \frac{3 \times 3 \times 12}{3 \times 3 \times 12 - 1.25(3 \times 3 - 1)} = 1.1$$

From these considerations, some advantages of fuseless capacitor applications are noticeable:

- A small quantity of capacitor section failures does not create intolerable stresses on the remaining sections of the affected strings.
- Sensitivity of unbalance protection is not a problem, especially at high voltages, as the overvoltage limit is reached at considerably larger unbalance.
- Unbalance protection relay alarm and tripping settings can be made extremely accurate, as co-ordination with the fuse operation is not required.
- The time delay for the alarms of the unbalance relay can be set much longer (as it is used to indicate long term unbalances in the bank), so that the bank reliability is enhanced.
- Voltage stresses on the fuseless capacitor are not localised as in the case of fused capacitors, and impact less on the efficiency of the capacitor dielectric system. As a result of this, fuseless capacitor units should last longer.
- The parallel string configuration reduces the stress due to the high-energy currents, which, in fused capacitor banks, discharge into the faulty units/elements from units/elements in the same series group, and adjacent units/elements.

Fuseless capacitor technology is also an attractive proposition because of the lower costs involved when compared to fused capacitor applications. These lower costs result from the following factors (Francocci,1992:12):

- There is no need for fuses, fuse busbars, fuse insulation and associated equipment.
- The capacitor bank is smaller in size due to smaller units being used and the simplicity of connections. Thus less substation space needs to be allocated to the capacitor bank
- Field maintenance is speeded up, since the fuse assembly and lead disconnections for capacitance checking are minimised. Fewer capacitance measurements are needed to find defective capacitor units.

Taking into account what has been covered in the last three sections on capacitor fusing, and due to the fact that this thesis concentrates on the protection of HV shunt capacitor banks, all investigations undertaken for this project are based on banks with fuseless capacitor units.

3.3 Neutral Earthing of Shunt Capacitor Banks and Surge Voltage Problems

3.3.1 Local and International Earthing Standards

According to Francocci (1998:8), on overseas transmission, sub-transmission and distribution primary substation buses, shunt capacitor banks are normally built in a single or double star configuration with the neutral earthed. When applying earthed capacitor banks it is important that the system is effectively earthed. If a system is not effectively earthed the use of neutral-earthed capacitor banks is not recommended for two main reasons.

Firstly, harmonics that are flowing back to their sources through the capacitors, the substation earth mat and ground, may cause communication interference and disturbance to the protection relays on unearthed circuits.

The second reason is that a fault to earth of a supplying phase feeder may cause severe overvoltages across the capacitors in the other two phases. This excessive voltage stress may cause the capacitors of the affected phases to rupture or even explode.

In South Africa, for banks operating at 88 kV or less, most small capacitor banks have single-star configurations while larger sized banks have double-star configurations. In both configurations the neutral is left unearthed, which is a correct practice since the systems at 88 kV or less are not effectively earthed. In the past Eskom used a standard double-star configuration with unearthed neutrals for all system voltage ratings. Moreover, two standard sizes of capacitor banks were decided upon to cope with the shunt compensation requirements of each system voltage (Francocci, 1998).

Since 1992, however, neutral-earthed capacitor banks in single-star, double-star and even in H-bridge configurations have been commissioned for operation on 132 kV, 275 kV and 400 kV Eskom substation buses. Using computer simulations and by monitoring and analysing transient phenomena in several Eskom networks, it was shown that shunt capacitor banks applied to effectively earthed systems of 132 kV and above perform better, and are thus more reliable if the bank neutrals are earthed. Backing these results are the recommendations in IEEE standards (1979, 1987) that, at voltage levels of 121 kV and above, the capacitor bank and the system should be grounded.

3.3.2 Surge Voltage Protection

The main sources of surge (or transient) voltages on capacitor banks are the switching in and out of banks and lightning strikes. Most of these surge voltages may be curtailed with standard overvoltage protection such as surge arresters (IEEE, 1990:22). However, the placement and voltage rating of these arresters is crucial, as many important and specific details of the system have to be considered. Also, in the case of a grounded bank, the bank itself provides a low impedance path to ground for lightning surge currents and gives some protection from surge voltages. In cases where the banks are large, they are operated without surge arresters (EPRI, 1998:9-4). Other ways of reducing the effect of surge voltages is to include synchronised capacitor breaker switching, "tuning reactors" in series with medium voltage capacitor banks and damped RL circuits in series with capacitor banks.

The overvoltage on a bank depends on the length of line between the shunt capacitor bank and the point at which the transient voltage is generated, as well as on the surge duration (IEEE, 1990:22). Table 3 shows the recommended overvoltages allowed for different overvoltage periods as specified by the IEEE (1990:22). Note that the short time power frequency overvoltage values here are for subzero temperatures. Higher limits may be permissible where less severe conditions apply.

Duration	Multiplying Factor Times Rated rms Voltage
5 ms	3.0
10 ms	2.7
60 ms	2.2
150 ms	2.0
1 s	1.7
15 s	1.4
1 min	1.3
30 min	1.25

Table 3. Limits of short time power frequency overvoltage at subzero temperatures (IEEE, 1991: 22)

With regard to switching, when two capacitor phases which are opposite in polarity are closed simultaneously transient over-voltages, approaching twice the system peak voltage, occur at the switched bus (Francocci, 1998:9). As a result of high peak voltages on closing, phase-to-phase surges may be generated on other equipment, such as transformers connected at remote locations. Reflections can produce transients approaching 3 pu, and if multiple prestrikes occur during the energisation of the bank, significantly higher overvoltages can result (IEEE, 1996:1802). The probability of these phenomena occurring is high in unearthed capacitor banks.

Problems associated with capacitor de-energisation arise only from abnormal switching and these problems are more serious if the capacitor bank is unearthed. The normal opening sequence of unearthed capacitor phases leads to (Francocci, 1998:9):

- Different trapped charges on the capacitor bank phases.
- Maximum trapped charge on the first phase to open (1 pu of the system voltage peak).
- Bank neutral capacitance to earth charged at 0.5 pu of the system voltage peak.

Francocci continues to state that, as a result of this, a maximum voltage of 2.5 pu will appear across the breaker pole that opens first, when the source voltage reaches its maximum value. If, after the first phase opens, one or both of the other phases are delayed on opening, the recovery voltage across the first phase opened reaches higher values, depending on the delay duration. The neutral voltage of the capacitor bank will rise dramatically, and consequently, the other two breaker poles will be subjected to extremely high recovery voltages. These two poles are likely to restrike as well, resulting in other voltage swings of the bank neutral, and again a new favourable condition for restriking.

This process will eventually lead to the destruction of the breaker and to a very damaging flashover within the capacitor bank (i.e. flashover of the neutral to earth is a great possibility). It is important to emphasise that with a single restrike of the first phase to open, the bank neutral voltage swings to such a voltage level that the neutral flashover to earth becomes unavoidable.

In earthed capacitor banks the three bank phases can be considered as three independent single-phase circuits. Thus a maximum voltage charge of 1 pu is theoretically trapped in each bank phase and the voltage across the breaker pole reaches a peak of 2 pu one half-cycle after opening. It is clear that the recovery voltage across the breaker poles is reduced due to the elimination of accumulation of charges in the neutral because of earthing, and thus restrikes and associated phenomena are less likely to occur (Francocci, 1998:10).

From the information described in this section, there are two main reasons why the neutral-earthing of capacitor banks on effectively earthed systems is preferred:

- Negligible voltage fluctuations on the neutral during bank switching lower the probability of breaker restrikes on opening.
- Transient overvoltages at remote capacitor banks and remote transformer terminals are reduced.

3.4 Bank Overcurrent Protection

Protecting against a major fault, such as a line-to-line fault or a line-to-ground fault, will generally require some form of external protection for the capacitor bank. This includes power fuses (discussed in Section 3.2), circuit breakers, or circuit switchers with associated relay circuits (IEEE, 1990:17).

The protection scheme shown in Figure 19 is one of the more common schemes for large shunt capacitor banks, although there are in fact many other schemes that are used (EPRI, 1998:9-3). Also, for this scheme the bank is earthed, which means the backup protection need only respond to high-magnitude faults (since smaller faults will pass through the bank relatively harmless to ground). Here the protection of major faults such as line-to-ground faults is achieved by using a circuit breaker and overcurrent relay. Two sets of instantaneous devices (50/51) are attached to very-inverse non-directional time-overcurrent relays. These provide primary and backup protection for the capacitor bank for phase faults as well as ground faults. Schemes may also employ a non-directional time-overcurrent relay (51N) in the neutral connection with an inverse time-current characteristic. This relay is usually supervised with an overvoltage relay, 59R, to prevent misoperation of the 51N during line-to-ground faults that are external to the shunt capacitor bank. For faults involving high values of ground current, device 59R prevents the bank from tripping through the placement of a normally closed trip contact in series with the 51N contact.

Time-overcurrent relays can generally be applied with normal settings without encountering false operations due to inrush currents. Instantaneous relays, however, should be set high to override these transients, or have tuned circuits so that pickup increases with frequency.

3.5 Bus Overvoltages and Undervoltages

In Figure 19 device 59B monitors the bus voltage to de-energise the bank for extreme overvoltages (EPRI, 1998:9-4). Time delays are usually added to the operation so that transient overvoltages are prevented from causing a nuisance tripping of the bank.

In the event of a loss of bus voltage, device 27B, an undervoltage relay, is connected to the bus to trip the bank. A time delay is also added to this relay to prevent the de-energisation of the bank under transient undervoltage conditions.

3.6 Harmonics

Harmonics can result from disturbances such as voltage dips, or the switching out of a transformer in parallel with shunt capacitor banks on a busbar carrying a load. The transient and persistent harmonic laden currents are large enough to cause capacitor can fuses to blow and the capacitor banks to trip (Rogers, 1997:11). The large harmonic laden magnetising currents are probably damaging the transformers and shortening their useful life. This applies to the harmonic current in the capacitors as well. These currents exist long after the transient has gone and thus quality of supply is affected.

These problems can be partially solved by:

- Using point on wave switching to switch the capacitor bank in at a voltage maximum.
- Selecting a capacitor bank size that does not give rise to an unstable harmonic response.
- Carrying out point on wave opening of the capacitors and the transformers so that they are opened when they are storing the minimum energy (Rogers, 1997:11).

4. An Investigation into Signature Detection of an Unhealthy Fuseless Capacitor Unit

The objectives of the investigations covered in this chapter were:

- To find various signatures of an unhealthy capacitor unit.
- To identify these signatures accurately for use in protection systems.

Since the failure of an element within a capacitor unit is one of the earliest signs of an unhealthy capacitor unit, much of this chapter concentrates on the detection of element failures. As it was shown in Chapter 3 that fuseless shunt capacitor banks are preferred for HV applications, investigations were restricted to fuseless capacitor units.

4.1 Economic Implications of Protection Philosophies

The cost of an improved protection method plays an important role in determining whether that particular method is worth implementing. What is required is a method that works reliably, and whose cost is commensurate with the potential savings it offers.

Depending on the type of protection used, different considerations will have to be made with respect to cost and reliability. For example, if a monitoring device is inserted inside a capacitor unit (as is discussed in Section 4.3) the reliability of the device is of the highest importance. If the device fails to operate effectively inside the unit there is no way of replacing or repairing it, as the capacitor unit is sealed. This means that either the capacitor unit has to be replaced, at a cost of about R8000, or no monitoring of the unit can take place. On the other hand, an upper limit might have to be put on the cost of the protection to make it economically viable for widespread use.

If the protection method used has no direct effect on the capacitor unit then the method does not have to be as reliable as the above example (consider a VT attached across the outside terminals of a capacitor unit and not inside the unit). That is not to suggest that it will be expected that the protection will fail to operate at times. Having a monitoring device inside a capacitor unit implies that the device must have the same life expectancy as the unit, while an external device can be replaced at lower cost if the need arises.

Another important aspect to consider is how important it is to Eskom or any other power utility to improve on existing protection schemes in use. Will spending more money on better protection make up for the losses suffered due to inefficient protection methods, and what exactly are these losses in economic terms?

The first and most obvious loss is actual capacitor units. Consider, for example, a capacitor bank where some of the units are in an unhealthy state. This 'unhealthy state' refers to the units that are under severe stress due to continuous or transient overvoltages/currents, which can be caused by any of the conditions described in Chapter 3. Also, it could be a capacitor unit that is faulty, and is thus under similar stress. If the capacitor bank protection does not detect this, capacitor units will start failing. At this stage, with only a few failed units, the bank is not in danger, as the stresses on the healthy units have not reached critical levels yet. As units continue to fail and the resulting stresses become critical, the protection will come into action and switch the bank out. The failed units will now have to be replaced, at R8000 each.

Some interesting questions arise as to what form of action a new protection method should take. Consider that the protection system can detect an unhealthy unit that will fail soon. Should the whole capacitor bank be switched out? As discussed in Chapter 3, a fuseless configuration allows a bank with failed units to operate without any extreme negative effects. On a bank with twelve units per string, the whole bank can still operate if there is a failed unit in each string (assuming all the element sections in each unit have shorted out).

Switching out a whole bank before even a single element inside a unit fails is an extreme example but one that is pertinent to this discussion. It will save a utility from replacing not one but maybe more units, as a single failed unit might cause others to follow suit in the same string. However, by switching a capacitor bank out so soon, what losses will the utility suffer by not having that capacitor bank in operation? If the protection switches out the bank when it is needed most (at peak loads) to supply reactive power, this could cost the utility more than if it left the bank switched in and allowed some units to fail.

If a different protection method is used that detects when an element has failed inside a capacitor unit, the scenario changes somewhat. This is a more conservative (and realistic) method than the one described above, as it will be used to monitor the number of elements that have failed, so that the bank can be switched out before resulting stresses on healthy units become critical. So it is accepted that the capacitor units will need to be replaced at some time when the bank is not in use. Keeping the bank switched in as long as possible might have saved the utility from using other resources to keep the system stable.

This line of thinking is similar to capacitor protection methods currently used, except with the above method the location of a faulty unit is known. When the bank is not in operation, these faulty units can be replaced efficiently. Using prevailing protection methods, however, the location is not known, so capacitance readings have to be taken. This operation will increase the maintenance time, and thus maintenance costs will also increase. As can be seen from the above discussion, the final protection method chosen by a utility will depend on the specific needs and economic constraints as determined by the utility in question.

4.2 An Element Failure on a Single-Phase 200 V Shunt Capacitor Bank in the Laboratory

4.2.1 Design of the Capacitor Bank Model

In order to research new techniques of protecting a capacitor bank, the failure mechanism of a capacitor unit has to be fully understood. For this purpose, I constructed a model of one phase of a capacitor bank (using film-type capacitors) in the laboratory. The reason for one phase being used was that the tests done on the model were concerned only with the effect of an element failure on unit voltage and current, and normally the three phases would not interact with each other in this type of application.

Figure 22 shows a simplified circuit diagram: the capacitor bank was configured to operate at a voltage of 200 V, with a total capacitance of 15 uF. A variac was used to gradually increase or decrease the voltage supply across the bank, although in practice each phase of a capacitor bank is switched in or out directly, albeit in steps. The main reason for using a variac was that the tests focussed on the bank when it was in operation and not during switchings. Also, the chances of switching transients were eliminated. This is not the case in practice, where switching transients can cause extensive damage to capacitor banks. No preventative action was taken against the possible discharging of the capacitor bank, as the currents involved in this circuit were small (less than 2 A).

Based on a typical 132 kV shunt capacitor application, the model was configured in a fuseless capacitor unit style, which is the most common for capacitor banks of 66 kV and higher (see Section 3.2.4). The model bank consisted of six parallel strings with ten 25 uF capacitor units per string (see Figure 22b). Each unit comprised a 6 by 6 array of interconnected capacitor elements (25 uF each). That is, 6 element sections were connected in series and each element section consisted of 6 elements in parallel (see Figure 18 for an example of a similar fuseless unit, consisting of 4 element sections with 3 parallel elements per section).

If each element in the capacitor bank were to be represented in the model by a single 25 uF capacitor, a total of 2160 25 uF capacitors would be needed. Thus, to make construction of the model simpler, as many units as possible were grouped together such that a unit or string could be represented by a single capacitor. Figure 22c shows how this was achieved: the blue capacitors are 2.5 uF and each one represents a string, since 10 capacitor units of 25 uF in series is equivalent to a single 2.5 uF capacitor. In the first string there are 9 red capacitors of 25 uF where each one represents a single capacitor unit. The tenth unit of this string is represented by the remaining two sections in the diagram. The first section, consisting of a red 25 uF capacitor and a green 5 uF capacitor in parallel (with a total capacitance of 30 uF), represents 5 element sections of the unit, since 5 groups of six parallel elements each connected in series is equivalent to 30 uF.

The final section in the diagram represents the sixth group or element section of the unit, that is, six red 25 uF elements in parallel. This configuration uses only 22 capacitors compared to 2160, and the effects of an element failure on the system can still be investigated effectively. The following section covers the investigation of an element failure using this model.

4.2.2 Changes in Unit Voltage and String Current Profiles

Capacitor units form a solid weld after a dielectric failure. In the case of the unit configuration explained above, shorting a single element in a unit (which effectively simulates the failure or 'welding' of an element) would have the effect of taking a whole section of six parallel elements out of operation.

The changes in voltage and current profiles of the fuseless capacitor unit were studied as an element was shorted. It was decided to look at the failure of one element, as this is the earliest indication of a fault within a unit. Two different approaches were taken: firstly, the expected theoretical change in unit voltage and string current was calculated. These calculations were then compared with the actual results of tests done on the model. Table 4 shows the change in rms voltage across a unit when an element within the unit was shorted, for both approaches.

	Unit Voltage Before and After Element Failure		Change in Unit Voltage
Theoretical calculations	20 V	16.95 V	-15.25%
Actual results	20.20 V	17.10 V	-15.30%

Table 4. The effect of a simulated element failure on a capacitor unit's voltage

If each unit in a string did have a capacitance of exactly 25 uF then the expected unit voltage (before an element failure) would be 20 V per unit. The shorting of an element in a unit increases the capacitance of the unit to 30 uF, and at 50 Hz the impedance would decrease from 127.3 Ω to 106.1 Ω. The resulting voltage across the affected unit decreases to 16.95V. At the same time, the nine other units in the string will experience a voltage increase from 20 V to 20.4 V. When running this test on the model, the pre-shorting unit voltage was 20.2 V. After shorting an element the voltage decreased to 17.1 V. This result compares favourably with the calculated values, as the change in unit voltage is about 15% in both cases.

When studying the effect of a shorted element on the string current (which in this case is the unit current) theoretically the string current should increase from 157 mA to 160 mA. This result, along with the model's current-profile changes, is given in Table 5.

One can see from Table 5 that the actual results differ from the calculated values in terms of the before and after currents. The main reason for this is that, due to the expected inaccuracies in capacitor ratings, the total capacitance of the bank was not exactly 15 uF. It should also be noted that, in order to measure the current, a 1 Ω resistor was connected in series at the top of the string. The voltage across this resistor was taken as the current, the main reason being that such small currents are very difficult to measure with normal current measuring equipment. Also, the multimeter used to measure this voltage across the resistor was not as accurate as expected, but was implemented as it was able to measure on a milliamp scale. What these results show is that the current did increase by about the expected amount.

	String Current Before and After Element Failure		Change in String Current
Theoretical calculations	157.08 mA	159.74 mA	1.69%
Actual results	147.8 mA	150.4 mA	1.77%

Table 5. The effect of a simulated element failure on a capacitor bank's string current

These voltage and current test results can now be used to study further new or different ways of detecting element failures that are applicable on a HV capacitor bank.

4.3 An Element Failure on a 132 kV Shunt Capacitor Bank

4.3.1 Comparisons with 200 V Findings

While it has been established what changes occur with respect to string (unit) current and the unit voltage when an element fails in a 200 V system, it is important to verify whether similar changes will take place on a large HV capacitor bank used in practice.
Francocci (1992:10,11) lists combinations of capacitor bank ratings for fuseless capacitor banks as implemented by Eskom. There are two different types of capacitor units used in these capacitor banks, with reactive power and voltage ratings as follows:

1. 250 kVAR, 6351 V
2. 333 kVAR, 6351 V

One such configuration mentioned in the list is a 132 kV, 72 MVAR double-star capacitor bank consisting of 6 legs (2 legs per phase) with 3 strings per leg. There are 12 series units per string, and each unit comprises 6 element sections with 6 parallel elements per section. By looking at the operation of a single string in one of the legs, one can compare the failure of an element in a unit to the results from the 200 V-model tests. This string has a rated output of 4 MVAR, and the 12 units in series are of the 333 kVAR, 6351 V variety. Each unit, therefore, has a capacitance of 26.28 uF at 50Hz. Table 6 shows the changes an element failure will cause in the string current and the voltage of the unit in which the element is situated. Note that these calculations assume ideal capacitance ratings and a system frequency of 50 Hz.

String of 12 units, 6 sections per unit	Before and After Element Failure		Change
Unit voltage	6351 V	5367 V	-15.49%
String current	52.43 A	53.17 A	1.41%

Table 6. Effect of an element failure in a HV capacitor unit.

When comparing the effects of a failed element in both cases, namely the 200 V and 132 kV systems, it can be seen that there is a large change in the voltage across the affected unit while there is a very small change in the string current. Considering these facts, it seems that using voltage detection for element failures would be a better form of protection than current detection. A voltage detection method would indicate exactly in which unit an element has failed, while the current detection method would only indicate in which string the failed element exists, since the current through each unit in this design is the same as the string current. With such a small change in current, detection would be severely hampered by the presence of noise and harmonic interference.

After a number of element failures the change in current would be easier to detect as the current increases. Using current detection at later stages of element failure is thus an option as well, although the location of the failed elements would not be known.

4.3.2 Measurement Logistics on HV Banks

Taking readings on a HV capacitor bank can be a problem, as the high voltage and current levels involved can put limitations on the type of measuring devices used. With unit voltages of 6351 V and string currents of about 50 A (on 132 kV banks), some sort of buffering is needed such that a much smaller signal can be sent down the rack to ground level. This signal then indicates to the protection system the condition of the capacitor unit.

It is Eskom standard to use a Current Transformer (CT) for phase overcurrent protection, so there is already a reference for the current detection technique mentioned above. However, there are three problems associated with this:

- A CT would be needed for every string, which means more CTs would have to be installed.
- As the change in string current is so small when an element fails, an intelligent relay device would be needed to differentiate between an element failing and general disturbances in the string current.
- This method detects only the string where the faulted element is situated.

By using the voltage method, the exact unit where the faulted element is can be detected. The large change in unit voltage when an element fails also makes it easily detectable. In a practical sense though, how one monitors the condition of the unit is very important. It has to be done in an economical and non-cumbersome way. Also, it is not safe to use measurement techniques that will leave equipment floating at very high voltages with respect to ground. If a Voltage Transformer (VT) had to be used on each unit in the 132 kV bank, a total of 216 VTs would be needed. As with the current detection technique, problems would arise:

- Mounting a VT onto every capacitor unit will clutter up an already complex array of equipment.
- A VT rated at 6351 V would not be cheap to manufacture.

4.4 Modifying Capacitor Unit and Bank Configurations

When discussing an element failure in a 6351 V capacitor unit in 4.3.1, it was assumed that the capacitor unit was made up internally of a 6 by 6 array of interconnected elements. The effect of changing this configuration is seen by now considering that the unit is made up of a 4 by 3 array of interconnected elements (4 series sections with 3 parallel elements per section). Table 7 shows the theoretical change in current and voltage profiles at 50 Hz for an element failure.

String of 12 units, 4 sections per unit	Before and After Element Failure		Change
Unit voltage	6351 V	4865 V	-23.40%
String current	52.43 A	53.55 A	2.13%

Table 7. Effect of an element failure in a HV capacitor unit with 4 element sections

By reducing the number of sections the unit voltage drops by 23.4%, which makes voltage detection even more effective for use in a protection device. The string current increases by 2.13%, which is slightly more than what was experienced with the six by six array. However, it will still be difficult to differentiate between an element failing and general system noise and harmonics. In order to attain a more substantial change in the string current, the number of sections will have to be reduced again. Doing so will eventually lead to a design with only one section, requiring the capacitor units installed to have very high voltage and power ratings. It is also contrary to the aim of using a number of smaller capacitor elements in a unit, which is to reduce the need for expensive capacitors with high ratings.

Calculations were made to see whether a capacitor bank operating at a different voltage would achieve similar results to the 132 kV bank. One of the standard Eskom 66 kV capacitor banks is a 48 MVAR double-star design using 6351 V, 333 kVAR units. There are 4 parallel strings per leg with 6 units per string. Table 8 shows the effects of an element failure in a capacitor unit, with a 4 by 3 array of interconnected elements, at 50 Hz.

In this case, the string current increases by 4.35% after an element failure. Compared to the 132 kV bank, this is a twofold improvement on 2.13%. The reason for the higher current change is that there are only six units per string in the 66 kV bank, while the 132 kV bank has twelve units per string.

String of 6 units, 4 sections per unit	Before and After Element Failure		Change
Unit voltage	6351 V	4970 V	-21.74%
String current	52.43 A	54.71 A	4.35%

Table 8. Effect of an element failure in a HV capacitor unit (with 4 sections) on a 66 kV capacitor bank

When an element fails and the impedance of the affected unit drops, the change in the total string impedance is more exaggerated with four units per string. Since the same 6351 V capacitor unit is used in both banks, this result is expected.

Similar conclusions can be made about the number of units in a string and the number of series sections in a unit: in order to make current detection a more effective technique at 132 kV, the number of units per string has to be reduced. To achieve this, capacitor units with higher ratings will be needed, which is not a practical option unless these units can be manufactured economically. Thus, it appears that using voltage detection to identify the failure of an element in a unit (on a standard fuseless 132 kV system) is still a more useful method to investigate than current detection.

4.5 Using Voltage Transformers inside a Capacitor Unit

In Section 4.2.2 it was found that, when an element fails inside a capacitor unit, the unit voltage drops by more than 15% (depending on the element configuration). The main problem with using this change in voltage to monitor the capacitor unit's health is the actual measurement. Since it is not practical to connect a VT (see Section 4.3.2) on the outside of every unit, another option is to insert measurement equipment inside the unit.

Figure 23 shows the internal configuration of a fuseless 6351 V, 333 kVAR capacitor unit, which consists of a 4 by 3 array of interconnected elements. Connected across each element section is a VT. Since the capacitor unit is insulated with oil (or a non-PCB impregnant), the VTs need to be encased in an epoxy so that they do not come into contact with the oil. Under normal operating conditions, each section has a voltage across it of just under 1600 V, so the VTs need to be rated higher than 1600 V to account for overvoltages. Basically, they must have the same ratings as the elements used. Note that I have not covered the technical aspects of this VT method, as this is beyond the scope of this thesis. What is of importance is the application of this method.

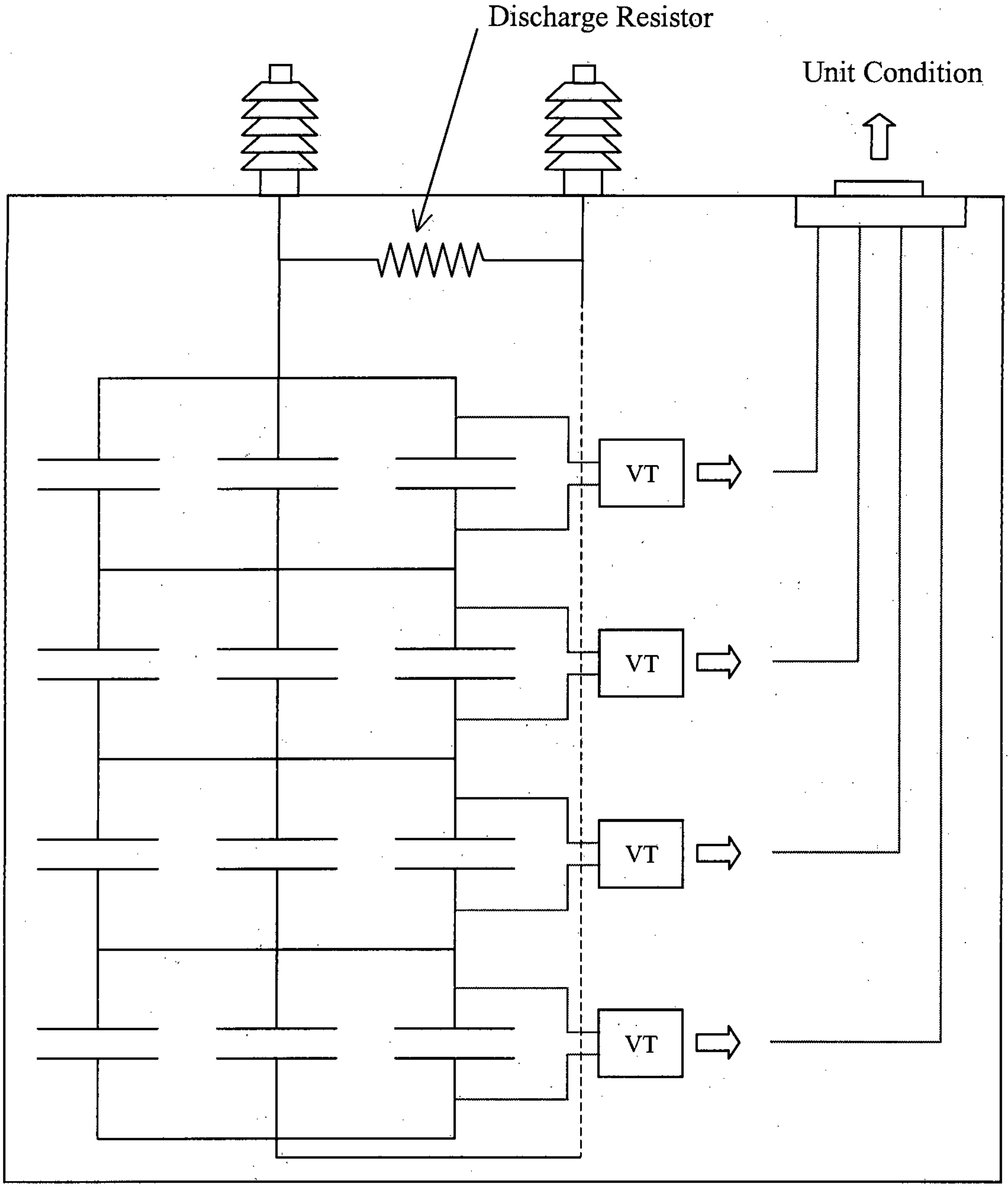


Figure 23. Voltage measurement inside a capacitor unit

The VTs are used to monitor the condition of each respective section. If an element fails, and thus forms a solid weld, the entire section will be shorted out, reducing the VT primary voltage from 1600 V to 0 V. This change in voltage can then be used to indicate to a protection system that an element has failed.

As can be seen in the diagram, each VT's signal is sent to a single point, where this information can be transformed into a suitable form for output purposes. The output can be in any form, as long as it is reliable and easy to examine. A small box could be placed on the outside of the unit, and on this box there could be four LEDs showing the health status of each section. For example: an off LED would signify a failed element in a certain section. The indication could be less accurate if wanted, as in a single LED that indicates whether an element in any of the four sections has failed.

Another form of output that can be used is to plug a fibre-optic cable into a socket on the unit, and then send the cable to ground level where each unit's health can be monitored by a microprocessor relay device. This method therefore uses less manpower than the LED method mentioned above, as the LEDs have to be checked physically, while a microprocessor can send details of the units' status to a remote position. Overvoltages across remaining element sections could also be monitored, which could help in indicating when the overvoltages are reaching undesired levels.

Both of the above-mentioned methods show the level of protection used depends on how developed the utility wants it to be. This decision is weighted heavily by cost, so a situation is needed whereby the cost of applying such detection methods is less than the cost of replacing failed capacitor units that would have failed with existing protection methods in use.

4.6 Further Concepts in Signature Detection

So far this chapter has dealt mainly with the changes in capacitor unit current and voltage profiles as an element within a unit fails. There may, however, be other signs that elements in a unit are about to, or already have, failed. These signals could be of use when designing a protection module for shunt capacitor banks and are thus investigated here.

4.6.1 Description of Model

A second model was built for the tests referred to in this section. In the laboratory ten 4.7 uF film-type capacitors, rated at 30 V (ac), were connected in parallel to form a 'single capacitor' of 47 uF. The reason for this was to allow for more accurate current measurement than if a single 4.7 uF capacitor was used, as the total current drawn was

740 mA instead of 74 mA. The main objective of this experiment was to monitor the temperature and current as the voltage was increased over 10-minute intervals, until the capacitor failed. From these results I hoped to gain some insight of the effectiveness of using unit current or unit temperature as an indication of an unhealthy capacitor unit.

A single-phase 50 Hz variac was used as a voltage source. To measure the temperature, a transducer, with a suppliers reference code LM35, was attached to the capacitor (note that the ten 4.7 uF capacitors were fixed together, so the LM35 could detect the temperature change as a whole). The output of the LM35 is a voltage that increases by 10 mV per °C. Initially, the source voltage was set to 50V (ac), and then increased by 5V every ten minutes. When monitoring the current, the frequency spectrum was also observed to see how the current harmonics reacted as the capacitor was put under increasing stress.

4.6.2 Temperature Detection

Table 9 shows the temperature readings for an increasing rms source voltage across the capacitor. Before a voltage was applied across the capacitor, the ambient temperature reading was 26.05 °C. Figure 24 shows how the temperature of the 47 uF capacitor changed as the voltage across the capacitor was increased until the capacitor failed. On this graph it is easy to see how the temperature increases as the voltage is stepped up. Up to 95 V, the graph has an almost linear character but with a slight exponential factor, which can be attributed to power losses of I^2R.

The capacitor failed after 3 minutes at 100 V (a total of 103 minutes), causing the case to rupture and the inside section to burn out. After the failure, the temperature increased abruptly to 40 °C. This short time in which the temperature changes and the larger than usual change could be the key to accurate detection. In a 6351 V capacitor unit used in HV operations, an element will form a solid weld when it fails. This incident should cause a similar sudden temperature change, although tests will have to be done on HV units to verify this. This fluctuation will then be picked up by the protection and deduced as an element or elements failing.

Source Voltage (V)	Time (minutes)	Temperature (°C)
50	10	27.21
55	20	27.51
60	30	27.84
65	40	28.19
70	50	28.58
75	60	29.12
80	70	29.66
85	80	30.27
90	90	30.93
95	100	31.7
100	Failed at 103	40 after failure

Table 9. Temperature detection: results of applying an increasing overvoltage to a 47 uF capacitor

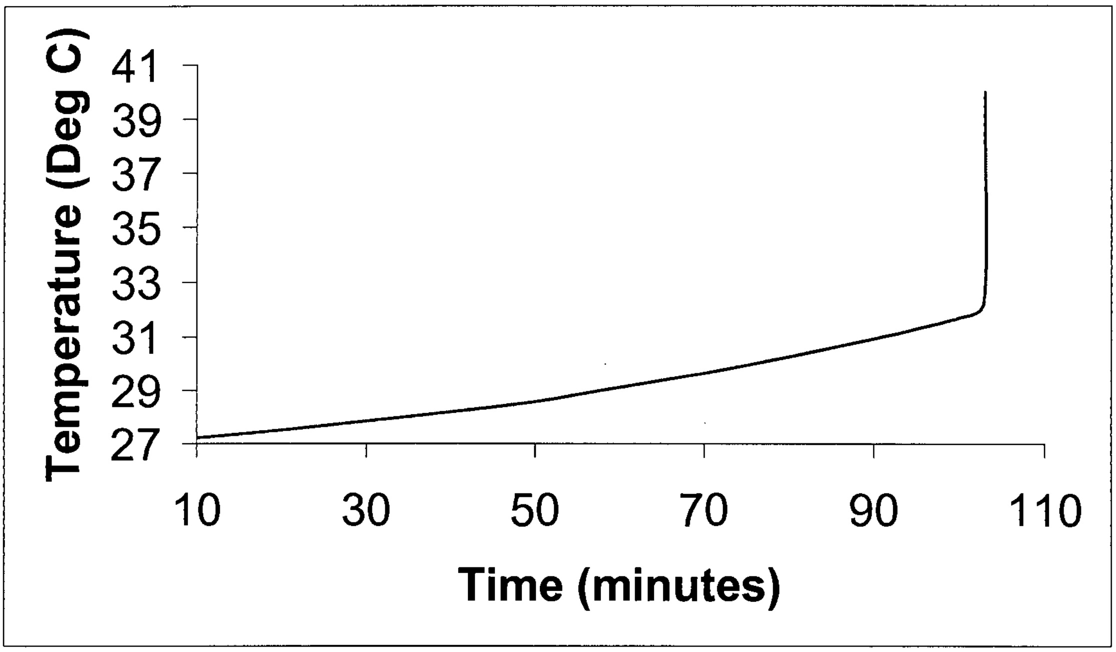


Figure 24. The change in capacitor temperature vs. duration of capacitor overvoltage

Capacitors in service in outdoor sub-stations can have varying temperatures depending on the weather conditions. At most times during the day there will not be a uniform temperature across the whole bank, as parts of the bank may be in the shade while others in direct sunlight. However, the effects of weather conditions are not instantaneous: if a capacitor unit that has been in the shade suddenly comes under direct sunlight, the temperature of the unit will increase over a gradual time period. Thus a protection module could look for more sudden changes in temperature, which would be an indication of capacitor elements failing and not a change in weather conditions.

Measuring the temperature inside a HV capacitor unit will provide similar problems as measuring voltage within a unit. One of the main considerations is how a temperature transducer will be powered inside a capacitor unit, as the transducer will need very little voltage, while the units are operating at extremely large voltages.

4.6.3 Current Harmonics Detection

While monitoring the temperature (see above section), I also monitored the current (including harmonics) by using a power meter. Generally, most of the harmonics reacted similarly to the fundamental current, increasing as the source voltage was increased. However, the 13th harmonic reacted differently, decreasing for every voltage step up. Table 10 and Figure 25 show the change in the 13th harmonic as a percentage of the fundamental current.

Source Voltage (V)	Time (minutes)	Capacitor Current (A)	13th Harmonic (A)	13th Harmonic (% of fundamental)
50	10	0.75	0.11	15.60
55	20	0.82	0.09	10.50
60	30	0.90	0.07	8.40
65	40	0.97	0.07	7.80
70	50	1.05	0.05	5.50
75	60	1.12	0.05	5.10
80	70	1.20	0.05	4.60
85	80	1.28	0.05	4.10
90	90	1.35	0.04	3.60
95	100	1.43	0.04	3.30

Table 10 Changes in 13th current harmonic as the capacitor voltage increases

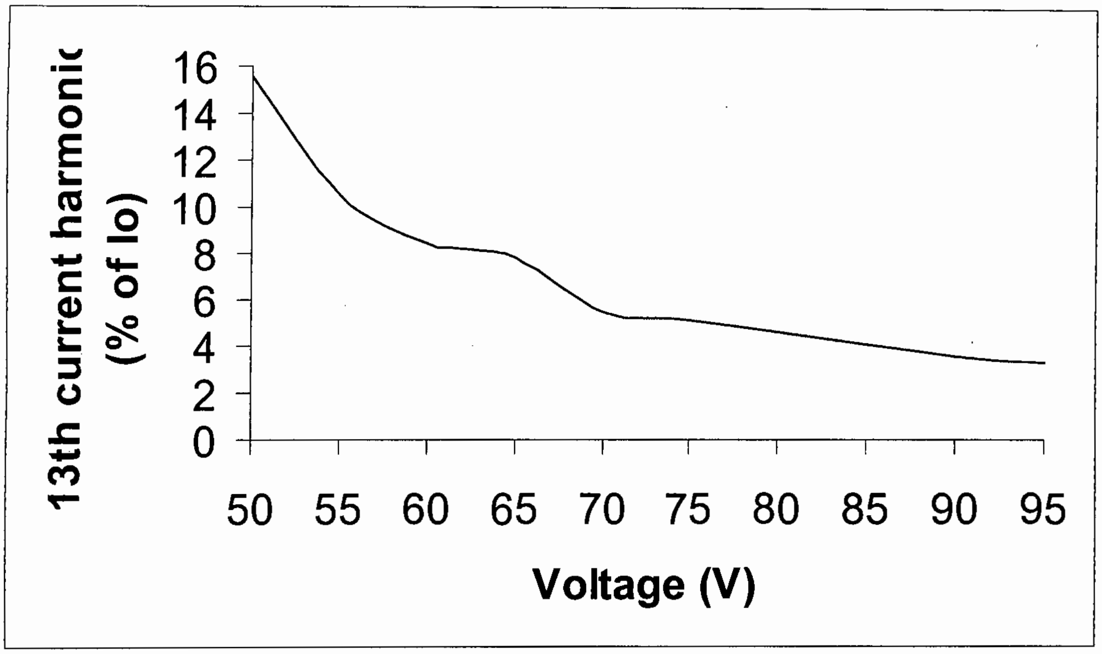


Figure 25 A 13th current harmonic response to an overloaded capacitor

Table 10 shows the actual value of the 13th harmonic does not change much at 70 V and higher. In relation to the fundamental current, however, there is a change, which is clearly shown in the Figure 25. Thus, the harmonic current must be compared to the fundamental current when looking for stressed elements.

This interesting result could be used as a signature of a stressed unit. By monitoring this current, a protection device, depending on the extent of protection needed, could determine the status of the unit and allow suitable action to be taken. However, the logistics of measuring this current need to be considered.

These tests were carried out on a single capacitor (10 capacitors in parallel to represent a single 47 uF capacitor), which in a practical HV case is meant to represent an element within a capacitor unit. In a fuseless capacitor unit design, current measurement is limited to a string that comprises numerous units. Thus, the problem of connecting a CT to each string arises, unless some other method of current detection is used. What is needed are tests on a HV capacitor bank to see if this decrease in a particular current harmonic is detectable in the string current, bearing in mind that it could be any number of elements that are under stress. Because of general noise on HV equipment, this change might not be as easily detectable as it is in the laboratory.

It is important to note that the variation in the 13th harmonic in this experiment could be a specific and localised phenomenon. In other words, because these results were achieved on this model does not mean that the same results will be found on HV capacitor units.

What the results do show, however, that there could be some harmonic signature that a capacitor unit is under stress. Again, tests need to be done on HV units looking at all the current harmonics.

5. Computing Element Failures within Capacitor Units

The chapter focuses on the application of a computer program that can help to investigate new or improved ways of protecting a shunt capacitor bank. With the aid of the program the results and discussions of the previous chapter are substantiated, and in some instances improved upon. In contrast to the earlier investigations, however, the program is not restricted to a single-phase model but will able to simulate a three-phase shunt capacitor bank.

In Chapter 4 the changing voltage and current profiles of a capacitor unit, due to internal element failures, were studied both theoretically as well as practically. It thus seems appropriate to have a computer program that could simulate these element failures. The main objective of the program would be to produce any relevant capacitor unit or bank information as output.

5.1 Description of Computer Model

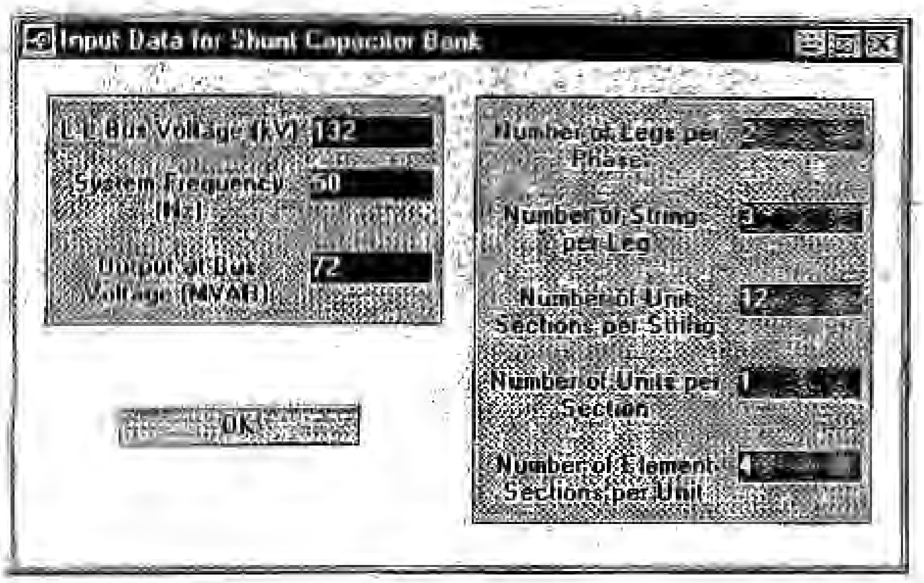
The model requires as input data the operating ratings and capacitor arrangements of a capacitor bank. This data is input via a dialog box (see example in Figure 26). Any number of element failures can then be simulated. A matrix data structure is used to keep track of which units have element failures. Each unit in the capacitor bank is represented in this matrix and a record kept of the number of element failures. An extensive user-guide for the model can be found in Appendix A.1.

All calculations carried out by the model are simple, reflecting general capacitor circuit algorithms. The power of the model lies with the fact that any number of simulations can be run, which may show interesting trends of capacitor element or unit failure.

5.2 Two Different Shunt Capacitor Bank Arrangements

5.2.1 Case 1

In Sections 4.3.1 and 4.4 the effects of an element failure in a 132 kV shunt capacitor bank were discussed. This included the detection of the element failure by measuring capacitor unit voltage and current. The same example is now applied to the computer model, firstly to show the model's workings, and secondly to serve as a base case that further model applications can be compared to.


Input Data for Shunt Capacitor Bank

L-L Bus Voltage (kV): 132

System Frequency (Hz): 50

Output at Bus Voltage (MVAR): 72

Number of Legs per Phase: 2

Number of String per Leg: 3

Number of Unit Sections per String: 12

Number of Units per Section: 1

Number of Element Sections per Unit: 4

Figure 26. Case 1: dialog box 1

Figure 26 shows the Input Data for Shunt Capacitor Bank dialog box. The 132 kV, 72 MVAR shunt capacitor bank has a double-star configuration with 3 strings per leg and 12 units per string. The capacitor units operate at 6351 V with outputs of 333 kVAR. Internally the capacitor units consist of 4 element sections in series. A single element failure in a unit in the first string is selected, as shown in the Element Failure Simulation dialog box in Figure 27.


Element Failure Simulation

Figure 27. Case 1: dialog box 2

Some of the more relevant results of the program are listed in Table 11. All angles cited are with reference to the initialised voltage angles of the 3 phases, which are:

$$V_{an}\angle = 0^\circ$$
$$V_{bn}\angle = -120^\circ$$
$$V_{cn}\angle = -240^\circ$$

The changes in unit voltage and current are the same as calculated in Section 4.4, which is expected. There is a large decrease in the unit voltage, which for protection purposes can be useful when trying to determine the state of the capacitor unit, while the change in unit current is very small and of no real use.

This small change in unit current translates into an even smaller change in the a-phase current, while the other phase currents are not effected by the element failure. However, what is of interest is the bank neutral current, which is the sum of the three phase currents.

With the neutral current increasing by 1.12 A from zero, detection of the element failure is possible. After a single element failure the neutral current angle can be useful, as it will indicate in which phase the unhealthy capacitor unit is situated. A processor could then be used to build up a store of successive failures, and then set off an alarm when the number of failures reaches a specified limit. However, to determine the phases where successive failures occur, the CT would have to rebalanced to zero. This might indicate the need for a separate device to measure the phase angle (in addition to using a CT). This method would be much cheaper than one where CTs are connected to each string, although in this case only the phase where the faulty unit is located is known and not the string.

As the voltage across the affected unit decreases with an element failure, the remaining healthy units in the string will experience increased voltages and higher power outputs, culminating in a higher total bank output of 72085 kVAR. If element failures continue to occur, the units can end up operating beyond their rating limits, and a dangerous situation can develop if the bank is not taken out of service. The question of just how many element failures the capacitor bank can handle while in operation, the theory of which was mentioned in Section 3.2.4, is investigated in Cases 3-5.

Case 1	Before and After Element Failure				Change
	Magnitude	Angle	Magnitude	Angle	
Unit voltage	6351 V	0°	4864 V	0°	-23.40%
Unit (string) current	52.49 A	90°	53.60 A	90°	2.11%
Unit output	333 kVAR	90°	261 kVAR	90°	-21.62%
A-phase current	314.92 A	90°	316.04 A	90°	0.32%
B-phase current	314.92 A	-30°	314.92 A	-30°	-
C-phase current	314.92 A	-150°	314.92 A	-150°	-
Bank neutral current	0 A	0°	1.12 A	90°	-
System output	72000 kVAR	-	72085 kVAR	-	0.12%
Remaining units in string:					
Unit voltage	6351 V	0°	6486 V	0°	2.13%
Unit output	333 kVAR	90°	348 kVAR	90°	4.5%

Table 11. Case 1 results

5.2.2 Case 2

A typical shunt capacitor bank configuration in the Western Cape, South Africa is modelled. The 132 kV, 72 MVAR bank has a double-star earthed arrangement (2 legs per phase), one string per leg, with 12 series sections per string. Figure 28 shows this arrangement of capacitors. Each unit section consists of 2 capacitor units in parallel, and at 132 kV the voltage across each unit is 6351 V and the output 500 kVAR.

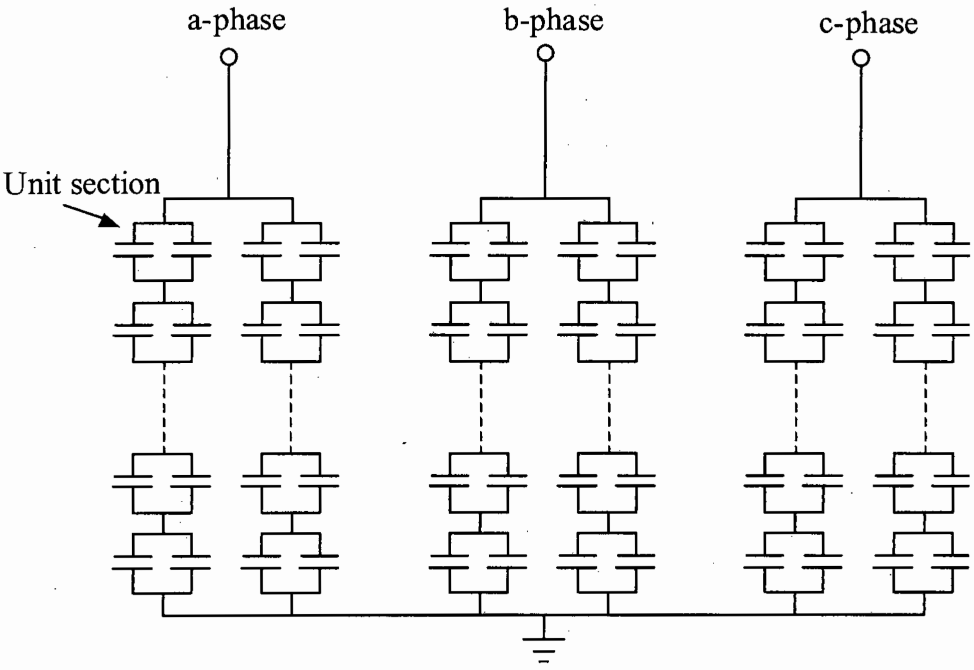


Figure 28. 132 kV shunt capacitor arrangement with 2 units in parallel per unit section

The main difference between this capacitor arrangement and that of Case 1 is that here there are 2 units in parallel per unit section (in Case 1 each unit section consisted of only a single unit). This will effect how voltage and current profiles change throughout the bank as elements fail. As with Case 1, an element failure is simulated in the first string.

With this capacitor arrangement the failure of an element results in a decrease of voltage across the affected unit (indicated in Table 12), but this decrease is not as substantial as that found in Case 1. It is, however, large enough to be used as a signature for protection devices.

The most interesting result of the element failure occurs with the change in the affected unit's current, which represents an increase of just less than 16%. In earlier investigations carried out in Chapter 4 and Case 1 (on banks with different configurations), the increase in current on a 132 kV bank after an element failure was very small, about 2%. Using this change in current in protection devices is not viable as general system noise and harmonics alone can contribute to a similar change. A 16% increase, however, could be more helpful in detecting the unhealthy capacitor unit. The reason for such a large deviation can be put down to the capacitor arrangements, specifically the fact that the strings consist of sections with two units in parallel per section.

Case 2	Before and After Element Failure				Change
	Magnitude	Angle	Magnitude	Angle	
Unit voltage	6351 V	0°	5509 V	0°	-13.26%
Unit current	78.73 A	90°	91.06 A	90°	15.66%
Unit output	500 kVAR	90°	501 kVAR	90°	0.20%
A-phase current	314.92 A	90°	316.82 A	90°	0.60%
B-phase current	314.92 A	-30°	314.92 A	-30°	-
C-phase current	314.92 A	-150°	314.92 A	-150°	-
Bank neutral current	0 A	0°	1.90 A	90°	-
System output	72000 kVAR	-	72145 kVAR	-	0.20%
Remaining unit in section:					
Unit voltage	6351 V	0°	5509 V	0°	-13.26%
Unit current	78.73 A	90°	68.30 A	90°	-13.25%
Unit output	500 kVAR	90°	376 kVAR	90°	-24.8%
Remaining units in string:					
Section (unit) voltage	6351 V	0°	6427 V	0°	1.20%
Unit current	78.73 A	90°	79.68 A	90°	1.20%
Unit output	500 kVAR	90°	512 kVAR	90°	2.4%

Table 12. Case 2 results

The 16% increase in unit current could be measured with a CT located at the unit. Similar considerations would have to be made as those made with unit voltage detection and VTs. It would not be ideal if the CTs were connected on the outside of each unit as this would clutter up the shunt capacitor bank. A form of measurement inside the capacitor unit would be more suitable. It is important that the costs of the CTs or whatever current measuring devices are used are kept as low as possible. While keeping the costs low, however, the measuring devices must be reliable since there would be no way of repairing or replacing them if they are inside capacitor unit.

Table 12 shows some other interesting results from this simulation, that effectively portray what happens to the remaining healthy units in the affected string. The voltages across these units increase by 1.20%, whereas in Case 1 an increase of 2.13% was found. This result suggests that this type of arrangement could allow for more element failures before overvoltage limits are reached. This is investigated further in the cases that follow.

5.3 Capacitor Units Operating in Overvoltage Conditions

5.3.1 Case 3

The object of the next three cases is to investigate how many elements can fail before the operating limits of the capacitor units are violated. In this case the bank arrangement of Case 1 is used. It was found that after 5 element failures occur in a single string the resulting voltages on the remaining healthy capacitor units are 111% of the nominal operating voltage, which exceeds the 110% limit recommended by the IEEE (1990:8). Table 13 lists this as well as other results from the model simulation.

Equation 3.2 stated that the resulting overvoltage on each remaining string unit after a complete unit failure can be calculated in pu:

$$Vpu = \frac{3SN}{3SN - n(3S-1)}$$

where S = number of parallel strings of units per phase
N = total number of units in series in each string
n = number of complete capacitor units short-circuited in one string.

Using this equation and the configuration modelled in this case, the failure of a single unit will cause an overvoltage of:

$$\begin{aligned} Vpu &= \frac{(3)(6)(12)}{(3)(6)(12) - (1)(3(6)-1)} \\ &= 1.09 \end{aligned}$$

This result, along with the 111% overvoltage as indicated by the model simulation, shows that the type of failure that takes place can have a large influence on the time it takes before the remaining healthy units suffer overvoltages above 110%. What this means is that if a fault does enough damage to ensure that a whole unit fails, the overvoltage level will without much delay already be at 109%. An additional single element failure in any other string unit will result in an overvoltage level above 110%. Thus the capacitor bank's

Case 3	Before and After 5 Element Failures				Change
	Magnitude	Angle	Magnitude	Angle	
Unit Voltages: R – unit row number C – unit string number					
R2 C1 (2 failures)	6351 V	0°	3545 V	0°	-44.18%
R4 C1	6351 V	0°	5317 V	0°	-16.28%
R8 C1	6351 V	0°	5317 V	0°	-16.28%
R11 C1	6351 V	0°	5317 V	0°	-16.28%
Unit (string) current	52.49 A	90°	58.59 A	90°	11.62%
Unit outputs:					
R2 C1 (2 failures)	333 kVAR	90°	208 kVAR	90°	-37.54%
R4 C1	333 kVAR	90°	312 kVAR	90°	-6.31%
R8 C1	333 kVAR	90°	312 kVAR	90°	-6.31%
R11 C1	333 kVAR	90°	312 kVAR	90°	-6.31%
A-phase current	314.92 A	90°	321.02 A	90°	1.94%
B-phase current	314.92 A	-30°	314.92 A	-30°	-
C-phase current	314.92 A	-150°	314.92 A	-150°	-
Bank neutral current	0 A	0°	6.10 A	90°	-
System output	72000 kVAR	-	72465 kVAR	-	0.65%
Remaining healthy units in string:					
Unit voltage	6351 V	0°	7089 V	0°	11.62%
Unit output	333 kVAR	90°	415 kVAR	90°	24.63%

Table 13. Case 3 results

condition has changed in a very short period. On the other hand, if only a single element short-circuited then it could take some time before 4 other elements followed suit, and the overvoltage limit reached for the remaining healthy units i.e. not all the elements will fail instantaneously. Whether a stress on a capacitor unit will cause either total unit failure or a single element failure will depend on the type and extent of the stress, as well as on the condition of the unit. If a capacitor unit was faulty in any regard, total unit failure could be promoted.

In Table 13 a specific unit is indicated by using the location as entered by the program user. For example: R2 C1 refers to a capacitor unit in the second row of the first string. This is how the capacitor unit arrangement is represented in the computer model. If there is more than one capacitor unit per section, then an extra column is added, even though the units are in the same string.

As this case deals with a situation where the bank is operating beyond specified limits, the resulting changes in voltage of the units with failed elements are considerably large. The decrease in voltage across the unit with 2 element failures is just more than 44%, while the units with single element failures experience decreases of about 16%.

The reactive power of the remaining healthy units will increase along with the unit voltage. However, with an output of 415 kVAR the units are not yet operating beyond reactive power limits of 135% (IEEE, 1990) for such overvoltage conditions. As current limits are set at 180% (IEEE, 1990) of normal operating currents, in this type of arrangement the voltage levels are first to exceed their specified limits.

Although the bank could be experiencing dangerous overvoltages, the total reactive power output of the bank is 72465 kVAR, which is only 0.64% more than the power output with no element failures. The bank would thus continue to deliver enough reactive power even with 5 failed elements.

5.3.2 Case 4

In Case 2 it was found that the voltages across the remaining healthy units of a string did not increase as much after an element failure as was found in Case 1. The main difference between the bank arrangements is that in Case 2 each string was not just a number of units in series (as in Case 1), but rather a number of unit sections in series. Each unit section was made up of 2 units in parallel. The results from these cases seemed to suggest that the capacitor bank arrangement of Case 2 could allow for more element failures before the overvoltage limits on the healthy units are violated. Cases 4 and 5 investigate this.

A whole capacitor unit failure is simulated (i.e. all 4 element sections short-circuited) with an additional single element failure from another unit. Since there are 2 units in parallel per unit section (see Figure 28), the failure of an entire unit will take the remaining unit of that section out of operation as all current will flow through the short-circuited capacitor unit. In total 5 element failures are simulated as in Case 3. Table 14 lists the results of the computer model.

Case 4	Before and After 5 Element Failures				Change
	Magnitude	Angle	Magnitude	Angle	
Unit voltages: R – unit row number C – unit string number					
R1 C1 (total failure)	6351 V	0°	0 V	-	-100.00%
R2 C1	6351 V	0°	6017 V	0°	-5.26%
Unit currents:					
R1 C1	78.73 A	90°	174.03 A	90°	121.05%
R2 C1	78.73 A	90°	99.45 A	90°	26.32%
Unit outputs:					
R1 C1	500 kVAR	90°	0 kVAR	-	-100.00%
R2 C1	500 kVAR	90°	598 kVAR	90°	19.60%
A-phase current	314.92 A	90°	331.49 A	90°	5.26%
B-phase current	314.92 A	-30°	314.92 A	-30°	-
C-phase current	314.92 A	-150°	314.92 A	-150°	-
Bank neutral current	0 A	0°	16.57 A	90°	-
System output	72000 kVAR	-	73263 kVAR	-	1.75%
Remaining units in effected sections:					
Unit voltages:					
R1 C2	6351 V	0°	0 V	0°	-100.00%
R2 C2	6351 V	0°	6017 V	0°	-5.26%
Unit currents:					
R1 C2	78.73 A	90°	0 A	-	-100.00%
R2 C2	78.73 A	90°	74.56 A	90°	-5.30%
Unit outputs:					
R1 C2	500 kVAR	90°	0 kVAR	-	-100.00%
R2 C2	500 kVAR	90°	449 kVAR	90°	-10.20%

Table 14. Case 4 results

Case 4	Before and After 5 Element Failures				Change
	Magnitude	Angle	Magnitude	Angle	
Remaining units in string:					
Section (unit) voltage	6351 V	0°	7019 V	0°	10.52%
Unit current	78.73 A	90°	87.02 A	90°	10.53%
Unit output	500 kVAR	90°	611 kVAR	90°	22.2%

Table 14. Case 4 results continued

With 5 element failures the remaining healthy sections have voltages that increase by more than 10%, which exceeds the allowable overvoltage level. Similar to Case 3, the capacitor bank operates in dangerous conditions after only a single unit failure and one additional element failure. So in this situation having two capacitor units in parallel per section does not help keep the overvoltage levels on the remaining healthy units below the specified limits.

The bank's neutral current increases from 0 A to 16.57 A after the 5 element failures. This is considerably more when compared to the change in the neutral current in Case 3 (6.1 A). Also, the total reactive power output of the bank increases by more than a MVAR, which once again is more than the result of Case 3. Both of these conditions can be attributed to the capacitor unit arrangement, as it is the arrangement that determines the voltage, current and power distributions throughout the string and bank.

5.3.3 Case 5

Continuing from Case 4, where 5 element failures were simulated with 4 of the failures in the same capacitor unit, the computer model is now used to investigate the effect of 7 element failures in 7 different capacitor units. Table 15 lists the results of the simulation.

Here the effect of having two units in parallel per section can be seen more clearly. After the failure of the 7 elements the resulting overvoltage on each of the remaining healthy unit sections is 6928 V, which is only about 9% more than the normal operating voltage. Thus no units are operating above the specified limit of 110%.

In Case 4 only 5 element failures were simulated, yet the remaining healthy units had voltages across them of above 110%. The fact that an entire unit was short-circuited is very important. If the element failures are spread out between the unit sections then more element failures can be tolerated before voltage limits are exceeded (as shown in the results of Case 5). Again, this can vary the time period that the bank stays in a healthy condition. A single unit failure will have the rest of the healthy units operating at undesired levels almost instantly, while it could take some time before the same occurs for separate element failures in different unit sections.

Case 5	Before and After 7 Element Failures				Change
	Magnitude	Angle	Magnitude	Angle	
Unit voltages: R – unit row number C – unit string number					
R1 C1, R2 C1, R3 C1, R4 C1, R5 C2, R6 C2, R7 C2	6351 V	0°	5939 V	0°	-6.49%
Unit currents:					
R1 C1, R2 C1, R3 C1, R4 C1, R5 C2, R6 C2, R7 C2	78.73 A	90°	98.16 A	90°	24.68%
Unit outputs:					
R1 C1, R2 C1, R3 C1, R4 C1, R5 C2, R6 C2, R7 C2	500 kVAR	90°	583 kVAR	-	16.60%
A-phase current	314.92 A	90°	329.23 A	90°	4.54%
B-phase current	314.92 A	-30°	314.92 A	-30°	-
C-phase current	314.92 A	-150°	314.92 A	-150°	-
Bank neutral current	0 A	0°	14.31 A	90°	-
Bank neutral current	0 A	0°	14.31 A	90°	-
System output	72000 kVAR	-	73091 kVAR	-	1.52%

Table 15 Case 5 results

Case 5	Before and After 7 Element Failures				Change
	Magnitude	Angle	Magnitude	Angle	
Remaining units in affected sections:					
Unit voltages: R1 C2, R2 C2, R3 C2, R4 C2, R5 C1, R6 C1, R7 C1	6351 V	0°	5939 V	-	-6.49%
Unit currents: R1 C2, R2 C2, R3 C2, R4 C2, R5 C1, R6 C1, R7 C1	78.73 A	90°	73.62 A	90°	-6.49%
Unit outputs: R1 C2, R2 C2, R3 C2, R4 C2, R5 C1, R6 C1, R7 C1	500 kVAR	90°	437 kVAR	90°	-12.60%
Remaining units in string:					
Section (unit) voltage	6351 V	0°	6928 V	0°	9.09%
Unit current	78.73 A	90°	85.89 A	90°	9.09%
Unit output	500 kVAR	90°	595 kVAR	90°	19.00%

Table 15 Case 5 results continued

5.4 Modeling Random Element Failures

5.4.1 Case 6

In this final case study, I randomised the failure of elements in a 3-phase 132 kV, 72 MVAR double-star shunt capacitor bank with 3 strings per leg and 12 units per string. This was the same bank arrangement as used in Case 1 (no interconnection between any units in each string).

The computer model was used to generate random locations of capacitor units in the bank, and then an element failure was simulated. This process was continued until the limit of 110% overvoltage was violated on any of the units in the bank. Rather than using a totally random process to generate the unit location, I used a weighting system to favour the failure of elements in strings where failures had already occurred, making the simulation more realistic than one using a totally random process.

The basis for this weighting is that the string current and element section voltage in each unit will increase after an element failure. The chance of further element failure in this string is thus greater than the chance of an element failure in a string with no previous failures. For the model it was assumed that the chance of failure in a string with previous failures would be twice that of the chance of failure in a healthy string.

This simulation provided interesting results on how many element failures could occur throughout a 3-phase bank. After running the simulation 100 times, it was found that for this specific arrangement a total of 16 element failures throughout the bank, on average, would be sufficient to cause unit overvoltages in a string in excess of 110%. Table 16 shows this result, as well as the maximum and minimum number of element failures recorded that violated overvoltage limits.

Case 6	Number of Element Failures Required to Violate Overvoltage Limits
Average	16
Maximum	28
Minimum	6

Table 16. Case 6: results of random element failure modelling after 100 simulations

The large difference between the maximum and minimum values highlights the fact that the failure of elements within capacitor units is not a predictable science. The bank could stay in service for a considerable time if the element failures were to occur in different strings. On the other hand, the bank might have to be taken out of service after only a few element failures in the same string (as mentioned previously in this chapter). The governing factor, therefore, is whether the element failure is isolated or spread across different strings. As long as the protection can detect these failures, the bank should be switched out at the appropriate moment.

6. Conclusions

The following notes conclude on the thesis as a whole, while also summarising the main results achieved from the experimental phase of the thesis, including both practical and computer models.

1. Existing protection techniques for shunt capacitor banks rely mainly on unbalance sensing. This unbalance sensing works so that, during any type of capacitor failure, a bank can be switched out before a critical situation is reached. However, the protection techniques do not offer much information with respect to locating the faulty capacitor units (a visual inspection of the bank would determine which units needed replacing). A protection technique that detects which units have failed (or are about to fail) means less time spent out in the field checking for failed units. More importantly, the overall protection of the bank could be managed in a more effective manner.

2. The failure of an element inside a fuseless capacitor unit leads to the voltage across the unit decreasing significantly. This was found to be true for all capacitor arrangements considered. By monitoring the voltage across each unit in a capacitor bank, such an occurrence could be easily detected. Thus the location of the faulty capacitor unit would be known. Two possible methods of voltage detection are:

    - Connecting VTs across each capacitor unit (outside the unit). This is not practical, as it will increase the amount of equipment present on the capacitor bank structure.
    - Manufacturing capacitor units with built-in VTs connected across each element section. As an element fails and thus shorts out the entire element section, this information can either be sent down the bank via fibre-optics to a microprocessor relay device, or it can be displayed on the outside of the unit casing using LEDs. Reliability of the VTs and associated circuitry is very important, as this equipment is sealed inside the capacitor unit.

3. Unlike capacitor unit voltage detection, monitoring the current is not always useful in assessing the health of a capacitor unit. The effectiveness of unit current detection depends largely on the bank arrangement. In a fuseless system consisting of parallel strings of units with no interconnection (unit sections with one unit), the increase in unit current after an element failure is no more substantial than general system noise and harmonics.

4. If each string consists of unit sections with 2 units per section (such as the 132 kV bank at Muldersvlei, Western Cape), there will be a substantial increase in the unit's current. Detecting these current changes could be achieved using similar methods as described above for voltage changes: capacitor units with built-in CTs, which will trigger alarms when element failures occur.

5. A more simple current detection method involves monitoring the bank neutral current for sudden and large changes. The disadvantage of this method is that only the phase where the element failure occurs can be located.

6. Element failures in fuseless capacitor units cause overvoltages on the remaining healthy capacitor units in a string. The extent of these overvoltages depends largely on the capacitor arrangement. In a system where the unit sections consist of only one unit, the overvoltages will increase uniformly across the remaining healthy units until the specified overvoltage limit is reached. The bank should then be taken out of service.

   The number of element failures allowed per string (before overvoltage limits are violated), can be increased by having 2 units in each unit section. This is achieved if the element failures are not isolated to a single unit, but spread between various units in a string. If a unit fails (short-circuits) completely, the remaining healthy unit sections in the string will experience overvoltages similar to cases involving sections with only one unit.

7. The temperature inside a capacitor unit could be used to establish the health of a unit. As element failures occur, there would be a change in the temperature inside the unit. The rate of change in the temperature would be more rapid than the change due to weather conditions, and thus could be detected using a transducer and a record kept of the location of the unit and the number of element failures. A maximum temperature limit could also be used for protection purposes, although in this case the weather factor needs to be considered. More experimentation is needed at HV levels on actual capacitor units, as these results are based on experiments done on a much smaller scale in the laboratory.

8. By monitoring the current harmonics of a unit, certain signs of element failure may be detectable. For example, a certain harmonic may respond differently than expected when a capacitor unit is under stress, or as an element fails. As with temperature detection, more experimentation is needed at HV levels on actual capacitor units, as

the results gained from these experiments could be specific to the laboratory where the experiments took place.

9. Improving the protection of HV shunt capacitors relies heavily on the balance attained between the cost and the effectiveness of applying new protection methods. For example, a method dictates that a capacitor bank must be removed from service if there is an indication that elements inside capacitor units are close to failing. This is an extreme protection method, as a bank can operate for some time with failed elements. It might save the utility from having to replace a couple of faulty units, but at the same time the capacitor bank cannot operate. The utility could be losing money since without the capacitor bank losses would increase. This topic needs to be studied further to determine when it is more economical to take a bank out of service, rather then letting it operate with failed capacitor units.

   A more pragmatic approach is to use the ideas and results of this project to consider improvements to existing protection methods. The number of element failures occurring can be monitored, and the bank taken out of service only when it is operating outside the recommended limits. Once the bank is out of service, the faulty capacitor units can be replaced efficiently, as their locations would be known. This will save the utility in time spent servicing the shunt capacitor bank, and thus the maintenance expenses as well.

   Having more than one unit per section, however, could be detrimental if a capacitor unit was to rupture or go open circuit from a serious fault (even though capacitor elements are expected to short during failure). This is stated because if an open circuit did occur, any units in parallel would then experience an extra load of current, and thus the chances of extensive failures are increased. Thus the reliability of short circuits occurring is paramount to this arrangement's effectiveness.

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Appendices

A.1 Features of Computer Model

When deciding what programming language was to be used for this shunt capacitor bank application, the main concern was the level of coding complexity for mathematical formulae. Considering Matlab's efficient handling of these and the fact that some knowledge of programming in this language had already been acquired, Matlab seemed a more than efficient option. What follows is an explanation of the model program, which also serves as a user-guide for future use.

The program begins by requesting the operation ratings and capacitor arrangements of the capacitor bank. Any bank configuration can be entered as input. The program does not, however, take into account whether fuses are used or not. As the output does not supply voltages or currents of specific elements within capacitor units, this program would be more suitably applied to fuseless or externally fused capacitor banks. Figure A1 shows the first dialog box, Input Data for Shunt Capacitor Bank, after the program is run.

A number of input requests exist in this dialog box. An explanation of each of these requests is given, except for System Frequency (Hz).

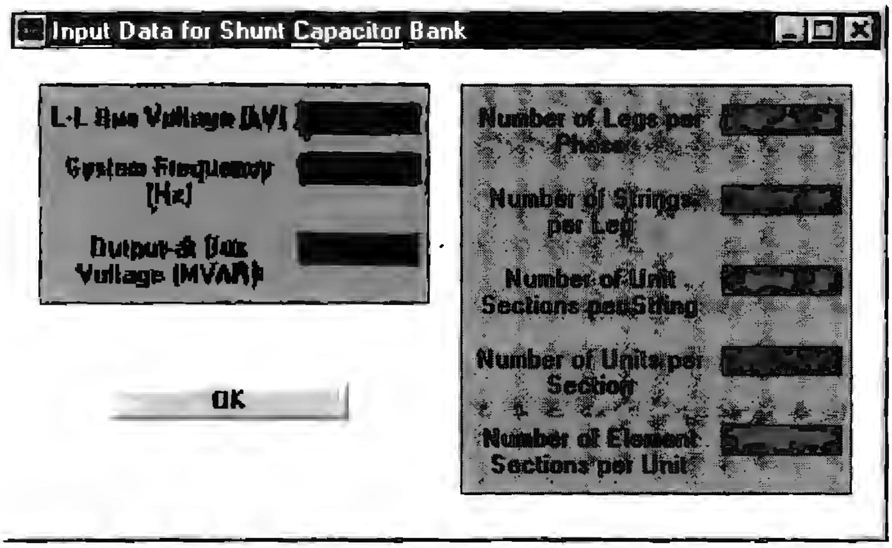


Figure A1. Input dialog box for capacitor bank properties

L-L Bus Voltage (kV): the line-to-line shunt capacitor bank bus voltage is expected (this is the voltage at which the capacitor bank will operate not the voltage at which it is rated).

Output at Bus Voltage (MVAR): the reactive power output of the capacitor bank, operating at the voltage entered above.

The remaining inputs are for capacitor arrangements.

Number of Legs per Phase: most capacitor banks have single- or double- star arrangements, and thus there will be one or two legs per phase respectively. Figure A2 demonstrates a typical double-star arrangement.

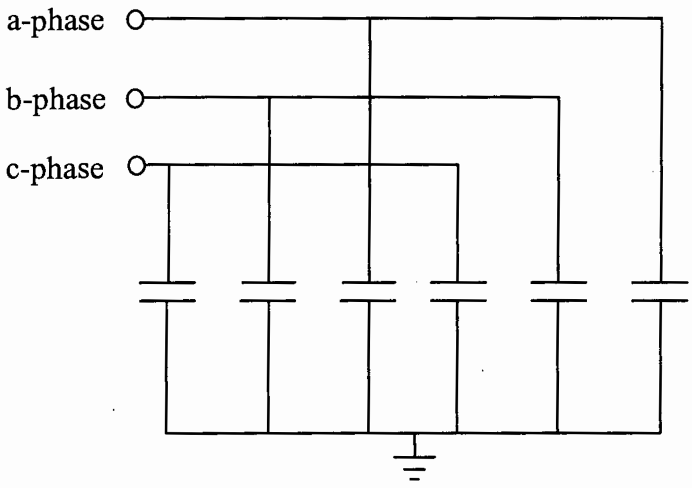


Figure A2. Double-star shunt capacitor bank

Number of Strings per Leg: each leg consists of a number of parallel strings, where each string is made up of unit sections.

Number of Unit Sections per String/ Number of Units per Section: Figure A3 portrays an example of a fuseless capacitor bank where each unit section consists of only one capacitor unit, and thus the string is just a number of units in series. The unit sections can, however, consist of a group of units in parallel.

Number of Element Sections per Unit: depending on the type of unit used, each unit is made up of element sections in series, where each section is a group of elements in parallel.

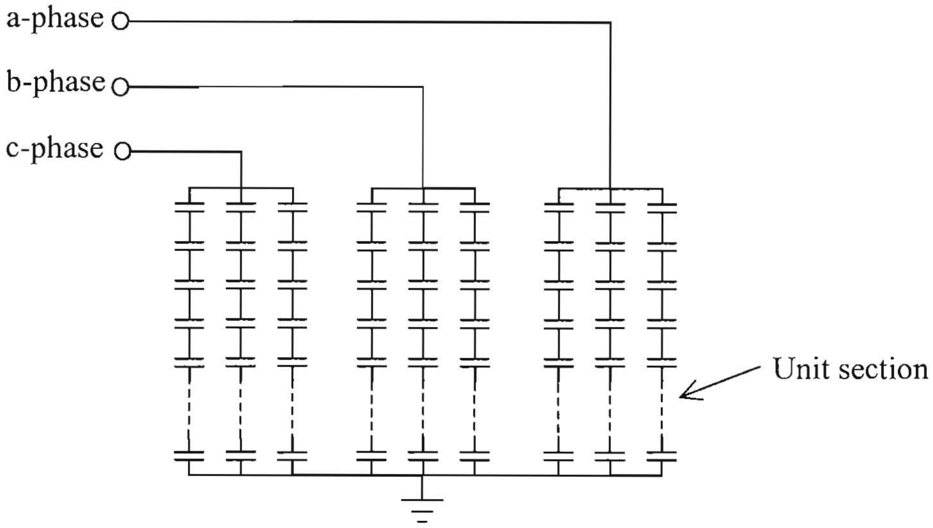
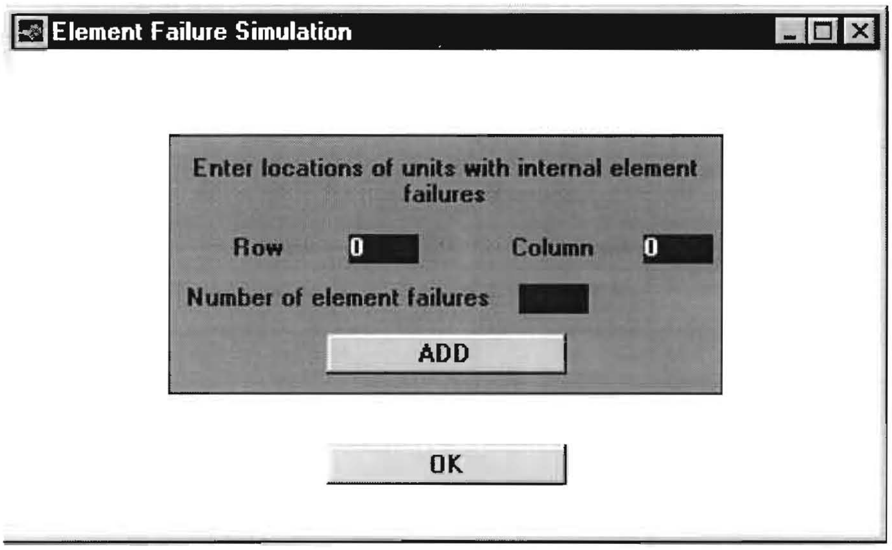


Figure A3. An arrangement with 1 unit per unit section

Using the above information, the program now knows the exact configuration of the bank and the voltage, current and power distributions. Once this information has been entered and the OK pushbutton has been clicked on, a second dialog box, Element Failure Simulation, appears (as shown in Figure A4).


Element Failure Simulation

Enter locations of units with internal element failures

Row 0 Column 0

Number of element failures

Figure A4. Input dialog box for selection of capacitor units with failed elements

The objective of this dialog box is for the user to enter a link to a specific capacitor unit in which an element failure will be simulated. A simple matrix system is used to provide the link to the unit. For example, a double-star bank with 3 strings per leg and

12 units per string would have a total of 18 strings over three phases. Thus a matrix with 12 rows and 18 columns is set up. Each column represents one of the strings while the rows represent each of the 12 units in each string. By entering a row and column number as input, the program can determine in which unit the user wants an element failure to be simulated.

In addition to the unit's location, the dialog box also requests the user to enter how many element failures are to be simulated in this unit. It must be noted that the failure of an element will result in the short-circuiting of an entire element section. So the number of element failures entered by the user is limited by what was entered in the first dialog box as Number of Element Sections per Unit. Once the location of the unit and the number of element failures have been selected, the user must click on the ADD pushbutton if further unit locations need to be selected, or on the OK pushbutton to allow the program to continue.

Using a matrix as explained above, the program keeps track of which units have failed elements, or more accurately (with respect to the simulation) which units have short-circuited element sections. At first, each unit represented in the matrix is assigned the value of Number of Element Sections per Unit from the first dialog box. As the user enters which units have element failures, the values in the matrix are adjusted accordingly. For example, if each capacitor unit consisted of 4 element sections and the user entered information as shown in Figure A5, the resulting matrix would be as indicated in Figure A6. Here an element failure is simulated in a unit in the third string of the first leg of the a-phase.

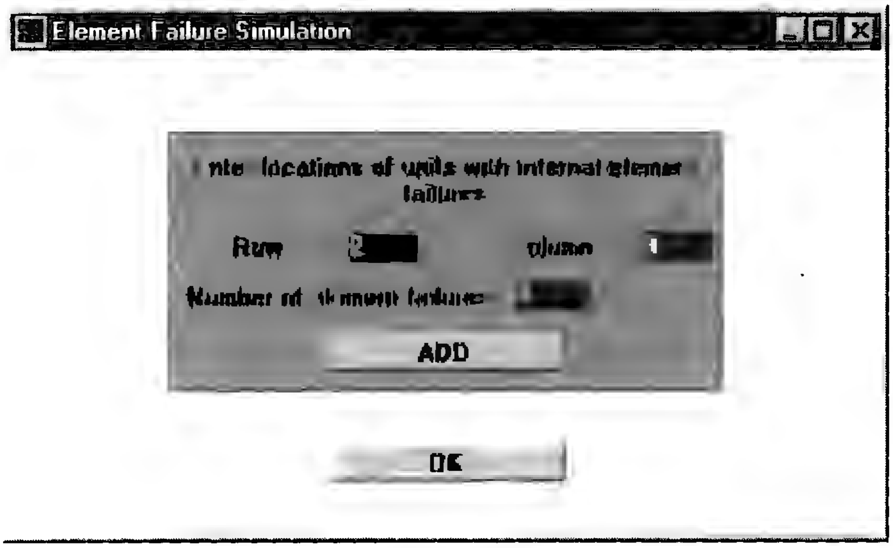


Figure A5. User input for a single element failure

```
Columns 1 through 18
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  3  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
```

Figure A6. Keeping track of element failures in capacitor units

Once the user has entered all the locations of units with failed elements the program will then calculate, using the matrix:

- The voltage across each unit.
- The current through each unit.
- The reactive power output of each unit.
- The current of each phase.
- The reactive power output of each string.
- The neutral current to earth.
- The total reactive power output of the capacitor bank.

The program does not automatically output these values. Rather, the user can specify which results are output through the Matlab Command Window (see Appendix A.2 for these specific commands).

A.2 Commands for Computer Model

The executable file that runs the program to simulate element failures in a shunt capacitor bank is **shunt1.m**, while the following commands can be used to acquire specific output values:

Command	**Description**
vumag	Magnitude of voltage across each unit
vuangle	Angle of voltage across each unit
Iumag	Magnitude of current through each unit
Iuangle	Angle of current through each unit
varumag	Magnitude of reactive power output of each unit
varuangle	Angle of reactive power output of each unit
Inph	Magnitude and angle of neutral current to earth
Iaph	Magnitude and angle of a-phase current
Ibph	Magnitude and angle of b-phase current
Icph	Magnitude and angle of c-phase current
varstr	Magnitude of reactive power output of each string
stotal	Magnitude of total reactive power output of bank

Table A1. Description of Matlab program commands

A.3 Source Code for Matlab Program

shunt1

```
figure('menubar','none','position', [100 180 433 241],... % set-up input data dialog box
    'Name', 'Input Data for Shunt Capacitor Bank',...
    'color','w','numbertitle', 'off');
fig=gcf;
sys_frame = uicontrol(fig,...
       'style','frame',...
       'position', [14 115 195 110]);
vbus_txt = uicontrol(fig,...
      'style', 'text',...
      'position', [19 200 120 15],...
      'string', 'L-L Bus Voltage (kV)');
vbus_inp = uicontrol(fig,...
      'style', 'edit',...
      'position', [144 200 60 15],...
      'backgroundcolor','b','foregroundcolor','w',...
      'callback', [...
       'vbus3=str2num(get(vbus_inp,"string"));',... % input 3-phase bus voltage
       'if vbus3 <=0,',...
         'disp("ERROR - Value must be positive"),',...
       'end']);
freq_txt = uicontrol(fig,...
      'style', 'text',...
      'position', [19 160 120 30],...
      'string', 'System Frequency (Hz)');
freq_inp = uicontrol(fig,...
      'style', 'edit',...
      'position', [144 175 60 15],...
      'backgroundcolor','b','foregroundcolor','w',...
      'callback', [...
       'freq=str2num(get(freq_inp,"string"));',... % input system frequency
       'if freq <=0,',...
         'disp("ERROR - Value must be positive"),',...
       'end']);
varbank_txt = uicontrol(fig,...
      'style', 'text',...
      'position', [19 120 120 30],...
      'string', 'Output at Bus Voltage (MVAR)');
```

```
varbank_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [144 135 60 15],...
        'backgroundcolor','b','foregroundcolor','w',...
        'callback', [...
          'varbank=str2num(get(varbank_inp,"string"));',... % input reactive output of
          'if varbank <=0,',...                              % total bank
             'disp("ERROR - Value must be positive"),',...
          'end']);
config_frame = uicontrol(fig,...
        'style','frame',...
        'position', [224 20 195 205]);
legsperph_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [229 185 120 30],...
        'string', 'Number of Legs per Phase');
legsperph_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [354 200 60 15],...
        'backgroundcolor','r','foregroundcolor','w',...
        'callback', [...
          'legsperph=str2num(get(legsperph_inp,"string"));',... % input no of legs per
          'if legsperph <=0,',...                                % phase
             'disp("ERROR - Value must be positive"),',...
          'end']);
strperleg_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [229 145 120 30],...
        'string', 'Number of Strings per Leg');
strperleg_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [354 160 60 15],...
        'backgroundcolor','r','foregroundcolor','w',...
        'callback', [...
          'strperleg=str2num(get(strperleg_inp,"string"));',... % input no of strings per
leg
          'if strperleg <=0,',...
             'disp("ERROR - Value must be positive"),',...
          'end']);
sectperstr_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [229 105 120 30],...
```

```
        'string', 'Number of Unit Sections per String');
sectperstr_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [354 120 60 15],...
        'backgroundcolor','r','foregroundcolor','w',...
        'callback', [...
          'sectperstr=str2num(get(sectperstr_inp,"string"));',... % input no of sections
per
          'if strperleg <=0,',...                                 % string
             'disp("ERROR - Value must be positive"),',...
          'end']);
unitpersect_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [229 65 120 30],...
        'string', 'Number of Units per Section');
unitpersect_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [354 80 60 15],...
        'backgroundcolor','r','foregroundcolor','w',...
        'callback', [...
          'unitpersect=str2num(get(unitpersect_inp,"string"));',... % input no of units
          'if unitpersect <=0,',...                                 % per string
             'disp("ERROR - Value must be positive"),',...
          'end']);
unitintsect_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [229 25 120 30],...
        'string', 'Number of Element Sections per Unit');
unitintsect_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [354 40 60 15],...
        'backgroundcolor','r','foregroundcolor','w',...
        'callback', [...
          'unitintsect=str2num(get(unitintsect_inp,"string"));',... % input no of internal
          'if unitintsect <=0,',...                                 % sections per unit
             'disp("ERROR - Value must be positive"),',...
          'end']);
OKinput = uicontrol(fig,...
        'style','push',...
        'string', 'OK',...
        'position', [49 57 120 20],...
        'callback', ['delete(fig);','count=1;','colfail=0;',...
```

```
                    'rowfail=0;','shunt2,']);
```

The following functions, **shunt2** and **shunt3**, are called from within **shunt1**:

shunt2

```
figure('menubar','none','position', [100 180 433 241],... % set-up dialog box for
location
   'Name', 'Element Failure Simulation',...              % of element failure
   'color','w','numbertitle', 'off');
fig=gcf;
position_frame = uicontrol(fig,...
        'style','frame',...
        'position', [78 70 277 130]);
heading_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [83 160 267 30],...
        'string', 'Enter locations of units with internal element failures');
rowfail_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [83 135 80 15],...
        'string', 'Row');
rowfail_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [168 135 35 15],...
        'backgroundcolor','b','foregroundcolor','w',...
        'callback', [...
         'rowfail(count) =str2num(get(rowfail_inp,''string''));']); % input row no of unit
colfail_txt = uicontrol(fig,...
        'style', 'text',...
        'position', [230 135 80 15],...
        'string', 'Column');
colfail_inp = uicontrol(fig,...
        'style', 'edit',...
        'position', [315 135 35 15],...
        'backgroundcolor','b','foregroundcolor','w',...
        'callback', [...
```

```
            'colfail(count) =str2num(get(colfail_inp,"string"));']); % input column no of
unit
numfail_txt = uicontrol(fig,...
          'style','text',...
          'position', [83 110 160 15],...
          'string', 'Number of element failures');
numfail_inp = uicontrol(fig,...
          'style','edit',...
          'position', [253 110 35 15],...
          'backgroundcolor','b','foregroundcolor','w',...
          'callback', [...
            'numfail(count) =str2num(get(numfail_inp,"string"));']); % input no of
element
addinput = uicontrol(fig,...                                 % failures
          'style','push',...
          'string', 'ADD',...
          'position', [157 80 120 20],...
          'callback', ['delete(fig);','count=count+1;','shunt2,']); % recall shunt2 if ADD
OKinput2 = uicontrol(fig,...                         % is selected
          'style','push',...
          'string', 'OK',...
          'position', [157 25 120 20],...
          'callback', ['delete(fig);','shunt3,']);  % otherwise call function shunt3
```

shunt3

```
vbus = vbus3*1e3/sqrt(3);  % calculate bus voltage, unit reactive power, unit voltage
conv = inv(2*pi*freq);        % unit impedance
varunit = varbank*1e6/(3*legsperph*strperleg*sectperstr*unitpersect);
vunit = vbus/sectperstr;
strperph=legsperph*strperleg;
xrow=(vunit^2/varunit)/unitintsect;
u=unitintsect*ones(sectperstr,(legsperph*strperleg*unitpersect*3));
matrixsize=size(u);       % initialise matrix to keep track of which unit has an
vu=zeros(matrixsize);  % element failure
xu=zeros(matrixsize);
xusection=zeros(matrixsize(1),matrixsize(2)/unitpersect);
shortedu=zeros(matrixsize(1),matrixsize(2)/unitpersect);
row=matrixsize(1);
col=matrixsize(2);
```

```
for l=1:count
  if rowfail(1)~=0&colfail(1)~=0 % adjust matrix according to element failures
    u(rowfail(i),colfail(i))= u(rowfail(i),colfail(i))-numfail(i);
  end
end

for l=1:col
  for m=1:row
    xu(m,l)=xrow*u(m,l)*(-j); % calculate each unit's impedance
  end
end

for l=1:(col/unitpersect)
  for m=1:row
    check=0;  % calculate impedance of each unit section
    for n=(unitpersect*l-(unitpersect-1)):(unitpersect*l)
      if u(m,n)~=0
        xusection(m,l)=xusection(m,l)+inv(xu(m,n));
      else check=1;
      end
    end
    if check==1
      xusection(m,l)=0;
    else xusection(m,l)=inv(xusection(m,l));
    end
  end
end

xstring=sum(xusection); % calculate string impedances
Ia=0;
Ib=0;
Ic=0;
for l=1:strperph % calculate phase currents
  istr(l)=vbus/xstring(l);
  Ia=Ia+istr(l);
end

for l=(strperph+1):(2*strperph)
  istr(l)=(vbus*(cos(-120*pi/180)+j*sin(-120*pi/180)))/xstring(l);
  Ib=Ib+istr(l);
end
```

```
for l=(2*strperph+1):(3*strperph)
   istr(l)=(vbus*(cos(-240*pi/180)+j*sin(-240*pi/180)))/xstring(l);
   Ic=Ic+istr(l);
end

In=Ia+Ib+Ic;
Inph=[abs(In),angle(In)*180/pi];
Iaph=[abs(Ia),angle(Ia)*180/pi];
Ibph=[abs(Ib),angle(Ib)*180/pi];
Icph=[abs(Ic),angle(Ic)*180/pi];

for l=1:(col/unitpersect) % calculate voltage across each unit section
   for m=1:row
      vusection(m,l)=istr(l)*xusection(m,l);
   end
end

for l=1:(col/unitpersect)
   for m=1:row
      for n=(unitpersect*l-(unitpersect-1)):(unitpersect*l)
         if xusection(m,l)==0&xu(m,n)==0
           shortedu(m,l)=shortedu(m,l)+1;
         end
      end
   end
end

for l=1:(col/unitpersect)  % calculate unit currents and reactive power outputs
   for m=1:row
      check=0;
      for n=(unitpersect*l-(unitpersect-1)):(unitpersect*l)
         if xusection(m,l)==0&xu(m,n)==0
           Iu(m,n)=istr(l)/shortedu(m,l);
           varu(m,n)=Iu(m,n)^2*(xu(m,n));
         elseif xusection(m,l)==0&xu(m,n)~=0
              Iu(m,n)=0;
              varu(m,n)=Iu(m,n)^2*(xu(m,n));
         else Iu(m,n)=vusection(m,l)/(xu(m,n));
             varu(m,n)=Iu(m,n)^2*(xu(m,n));
         end
       end
    end
```

```
end

for l=1:col
   for m=1:row
      Iumag(m,l)=abs(Iu(m,l));
      Iuangle(m,l)=angle(Iu(m,l))*180/pi;
      varumag(m,l)=abs(varu(m,l));
      varuangle(m,l)=angle(varu(m,l))*180/pi;
      vu(m,l)=Iu(m,l)*xu(m,l);
      vumag(m,l)=abs(vu(m,l));
      vuangle(m,l)=angle(vu(m,l))*180/pi;
   end
end

varstr=(abs(istr).^2).*(xstring*j); % calculate reactive power output of each string
stotal=sum(varstr); % calculate total reactive power output of bank
```