Chapter 11

Differences in performance between SF_6 and vacuum circuit-breakers at distribution voltage levels

S.M. Ghufran Ali

11.1 Introduction

This chapter reviews the circuit-breaker designs which are type tested to IEC 60298 and IEC 62271–100 for use on distribution voltages up to 52 kV.

The design and service experience of different types of commercially available circuit-breakers are considered. The chapter also discusses some special switching duties and focuses on aspects which are necessary for the selection of circuit-breakers for various duties: for example, for switching capacitor banks, capacitive and inductive currents, generators, reactors and synchronised switching of transformers with reactors on the secondary side.

11.2 Circuit-breaker

A circuit-breaker is an electro-mechanical device which initiates (makes) or interrupts (breaks) the flow of current in a circuit and is used for controlling and protecting the distribution system. It has to be reliable as it may remain dormant in a closed position for a long period and yet, when it receives a trip command signal, it must operate without any hesitation. Depending on its rating, the circuit-breaker has to interrupt currents from as little as 10 A up to its full short-circuit rating which may be 40/50 kA.

From the turn of the century to the early 1970s most of the AC circuit-breakers used oil (bulk or small oil volume – SOV), airbreak and air blast interrupting techniques. These are now obsolete.

Interrupting devices utilising semiconductor technology are being developed and are not yet available commercially at a competitive price.

Since the mid-1960s vacuum and sulphur hexafluoride (SF_6) circuit-breakers have been available.

11.3 Vacuum circuit-breaker

A vacuum interrupter is a high technology, sealed for life, ceramic bottle. It has either a vapour condensation shield or a magnetic coil. It has butt contacts of disc or cup shape designs, a contact gap of about 8 to 10 mm and a vacuum of 10^{-6} to 10^{-8} torr.

Several contact materials have been tried since 1960. The semirefractory material, chromium (Cr), together with good conductor material, copper (Cu), has emerged as the best for circuit-breaker application.

The contact shape and material have been developed to reduce:

- contact bounce and contact welding
- contact wear
- chopping current.

The development of vacuum interrupters is a highly involved and extremely costly process. However, once the vacuum bottle is manufactured, it can be mounted in a circuit-breaker, in any position.

In general, vacuum circuit-breakers:

- are safe and reliable
- are compact
- have low contact wear
- require low maintenance.

Vacuum bottles rated at 50 kA, 4000 A are now available from several manufacturers. This relatively high rating has been made possible because of the inherent efficiency of vacuum circuit-breaker technology. The dielectric withstand level of a 1 cm gap in a vacuum of 10^{-6} mm of mercury is about 200 kV but increases only very slightly with increase in contact gap. Thus it limits the withstand voltage which can be applied to each break in vacuum.

The drawback facing switchgear designers using vacuum bottles is that they cannot change many design parameters to improve the circuit-breaker ratings. They have to depend on a limited number of vacuum interrupter manufacturers for a bottle to suit the required duty.

Vacuum circuit-breaker designs are now available for ratings of 50 kA–36 kV and 4000 A (Figure 11.1). In spite of considerable research and development, coupled with design improvements over the last two

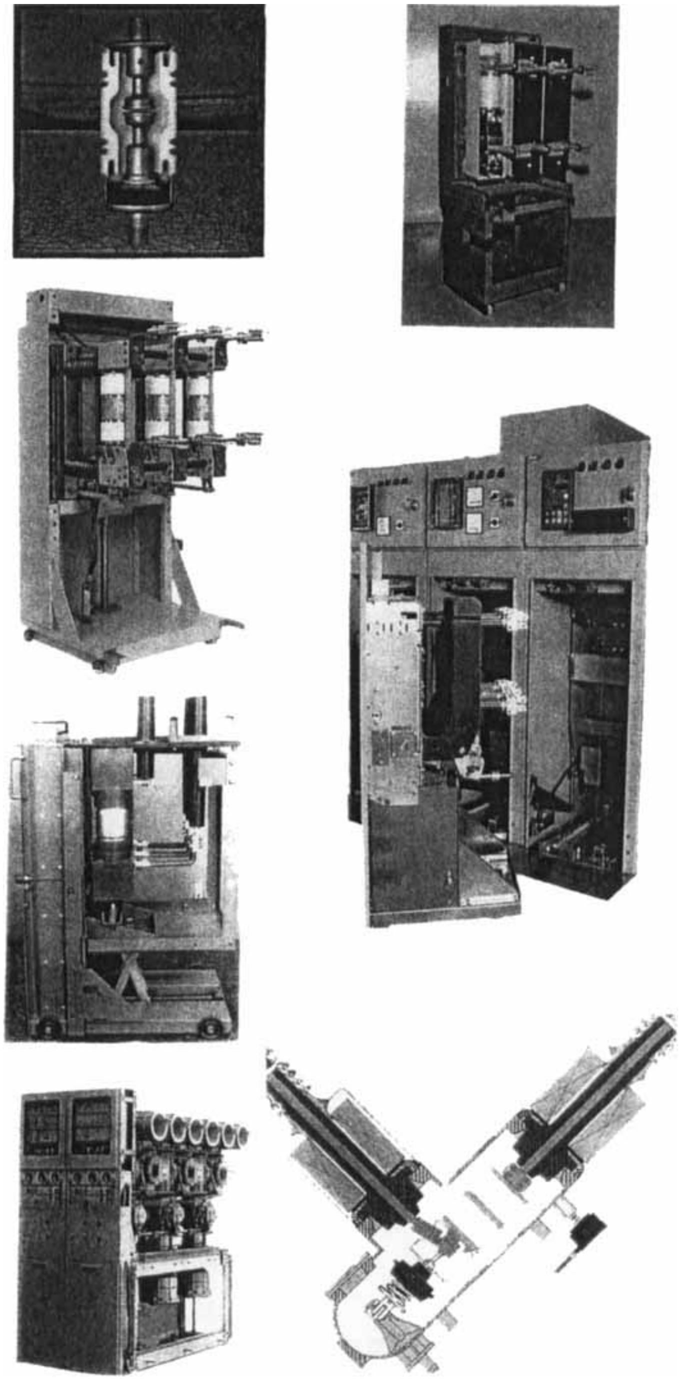


Figure 11.1 *Vacuum circuit-breaker*
Air/SF_6 gas insulated

decades, it is acknowledged that vacuum circuit-breakers are prone to reignitions and current chopping because of their excellent insulating and interrupting characteristics. The efficiency of the vacuum interrupting device therefore sometimes works against it and causes premature interruption of small inductive currents. Under these circumstances excessive overvoltages are produced, the magnitude of which depends on the high surge impedance of the switched circuit. Therefore care should be taken when selecting a vacuum circuit-breaker for small inductive and reactor switching duties. Metal oxide surge arresters have to be used in this application to provide additional protection for connected equipment.

Some manufacturers produce vacuum bottles up to 145 kV, but these are very expensive and are only used on circuit-breakers for special duties.

For reasons of cost, almost all the switchgear manufacturers in the world limit the use of the vacuum bottles on their general purpose distribution circuit-breakers up to the maximum voltage of 36 kV.

11.4 SF_6 gas circuit-breakers

SF_6 is a gas with unique features which are particularly suited to switchgear applications. It has been successfully employed in both the HV and EHV (up to 1000 kV) circuit-breakers for the last 25 years. There is a consensus of opinion that SF_6 gas has still much to offer, and therefore research and development continue. There is no single superior gas available at present to replace SF_6.

It is worth noting that some current interrupting designs have combined the excellent dielectric properties of SF_6 gas with vacuum technology. One has produced a compact gas insulated vacuum circuit-breaker design, based on their 170 kV GIS/SF_6 circuit-breaker. The 36 kV panel is a single-pole, fixed-mounted metal-enclosed construction in which vacuum bottles are housed in SF_6 gas to minimise the clearances to earth. The current is interrupted by the vacuum bottles and the resulting panel has a width of only 600 mm.

The knowledge and experience of SF_6 gained over the last three decades has been skilfully and successfully employed in the development of three efficient designs for distribution circuit-breakers. These are based on single pressure puffer, rotating-arc and auto-expansion techniques.

11.5 Puffer circuit-breaker

The principle of a single pressure puffer-type interrupter is explained by the operation of a universally known device, a bicycle pump. In this type of interrupter, SF_6 gas in the chamber is compressed by the movement of the cylinder against the stationary piston mimicking the operation of the bicycle pump. The high pressure gas is then directed across the arc in the down-stream region through the nozzle to complete the arc-extinguishing process (Figure 11.2).

During an opening operation, the gas pressure-rise generated by compression and heating of SF_6 gas by the arc produces retarding forces, acting on the piston surface. High energy mechanisms are required to overcome these forces and to provide consistent opening characteristics for all short-circuit duties. Puffer circuit-breakers are now well established on distribution systems for ratings up to 50 kA–36 kV and 4000 A. The performance of the present day puffer interrupters has now been considerably improved and some designs operate at SF_6 gas pressure only slightly above atmospheric pressure. This relatively low pressure not only assists to reduce the earlier problem of gas-leak through the seals but also reduces the energy requirement for the operating mechanism and therefore has a minimising effect on the cost.

There are a few 12 kV puffer-type circuit-breaker designs operating at 0.6 bar(g) which are capable of interrupting the rated short-circuit-breaking current at 0 bar(g).

Some puffer interrupter designs produce excessive switching overvoltages. For improved interrupter designs, the overvoltages for all switching duties are ≤ 2.5 pu. Therefore care should be taken when selecting a circuit-breaker for small inductive and reactor switching duties in service.

Switchgear manufacturers are constantly seeking to improve their circuit-breaker designs to achieve:

- cost and space reductions
- improved arc interruption technique
- increased fault current ratings
- longer contact life
- improved inductive and reactor switching performance producing very low overvoltages
- low energy and reliable circuit-breaker operating mechanisms
- ultimately a maintenance-free and sealed-for-life circuit-breaker.

As a result of this effort, the rotating-arc and auto-expansion designs have evolved.

11.6 Rotating-arc circuit-breaker

The principle of arc rotation for current interruption is not new and is not confined to SF_6 circuit-breakers. Arc rotation is also used to reduce contact erosion on some vacuum and SF_6 puffer circuit-breaker designs. Switchgear designers use different rotating-arc techniques, one of which utilises an electromagnetic coil. Unlike SF_6 puffer-type circuit-breakers, where the SF_6 gas is blown across in the arc, the arc in the rotating-arc device is rotated at a very high speed by an electromagnetic field. The field is produced by the coil through which the current to be interrupted flows during the period between contact separation and arc extinction (Figure 11.3).

This technique has been used for SF_6 circuit-breaker design, which has ratings up to 40 kA at 12 kV (Figure 11.4). The device requires a low energy mechanism and produces overvoltages less than 2 pu for all known switching circuits.

The sealed-for-life, maintenance-free, low operating energy, SF_6 and rotating arc circuit-breakers are now commercially available.

11.7 Auto-expansion circuit-breaker

Auto-expansion is a relatively new interruption technique to be used on distribution circuit-breakers and owes much to the development of third-generation puffer-type interrupters for 170 kV–40 kA circuit-breakers.

This technique essentially uses the power dissipated by the arc to increase pressure within the expansion chamber. The overpressure generated has the double effect of causing strong turbulence in the gas and of forcing the gas out of the chamber across the arc as soon as the nozzle starts to open, thus extinguishing the arc (Figure 11.5).

The auto-expansion type of circuit-breaker uses a low energy operating mechanism and produces switching overvoltages up to 2 pu. This technique is used to obtain up to 50 kA rating at 12 kV.

Another design combines the rotating-arc and auto-expansion techniques to produce circuit-breaker design for ratings up to 72.5 kV (Figure 11.6).

11.8 Operating mechanism

The trend towards increased remote control of distribution network has led to the requirement of either solenoid or motor charged spring operated mechanisms, suitable for multishot auto-reclose duty. Low energy, simple, motor-charged spring mechanisms avoid the extra cost of providing and maintaining battery/rectifier supplies for solenoid operation type mechanism.

Although IEC 62271-100 requires only 2000 satisfactory operations to prove its performance, the present tendency is to carry out extended 10 000 trouble-free operations tests to demonstrate compatibility of these mechanisms with the Vacuum and SF_6 interrupters which are virtually maintenance free.

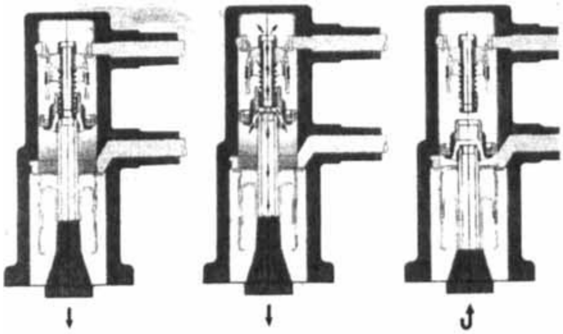
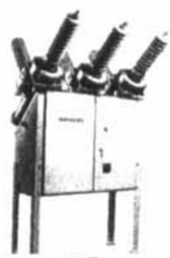


Figure 11.2 SF_6 puffer type circuit-breaker



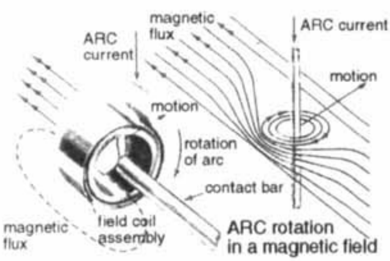
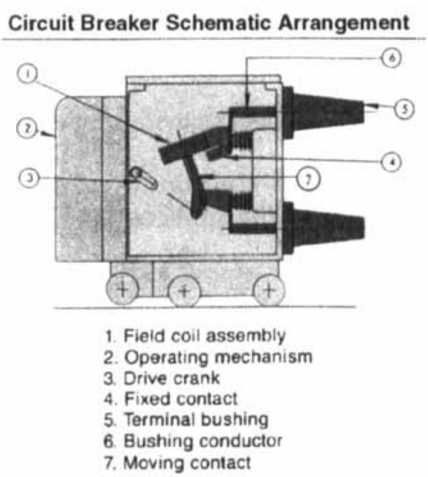


Figure 11.3 SF_6 rotating-arc principle



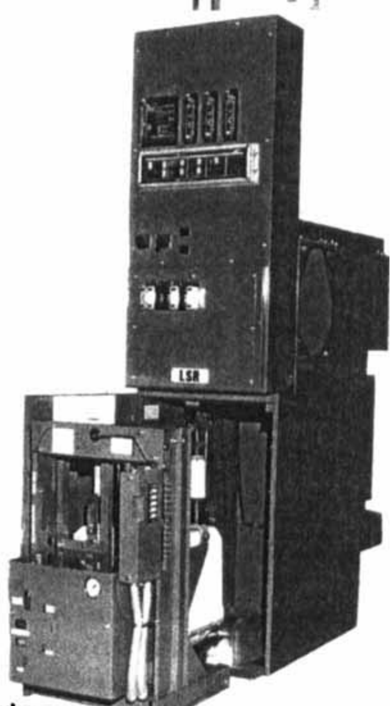


Figure 11.4 SF_6 rotating-arc circuit-breaker

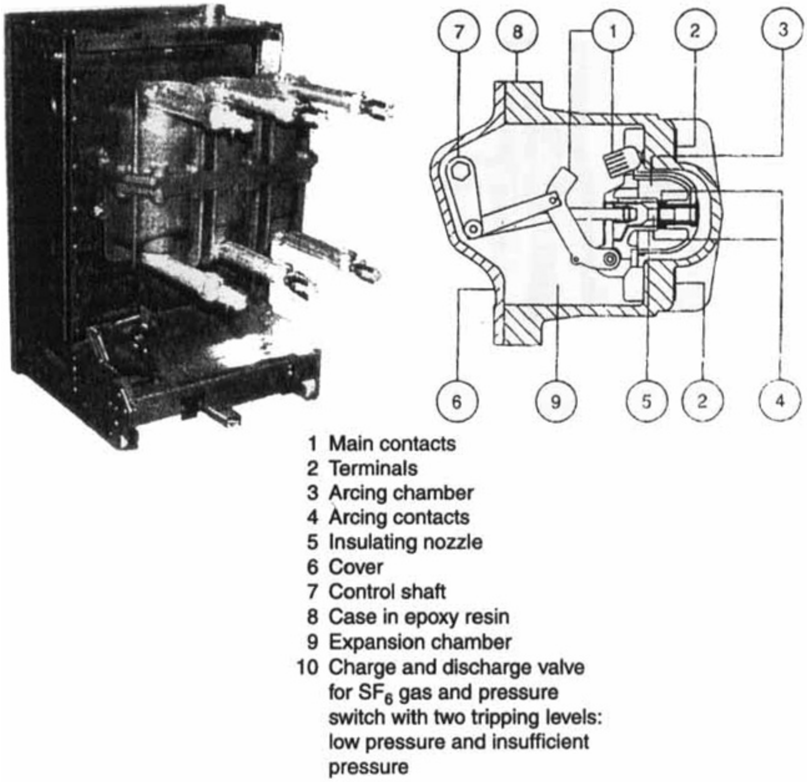


Figure 11.5 *SF_6 auto-expansion circuit-breaker*

11.9 Choice of correct circuit-breaker for special switching duties

System designers and users will need to give careful consideration to the choice and type of circuit-breaker for some of the applications identified below.

11.10 Capacitive and inductive current switching

The phenomena of current chopping and reignition and associated high frequency oscillatory overvoltages are well understood. It has also been established that the high frequency oscillations are governed by the electrical parameters of the circuit concerned, circuit configuration and interrupter design.

Sometimes higher frequency voltage oscillations are caused by

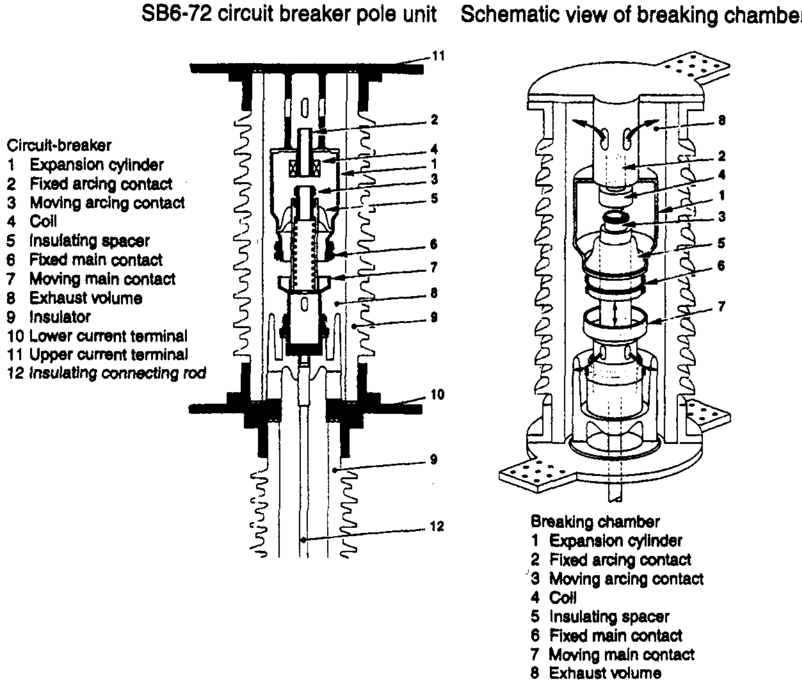


Figure 11.6 SF_6 rotating-arc/auto-expansion combined circuit-breaker

premature interruption of low capacitive and inductive currents. This premature interruption produces high frequency reignitions and overvoltages which can give rise to dielectric failures and extensive damage to system equipment.

Historical note: As a result of some circuit-breakers, after having been satisfactorily tested to the existing IEC 62271–100, subsequently failing in service, an IEC Working Group was established to investigate the problem of higher frequency overvoltages caused by circuit-breaker operation and submit their recommendations. The result of this work was the issue (in 1994) of IEC 61233 to cover inductive current switching. IEC 62271–100 covers the capacitive current switching requirements was also circulated for comments. This latter draft document is still under consideration. The final recommendations have been incorporated in IEC 62271–100.

In addition to testing the circuit-breakers to the latest specifications, where possible damping circuits and metal-oxide surge arresters should be used to ensure safe operation.

11.11 Circuit-breakers for generator circuit switching

Since there is no IEC standard for generator switching duties, the use of distribution voltage circuit-breakers for generator switching needs careful examination.

As may be expected, a circuit-breaker used for switching distribution circuits may be subject to prospective fault duties in service which are different from the prospective fault duties of a generator circuit-breaker. The difference in fault duty mainly results from the difference in X/R ratio between the distribution circuits and generator circuits as explained below.

Before choosing a circuit-breaker suitable for generator circuits the following two main requirements will have to be considered.

11.11.1 DC offset

Generator circuits (i.e. the generator and generator transformer combination) usually have a higher X/R ratio (40 to 70) than the distribution circuit ($X/R = 14$). This difference means that the DC offset of the fault current waveform in the generator circuit will decay much more slowly than the DC offset in a distribution circuit. A current zero in the generator circuit may not be reached until after full contact travel is achieved. Circuit-breaker designs tested to IEC 62271–100 may have difficulty in clearing fault current under these conditions. A key factor in switching generator circuits is the arc resistance which lowers the X/R ratio and so reduces the DC offset. Some types of circuit-breakers have inherently higher arc resistances than others, e.g. the now obsolete air-break and the present SF_6 rotating-arc and self-blast circuit-breakers have higher arc resistance than vacuum circuit-breakers. The high resistance of the arc column modifies the time constant of the circuit and helps to quench the arc in a relatively short duration.

In the absence of any IEC standard for generator circuit-breakers, all circuit-breakers offered for generator switching duty should be tested to IEEE C37–013:1989, which provides guidelines for asymmetrical interrupting capability found when switching generator circuits.

11.11.2 Current chopping and reignition

The amplitudes of overvoltages resulting from current chopping and reignition and their rates of change submit the windings of the inductive equipment including generators to different types of risks. The amplitude of the overvoltage stresses mainly the insulation to ground, whereas the rate of change of overvoltage stresses in particular the inter-turn insulation. It is therefore essential to choose the correct circuit-breaker for switching the inductive currents of the generator circuits.

Circuit-breakers which are prone to current chopping and reignition and produce excessive overvoltages may not be suitable for generator switching applications.

11.12 Synchronised switching

Circuit-breakers with different pole opening and closing points are offered for synchronised switching of capacitor banks or transformers loaded with reactors. The circuit-breakers offered for these duties have intentional pole scatter on the three poles and are operated by one mechanism. For suppressing any switching surges, controlled point-on-wave switching is carried out by an electronic synchronising device.

The application of these modified circuit-breakers is either for some special switching duties or for both the switching and the fault interruption duties as a general purpose circuit-breaker.

The novel nature of pole scattering on a circuit-breaker and the use of synchronising devices appear to be attractive, but before these can be fully accepted, they should be subjected to type testing using the Direct testing method and their performance proven for all duties.

Test evidence of circuit-breakers of similar design but without any intentional pole scatter (i.e. with simultaneous contact touch and part) should not be applied to the staggered pole circuit-breaker for the following reasons:

(a) Increased pre-arcing on the pole with maximum scatter during closing operations could affect its close–open performance.
(b) Increased arcing during every open operation on the pole with maximum scatter can cause heavy erosion of the contacts, resulting in increased pole scatter, and consequent effect on long term close–open and open performance.
(c) Increased, unbalanced short-circuit and mechanical stresses on the cranks and the operating rods could cause them to fail.
(d) Testing authorities agree that a test certificate is applicable only and exclusively to the particular circuit-breaker which is subjected to the test series.

If a manufacturer intends to use the maximum pole scatter allowed in Clause 5.101 of IEC 62271–100, then the type test should be performed on the most onerous condition required by IEC.

When choosing a suitable circuit-breaker for these special duties, consideration should also be given to the circuit-breaker designs, which are capable of performing all special switching duties without excessive overvoltages on the system.

11.13 Conclusions

Modern distribution voltage circuit-breakers are simple and virtually maintenance-free and some designs have now achieved ratings up to 50 kA at 12 kV.

The vacuum and SF_6 rotating-arc and self-expansion circuit designs up to 36 kV require low energy operating mechanisms and long service life. They provide reliable and low cost circuit-breakers.

Reactor switching causes difficulty for some circuit-breaker designs. These should be tested to IEC 61233 and for added safety it is recommended that metal-oxide surge arresters and R-C tuning (damping) circuits should be used with vacuum circuit-breakers. It is also essential to choose the correct circuit-breakers with overvoltage factor ≤ 2.2 pu for switching low inductive current circuits.

Distribution circuit-breakers type tested to IEC 62271–100 may not be suitable for generator switching circuits. Any breaker offered for this duty should be tested to IEEE C37–013, 1989.

Circuit-breakers which produce excessive overvoltages may not be suitable for generator circuit switching operations.

Circuit-breakers with intentional pole scatter for synchronised switching should be type tested on their own, using direct testing techniques.

11.14 Acknowledgments

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The views expressed in this chapter do not necessarily represent the views of Merz and McLellan Limited.

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