THE PROTECTION OF INDUSTRIAL CAPACITOR BANKS BY CURRENT LIMITING FUSES

By M.J. Smart and B. Wadcock

1.0 INTRODUCTION Capacitors are widely used for industrial power factor correction throughout the world, the advantages of using them being widely appreciated particularly in this era of expensive energy.

Capacitors for this application are generally protected by fuses and the application of these fuses presents problems to the fuse and capacitor designer because of the particular phenomena associated with capacitor banks. This paper describes these phenomena and how they are overcome in industrial applications at system voltages up to 11kV and bank ratings up to about 3Mvar.

2.0 GENERAL REQUIREMENTS Power Capacitor banks are always made up of series-parallel arrangement of capacitor sections, each section being protected by a fuse. The purpose of this fuse is to disconnect the faulty section in the event of its failure and permit the remaining healthy sections to continue functioning normally. The fuses selected for this duty must take account of the following requirements.

Transient Current Withstand On energisation of a capacitor a large inrush current occurs. This inrush current is limited only by the inductance and resistance in the energising circuit. For a single capacitor this source reactance is represented by the system impedance and approximately the peak inrush current can be calculated from the formula.

$$I \text{ peak inrush} = \sqrt{\frac{\text{System Fault level (kVA)}}{\text{Capacitor rating (kvar)}}} \times \text{capacitor rated peak rated current}$$

For a multi-section capacitor bank the inrush current into the first section is as for a single section bank, but for the second and subsequent sections there occurs a large interchange of energy between bank sections resulting in large inrush currents limited only by the inductance and resistance between the bank sections. This transient current is of high frequency and would normally decay within 10-20 milliseconds of inception. Any fuses incorporated in the capacitor circuit must of course withstand this current without deterioration.

Continuous Current Withstand Because the impedance of a capacitor is inversely proportional to frequency it will tend to receive a relatively high proportion of currents of frequency higher than system power frequency. This fact is particularly important in view of the present increasingly large scale use of power electronic equipment which is

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inherently harmonic generating. It is recognised in the current issues of most national specifications, BS1650 : 1971 typically laying down that the continuous current rating of a power capacitor should be 1.15 x current at rated voltage and frequency for medium voltage capacitors, this factor being increased to 1.3 x for high voltage capacitors. Because a capacitor also normally has a positive capacitance tolerance of 10%, these factors have to be increased respectively to 1.265 x and 1.43 x nominal power frequency current rating. This continuous overcurrent withstand must be incorporated into all associated capacitor equipment, in particular the capacitor fuses.

Discharge Withstand When a number of individually fused capacitor sections are connected in parallel, then on failure of one of these sections, the power frequency fusing current in the fuse of the faulty section will be that which results from short-circuiting the complete group of capacitors. In addition if, as is most likely, the short circuit occurs when the group of capacitors is charged to some voltage greater than zero the fuse of the faulty section must clear successfully against the resulting high frequency discharge current, and the fuse of each of the healthy sections must withstand the contribution to this discharge current from its own section.

3.0 FUSE TYPES As stated in Section 2.0 above capacitor banks are made up of series-parallel arrangement of capacitor sections, each section protected by a fuse. In practice capacitors are manufactured in standard unit sizes, these units being connected together to form a bank. Each unit in turn is made up internally of a number of elements or windings. Element voltages at present can be up to about 1.5 to 2kV so that units of voltage rating below this normally have all their elements connected in parallel. These units are generally protected by internal fuses, one fuse being connected in series with each element. Because of the comparatively large number of capacitor elements connected in parallel in this arrangement, it is relatively simple and economical to design an internal fuse to fulfill all the requirements of Section 2.0, above and in fact internal element fuses are usually used at these voltages. These are of course incorporated inside the units at the time of manufacture. Internal fuses can only disconnect dielectric failures, and for other faults, such as failure of the major insulation between the element pack and the unit case, they are not effective. External fuses are therefore normally necessary in addition to the internal fuses, and these are best incorporated in the incoming connections to the complete bank as described in Section 4.0 below.

For power factor correction capacitor banks of voltage rating above about 1.5kV to 2kV it is necessary to use capacitor units with two or more windings in series within the unit. Because of this series connection of elements there are correspondingly less elements connected in parallel in each element group within the unit and the design of an element fuse complying with the requirements of Section 2 is more difficult, unless an uneconomically large total number of windings per unit are used. In addition the internal fuse is not effective in disconnecting major insulation faults as described above. It is thus preferred practice to use external fuses for these applications, one fuse for each capacitor unit. The practical choice for an external fuse is then between a non-current limiting expulsion fuse and a current limiting h.r.c. fuse. The expulsion fuse is cheaper than the h.r.c. fuse and has a time/current characteristic (time plotted vertically) which is less steep, with the result that for a given ability to withstand high frequency transients its current rating and fusing time with the power-frequency fault current are both less. However the breaking capacity of an expulsion fuse is usually less than the fault level of the system where a capacitor is installed, and therefore the use of such a fuse is limited to those cases where the capacitor units are series connected in such a way that the power frequency fault current occurring upon unit failure is limited by the series connection. Since capacitor units are available with a single phase rating of up to 15kV, series connection of capacitor units is not normally necessary at industrial voltages up to this level unless the bank is sufficiently large to justify the use of the expulsion fuse on economic grounds. Thus capacitor banks of up to 3Mvar and higher at these voltages can be made up of capacitor units connected in parallel directly across the system line connections each with current limiting h.r.c. fuses connected so as to disconnect a faulty unit from the supply upon failure. Since the unit is connected directly across the system, the prespective power-frequency fault current is decided by the system fault level. For banks up to 3Mvar the discharge energy due to the short-circuit of parallel connected capacitors which occurs when a unit fails is negligible, so that only power-frequency fusing current need be considered in choice of fuse. Since the prospective power-frequency fusing current is large, being limited only by system impedance, correct operation of the fuse is ensured even if its rating considerably exceeds its normal operating current. Since a current limiting h.r.c. fuse normally has to be oversized to ensure correct high-frequency transient withstand this is an important advantage. It is emphasised that the connection of capacitors must be such as to ensure that capacitor failure results in system short circuit to obtain this advantage, and arrangements where power frequency fault current is limited by series connection of capacitors, such as in unearthed star arrangements, must be avoided.

4.0 <u>LOW AND MEDIUM VOLTAGE ARRANGEMENTS</u> Capacitor banks in the low and medium voltage range are assembled using capacitor units with individual output ratings up to 50kvar. These units can be two terminal type for single or two phase operation, or, three terminal type for three phase operation.

In the case of the two terminal units the elements are all parallel connected. In the three terminal units all elements are arranged in three groups with elements parallel connected, and the three groups arranged in a delta configuration.

Fig. 1A indicates the internal connection arrangement of elements for a typical two terminal capacitor unit rated 10kvar, 415 volts, 50Hz.

Fig. 1B indicates the internal connection arrangement of elements for a typical three terminal capacitor unit rated 50kvar, 415 volts, 50Hz.

Larger ratings of capacitors are achieved by parallel connection of multiple single unit assemblies.

These capacitor banks are usually controlled by suitably rated switches or contactors which are provided with line connected current limiting fuses.

Fig. 1C indicates the connection arrangements for a 100kvar, 415V, 3 phase, 50Hz capacitor bank complete with isolator, contactor, and line connected HRC type fuses.

5.0 HIGH VOLTAGE ARRANGEMENTS In high voltage capacitor banks, capacitor units up to 200kvar 15kV output rating are now commonplace Each unit usually comprises capacitor elements without fuses, these elements being arranged in a series/parallel grouping to meet the specified or required voltage rating.

Individual capacitor units of the three terminal type are available for working voltages up to 3.3kV 3 phase, and beyond this up to 15kV, two terminal types only are usually available.

Fig. 2A indicates the internal connection arrangement of elements for a typical three terminal 150kvar, 3.3kV 50Hz capacitor unit, and Fig. 2B the internal connection arrangement of elements for a typical two terminal 200kvar, 11kV 50Hz capacitor unit.

For capacitor banks of rated voltage above 3.3kV, two terminal capacitor units are used in multiple series/parallel grouped assemblies to achieve the desired rating.

For example a 600kvar, 11kV 3 phase capacitor bank could be arranged using 3 - two terminal capacitor units of individual rating 200kvar 11kV arranged in a delta configuration and protected by 3 line connected fuses. See Fig. 3A.

These capacitor units and fuses are normally accommodated in one of three ways.

a) Within a welded steel tank type construction complete with cable entry box. This tank is usually oil-filled to aid cooling and is ideal for difficult or exposed environments.

b) Within a fabricated sheet, steel cubicle complete with cable entry chamber.

c) In an open busbar arrangement where the capacitor units and associated line fuses are supported by a galvanised steel framework.

Higher capacitor bank ratings are achieved by addition of further two terminal capacitor units and fuses parallel connected in the delta configuration. For cubicles and open busbar designs the preferred arrangement is, as shown in Fig. 3C, with the units connected in delta in groups of three, with the fuses in the line connection to each delta group of units.

An alternative arrangement, is to connect the fuses within the delta as shown in Fig. 3B. Fuses connected in this fashion do not protect the arrangement for earth faults so that line fuses are required in addition for this purpose. This connection arrangement is usually used for oil-filled tank-type capacitors, where the physical arrangement makes it preferable.

Where line fuses are provided in addition to unit fuses it is important to ensure discrimination between the unit and line fuses. This can result in large line fuse ratings bearing in mind the 2 x factor which has to be applied to the unit fuse rating in accordance with Section 6.0 below.

6.0 FUSE RATING The fuses used in association with capacitors should have a rating which ensures the following requirements are satisfied:-

a) The fuse rated voltage and interrupting capability corresponds to the rated voltage of the system to which they are connected, and system fault level at the point of connection of the capacitor bank.

b) The fuses must be capable of handling the capacitor discharge currents, and also the capacitor bank/unit inrush transients as described in Section 2. On this point it is generally accepted, (based on practical operating experience) that for low and medium voltage capacitor banks line fuses of rating 150% of the capacitor current rating will accommodate without deterioration these discharge and transient inrush currents.

Because high voltage capacitors involve the use of fuses with smaller continuous current ratings and the ability of these fuses to withstand transient inrush and discharge currents is disproportionately less than for larger fuses, factors of 200% or more may be necessary. Fuse size can be significantly influenced again if back to back capacitor bank switching is employed. However in general for low and medium voltage capacitor banks because of the relatively small bank sections and high interconnecting inductance a fuse of 150% capacitor current rating will be satisfactory. For high voltage capacitors special steps may have to be taken to ensure sufficient transient withstand is incorporated in the fuses.

The consequences of incorrect rating, resulting in partial fuse failure caused by capacitor inrush or discharge current, is that when normal current is returned to the fuse, the fuse is no longer capable of its assigned duty, and overheating followed by complete and probably damaging fuse breakdown occurs. It is particularly important to avoid this in oil-filled tank capacitor designs.

c) The line fuses of the capacitor bank should discriminate with the fuses farther back in the supply system. In particular this may significantly influence the size of cable to a capacitor bank if correct protection of this supply cable is to be achieved.

The unit fuses of capacitor units within a capacitor bank should also be rated to achieve discrimination between the fuse protecting the faulty capacitor and those protecting the healthy capacitors. This on delta connected banks as recommended in this paper is easy to achieve as outlined in Section 3.0.

7.0 CONCLUSIONS Current limiting fuses offer considerable advantages when used for protection of industrial power factor correction capacitors in that they can generally allow capacitor requirements to be met by a physically small, simple installation. However to ensure reliable and correct operation of the installation it is important that the fuses are applied correctly as outlined in this paper.

Capacitor failure rates are considerably less than 0.1% per year and to ensure fuse operation matches this performance is particularly important.

Many years of experience of applying fuses in accordance with these guidelines have been acquired, and provided they are followed reliable and trouble free capacitor installations should be achieved.

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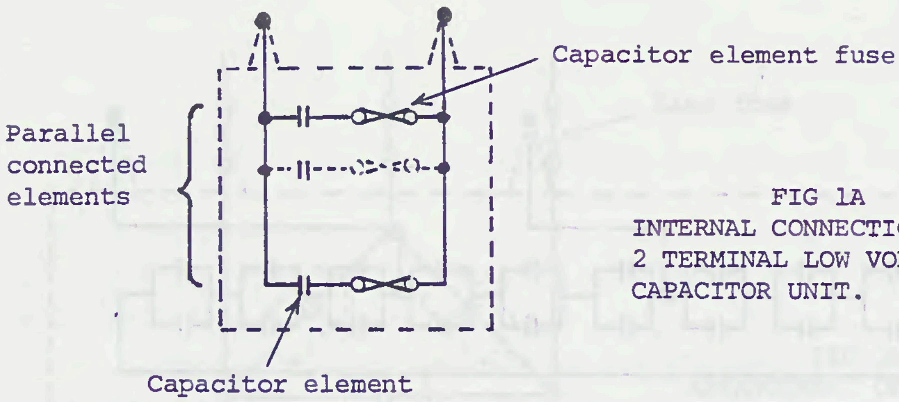

FIG 1A
INTERNAL CONNECTIONS FOR
2 TERMINAL LOW VOLTAGE
CAPACITOR UNIT.

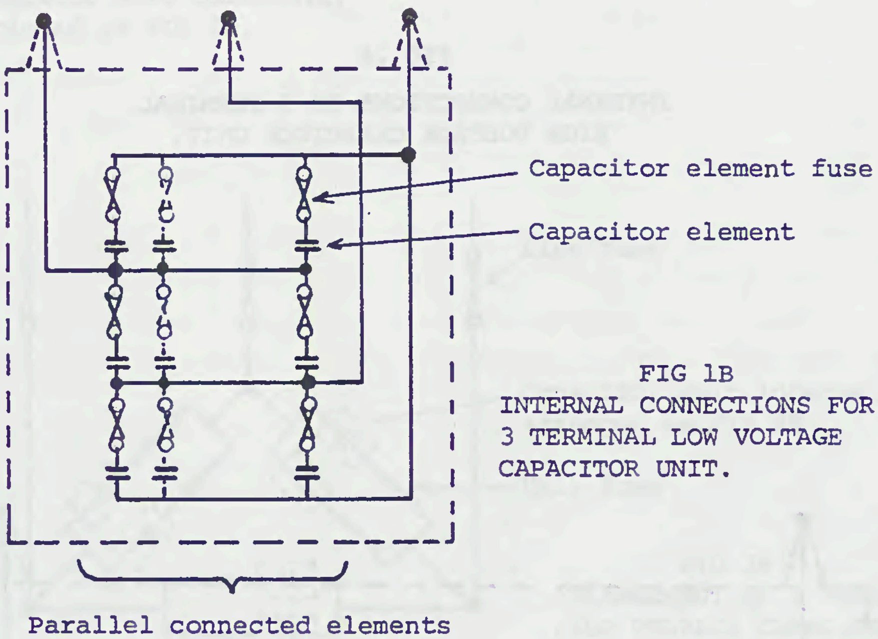

FIG 1B
INTERNAL CONNECTIONS FOR
3 TERMINAL LOW VOLTAGE
CAPACITOR UNIT.

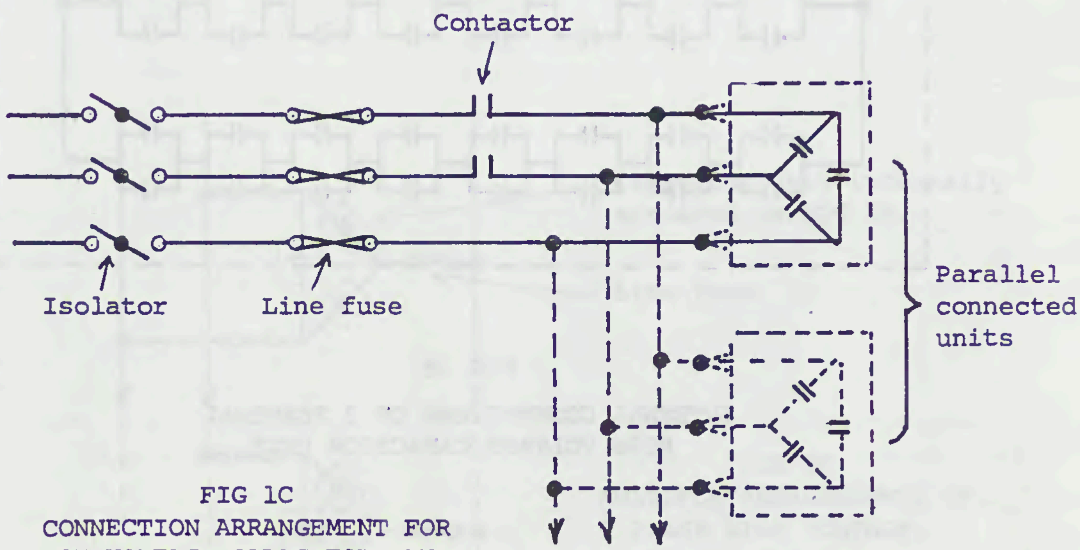

FIG 1C
CONNECTION ARRANGEMENT FOR
LOW VOLTAGE CAPACITOR BANK.

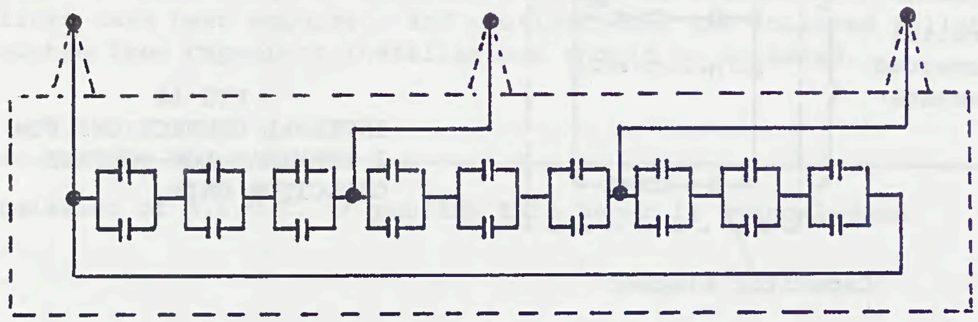

FIG 2A

INTERNAL CONNECTIONS OF 3 TERMINAL
HIGH VOLTAGE CAPACITOR UNIT.

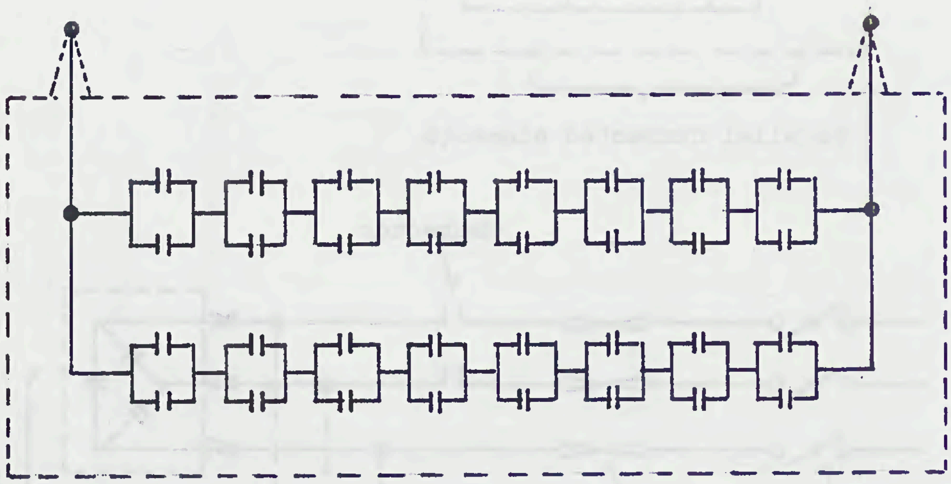

FIG 2B

INTERNAL CONNECTIONS OF 2 TERMINAL
HIGH VOLTAGE CAPACITOR UNIT.

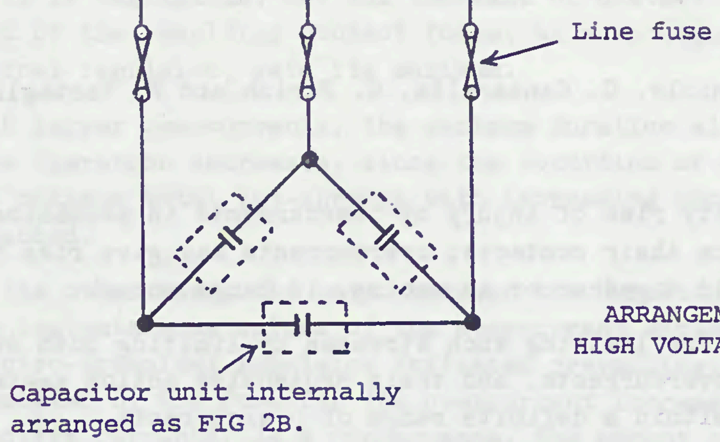

FIG 3A
ARRANGEMENT OF 3 PHASE
HIGH VOLTAGE CAPACITOR BANK.

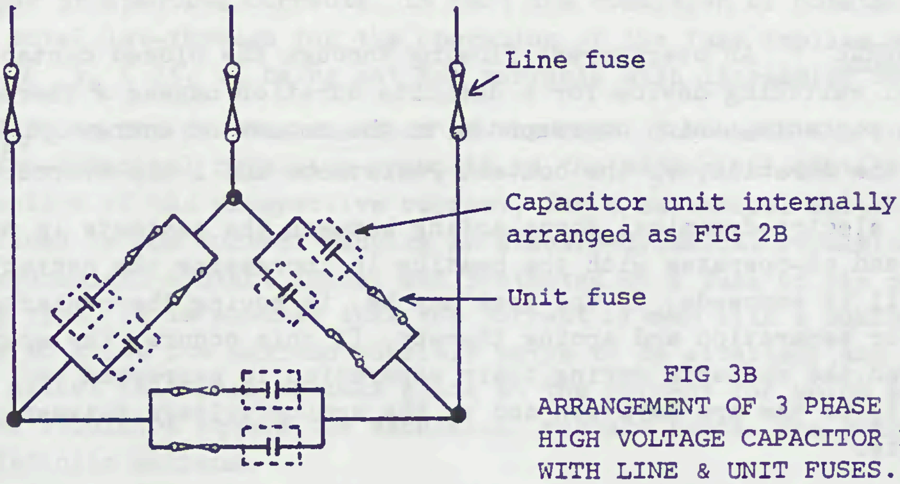

FIG 3B
ARRANGEMENT OF 3 PHASE
HIGH VOLTAGE CAPACITOR BANK
WITH LINE & UNIT FUSES.

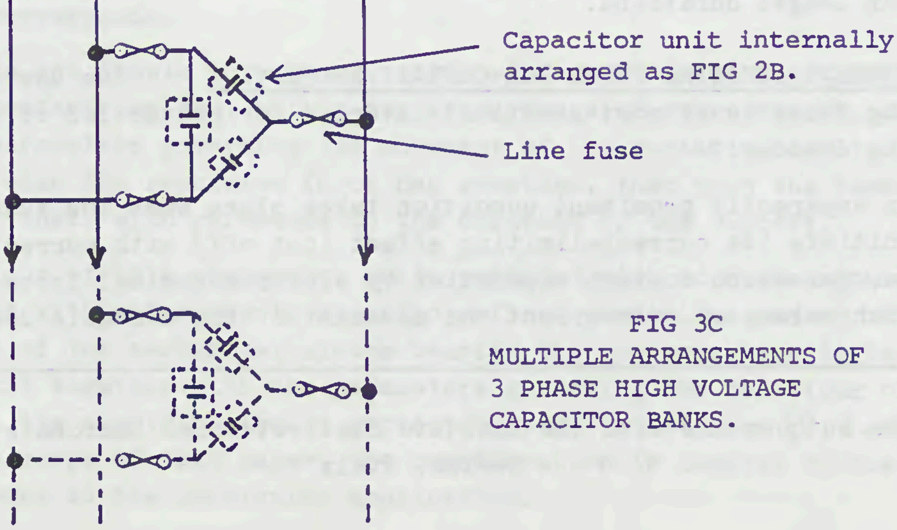

FIG 3C
MULTIPLE ARRANGEMENTS OF
3 PHASE HIGH VOLTAGE
CAPACITOR BANKS.