Engineering

technical memorandum

Daresbury Laboratory

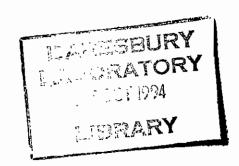
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TECHNICAL REPORT ON THE REQUIREMENTS FOR POWER FACTOR CORRECTION CAPACITORS AT DARESBURY LABORATORY

by

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Technical Report on the Requirements for

Power Factor Correction Capacitors at Daresbury Laboratory

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Abstract

Daresbury Laboratory provides advanced scientific research facilities for a large community of scientists from both the U.K. and overseas in a wide variety of fields including life sciences, material studies, surface science and atomic and molecular science.

The main facility at Daresbury is the Synchrotron Radiation Source (S.R.S.). This is an electron storage ring with an energy of 2GeV, producing synchrotron radiation from sixteen bending magnets and three insertion devices.

During 1992 - 1994 a programme has been completed to replace the twenty-five year old magnet power converters on the S.R.S., as they were expensive to maintain and their reliability was not acceptable for an accelerator required to deliver six thousand beam hours per hour.

This report details the electrical engineering aspects associated with the installation of the new power converters, namely power factor correction and harmonic distortion prevention.

Introduction.

Electrical power in a D.C. system is easy to define, it is simply the product of the voltage and the current. However, in an A.C. system power is not so easy to define. At any one instant the voltage may be high while the current is low. This is due to the fact that capacitance and inductance change the relationship between instantaneous voltage and current. If the circuit is purely capacitive (with no inductance) the A.C. current sinewave leads the voltage sinewave by ninety degrees phase angle, so that when the current is maximum, voltage is zero. For a purely inductive circuit, the current lags the voltage by ninety degrees, so that when the voltage is maximum, current is zero. The phase difference between the voltage and the current depends upon the nature of the load and not upon that of the supply from the generator.

Therefore the circuit's reactance affects the relationship between the applied voltage and the resulting current and consequently the power produced. All circuits contain some reactance, but are never purely capacitive or inductive.

There are three different types of A.C. power that are significant, and it is important to understand their relationships.

REAL POWER is the actual power in Watts utilised by the load, and therefore able to perform useful work.

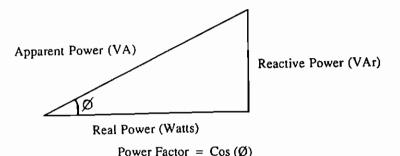
REACTIVE POWER is in VARs (Volt - Amperes Reactive) is power not utilised by the load.

APPARENT POWER is the total power, the product of Volts x Amperes (VA).

When both the current and voltage are sinusoidal, the portion of the Apparent Power that does actual work, the Real Power, is calculated using the phase angle (Ø) between the voltage and the current, which may be leading or lagging each other. The phase angle is the result of reactance, whose net effect is capacitive or inductive. The cosine of this angle is called the Power Factor and is used to calculate Real Power.

Real Power (W) = Apparent Power (VA) x Power Factor

or Power Factor = Real Power (W)
Apparent Power (VA)



Practical Implications of Power Factor.

If an A.C. generator is rated to give, for example, 2000A at a voltage of 400V it means that these are the highest current and voltage values the machine can give without the temperature exceeding a safe value. The rating of the generator is given as 800kVA.

If the Power Factor is unity, the Real Power is 800kW and the engine driving the generator has to be capable of developing this power.

If the Power Factor is, for example, 0.5 the Real Power is only 400kW, so that the engine is developing only about half of the power of which it is capable even though the generator is supplying its rated output of 800kVA.

Similarly, the conductors connecting the generator to the load have to be capable of carrying 2000A without excessive temperature rise. Consequently they can transmit 800kW if the Power Factor is unity, but only 400kW at 0.5 Power Factor for the same rise of temperature.

Therefore the higher the Power Factor of the load, the greater is the

Real Power that can be generated by a given generator and transmitted by a given conductor.

This can be illustrated differently, by saying that for a given Real Power, the lower the Power Factor the larger must be the size of the source to generate that power and the greater must be the cross-sectional area of the conductor to transmit it.

In other words the cost of generation and transmission of the electrical energy is higher.

It is for this reason why the Regional Electricity Companies (RECs) do all they can to improve the Power Factor of their loads, either by the installation of capacitors or special machines or by the use of tariffs which encourage consumers to do so.

Power Factor Charges at Daresbury Laboratory.

The REC which supplies electricity to D.L. is Manweb plc. Their tariff includes a chargeable reactive demand element to encourage consumers to improve their Power Factor. For D.L. the chargeable reactive demand charge is the maximum kVAr of demand in excess of the number obtained by multiplying the maximum kW of demand registered in any time during the month by 0.4. (It is stated as during the month as D.L. is charged monthly for electricity consumption.) At present the charge for each kVAr of chargeable reactive demand in each month is £ 1.40.

The value of 0.4 is that as shown in the example below.

5243 kVA 1948 kVAr 4868 kW

3

Tan
$$(\emptyset) = 1948 = 0.4$$

4868

$$\emptyset = 21.8$$
°

$$Cos(\emptyset) = 0.928$$

Therefore the Power Factor of D.L. must be greater than 0.928 lagging to avoid the reactive demand charge.

In the 1980s 600kVAr of power factor correction capacitors was installed at D.L., fed directly from the main site 11kV switchboard. Previously there had been local power factor correction capacitors at various locations throughout the site fed at three phase 415V.

The 600kVArs ensured that D.L. was not subject to the reactive demand charge.

Power Factor Correction Requirements at D.L.

A programme to replace the power converters feeding the D.C. magnets of the S.R.S. meant that there had to be an investigation into the power factor correction requirements.

The existing power converters used roller regulators for the control of the power and therefore had a good power factor at all times. The new thyristor phase controlled power converters have a variable power factor because firing delay has the effect of delaying the supply current relative to its phase voltage.

The new thyristor phase controlled power converters have the following ratings:

Two at 750kW fed at 11kV One at 250kW fed at 415V Two at 90kW fed at 415V.

The 750kW sets and the 250kW set are twelve pulse and the 90kW sets are six pulse. The pulse numbers refer to the number of D.C. current pulses they produce each cycle.

The new power converters were to be installed in two stages:

1) 415V supplied converters

2) 11kV supplied converters.

Due to the varying operating conditions of the power converters automatic power factor correction was required. The power converters fed at 415V required local automatic power correction capacitors to compensate for their power factor. New power factor correction capacitors were required fed from the main site 11kV switchboard to compensate for the new 11kV converters and the site in general.

Automatic Power Factor Correction.

The aim of automatic power factor correction is to ensure that the Power Factor remains at the required high value for fluctuating load conditions. To accomplish this it is necessary to continuously monitor the load system's kVAr component and then switch the optimum quantity of capacitor compensation in, or out, to achieve the desired Power Factor. It is necessary to monitor the current in the red phase and the voltage in the yellow and blue phases.

For the 415V automatic power factor correction capacitors this required a new current transformer to be installed on the red phase of the incoming cable to the switchboard to send a continuous signal to the power factor correction controller.

The situation for the 11kV capacitors was different. It was necessary to measure the power factor for the whole site. The site is fed on two 11kV cables and both of these have metering current transformers installed. To provide one red phase current signal to the power factor correction controller, it was necessary to take a signal from each of the existing metering current transformers into a summation current transformer. This then provided the signal to the power factor correction controller for the 11kV capacitors.

Harmonics.

The new thyristor phase controlled power converters have the disadvantage that the waveforms associated with them are non-sinusoidal. The switching action of them results in non-sinusoidal

current being drawn from the A.C. supply system.

Fourier stated that any non-sinusoidal waveform consisted of, and therefore could be broken down into, some number of pure sine waves.

The most common sinewaves that distort a power system are whole number multiples of the fundamental power frequency (50Hz in the U.K.). These whole number multiples are the 'harmonics' of the fundamental.

Equipment which causes harmonics to be generated back on to the supply system, in addition to causing disturbances on the system itself, can also have an adverse effect on power factor correction capacitors. This is because the reactance of capacitors is proportional to the inverse of the frequency. Therefore as the frequency increases the reactance decreases. This means that a greater proportion of currents at frequencies above the fundamental will be absorbed by the capacitors, and therefore all equipment associated with the capacitor must be designed for this increased current.

As the supply impedance is generally considered to be inductive, the network impedance increases with frequency while the impedance of a capacitor decreases, and the impedance of a circuit dictates the current flow in that circuit. This means that a greater proportion of currents at frequencies above the fundamental supply frequency will be absorbed by the capacitor, and all equipment associated with it.

These harmonic currents through the capacitor cause a corresponding harmonic voltage across the dielectric of the capacitor. The harmonic voltage due to each harmonic current added to the fundamental voltage dictates the voltage stress to be sustained by the capacitor dielectric and for which the capacitor must be designed.

Transformers are also particularly affected by harmonics. Their energy losses in general are a combination of excitation (no load) loss and load losses, which in turn consist of heating loss, eddy current loss and stray losses such as electromagnetic flux in windings, cores and shields. Excessive harmonics have a particularly pronounced effect on eddy current losses, since these increase as the square of the frequency. All losses, however, increase with harmonic distortion, and losses mean wasted energy, often in the form of increased heating which can raise the transformer temperature above its rating. Increased transformer heating

may degrade insulation, shortening life and possibly causing failure. It was to limit the allowable level of harmonic distortion on distribution networks that the Electricity Council Engineering Recommendation G 5/3, detailed in Appendix One, was formulated.

Harmonic Resonance.

As frequency varies, reactance varies and a point can be reached when the capacitor reactance and the supply reactance are equal. This point is known as the circuit resonance frequency.

Whenever power factor correction is applied to a distribution network, bringing together capacitance and inductance, there will always be a frequency at which the capacitors are in parallel resonance with the supply.

If this condition occurs at, or close to, one of the harmonics generated by, for example, power converters, then large harmonic currents can circulate between the supply network and the capacitor equipment, limited only by the damping resistance in the circuit. Such currents will add to the harmonic voltage disturbance in the network causing an increased voltage distortion. This results in an unacceptably high voltage across thecapacitor dielectric together with an excessive current through all the capacitor ancillary components. The most common harmonic currents are fifth, seventh, eleventh, thirteenth, seventeeth, nineteenth, twenty-third, and twenty-fifth, but resonance can occur at any frequency.

Overcoming Resonance.

A reactor is connected in series with each capacitor switching section so that the capacitor / reactor combination is inductive at the harmonic frequencies, but is capacitive at fundamental frequency (50Hz). To achieve this the capacitor and series connected reactor must have a tuning frequency below the lowest order harmonic present, which is usually fifth. The capacitor / reactor tuning frequency is therefore usually in the range 175Hz to 230Hz.

The inclusion of a reactor in the capacitor circuit increases the fundamental voltage across the capacitor by a value in the order of five to nine per cent in addition to the harmonic voltages.

Limits of Harmonic Distortion.

Harmonic distortion can cause severe disturbance to some electrical equipment and as it is the duty of the electricity supply companies to provide a 'clean' supply, many countries now set limits to the harmonic distortion allowed on the distribution network.

In the U.K. the Electricity Council Engineering Recommendation G 5/3 provides for three levels of acceptance for the connection of harmonic generating equipment, defined as stages. Appendix One illustrates the requirements of G 5/3.

Power Factor Correction Capacitor Requirements.

Appendix Two shows tables of values which illustrate the varying requirements for the power factor correction capacitors for the different operating conditions of the S.R.S. These tables were specified by Dr. D.E. Poole, SRA Power Supplies Section

415v Capacitors.

To compensate for the new 415V supplied power converters a specification for automatically controlled power factor correction capacitors was written which also included the requirement for each switched capacitor stage to be fitted with detuning reactors. Appendix Three details the specification.

Automatic power factor correction capacitors were specified to compensate for the variable loads as the S.R.S. is operated under different conditions.

The capacitors were to be fed from the same local switchboard as the power converters so that the Power Factor of that switchboard was maintained as near to unity as possible, and so that no harmonics were fed back into the D.L. electrical distribution network. The tuning frequency of the capacitor / reactor combination was 210Hz.

The 415v power factor correction capacitors were installed and commissioned in Spring 1993 at a cost of £6000, with Option A of the specification chosen as the most suitable.

11kV Capacitors.

The tables in Appendix Two, show that the most suitable configuration was 800kVAr fixed and 400kVAr automatically switched to give a total of 1200kVAr when necessary. The 600kVAr of power factor correction capacitors installed in the 1980s did not have series reactors installed, and therefore was not suitable due to the level of harmonics which would be present with the new power converters energised.

Installing new capacitors only would have caused magnification of eleventh, thirteenth and seventeeth harmonic currents. This could have damaged the capacitors, and would have increased the system distortion to a level beyond that permitted under G 5/3. Therefore each of the fixed and switched stages comprised a capacitor and reactor tuned below fifth harmonic at 225Hz to ensure reduction of the harmonic currents generated by the power converters.

The 11kV power factor correction capacitors were installed and commissioned in June 1994 at a cost of £28000 meeting the specification in Appendix Four.

11kV Switchgear for Power Factor Correction Capacitors.

There are special requirements for circuit breakers which are to be used for switching high voltage capacitor banks. The requirement which was of greatest concern at D.L. was the one detailing that the circuit breaker to be used must be designed to inhibit re-striking when the capacitor bank circuit is broken. The previously installed 600kVAr bank of power factor correction capacitors was fed from a Johnson and Philips oil circuit breaker (OCB) which was approximately thirty years old, and as the company no longer existed it could not be proved that the OCB was designed to be re-strike free.

It was therefore decided to feed the new power factor correction capacitors from a newer GEC OCB following discussions with GEC. This meant that cabling work had to be carried out to install a new cable from the GEC OCB to the capacitor bank, and also the circuit which was originally fed from the GEC OCB had to be re-terminated onto the Johnson and Philips OCB as it fed another part of the site.

Summary.

The total cost of the installation for both sets of automatic power factor correction capacitors was approximately £ 32000. Daresbury Laboratory meets the requirements of the Electricity Council Engineering Recommendation G 5/3, and has a sufficiently high power factor not to be subject to a monthly reactive demand charge saving approximately £ 1800 each month, and assuming that there are nine operational months for the S.R.S. each year, then the saving per year is over £ 16000. This shows that the payback period for the power factor correction element is only about two years.

The power factor correction capacitor project had to be managed to correspond to that of the replacement of the power supplies, and to the operational requirements of the S.R.S. Installation and commissioning was achieved to meet all programme requirements.

Appendix One

Electricity Council Engineering Recommendation G 5/3

Electricity Council Engineering Recommendation G 5/3

This provides for three levels of acceptance for the connection of harmonic generating equipment, defined as stages.

Stage One

This permits the connection of individual loads up to 14kVA at 415V and 250kVA at 11kV without special consideration.

Stage Two

This limits the total harmonic current which any installation may produce at the point of connection with the supply authority, as follows:

Harmonic	2	4	5	7	11	13
415V	48A	22	56	40	19	16A
6.6 - 11kV	13A	6	10	8	7	6A

Stage Three

Individual of systems is required to ensure total harmonic distortion does not exceed 5% at 415V and 4% at 11kV.

Appendix Two Tables of Calculations of Power Factor Correction Requirements as Specified by SRA Power Supplies Section - Dr. D.E. Poole

Power Factor Calculations

Circuit	
D.C. Voltage	
D.C. Current	
RF (kW)	
Trans Sec Volts	
Cos(alpha)	
Trans Imped. %	
A.C Power (kW)	
A.C. KVars	
415V Correction	
11kV Correction	
Sub-total Power	
Sub-total KVars	
Power Factor	

Dipole	F-Quad	Rest of Site	D-Quad	F-Sext	D-Sext	Klystron
0	0		0	0	0	
0	0		0	0	0	
						0
485	485		198	340	104	
0.00	0.00		0.00	0.00	0.00	
6	6		5	5	5	
0.00	0.00	1700	0.00	0.00	0.00	0
0.00	0.00	1520	0.00	0.00	0.00	0
				0	(kVars)	
	800	(kVars)			` ′	
	1700.00			0.00		0.00
	720.00			0.00		0.00
	0.92			1.00		1.00

Total Site Power Total Site KVars Site Power Factor SRS Off 1700.00 kW 720.00 kVars 0.921

Circuit	Dipole	F-Quad	Rest of Site	D-Quad	F-Sext_	D-Sext	Klystron
D.C. Voltage	128	90		33	80	19	
D.C. Current	403	261		126	135	58	
RF (kW)							11
Trans Sec Volts	485	485		198	340	104	
Cos(alpha)	0.20	0.14		0.12	0.17	0.14	
Trans Imped. %	6	6		5	5	5	
A.C Power (kW)	54.00	24.59	2375	4.36	11.32	1.16	30.25
A.C. KVars	270.91	177.21	1520	35.07	63.93	8.47	7.5625
415V Correction					100 (kVars)	
11kV Correction		800	(kVars)				
Sub-total Power		2453.59			16.83		30.25
Sub-total KVars		1168.11			7.46		7.56
Power Factor		0.90			0.91		0.97

Total Site Power Total Site KVars Site Power Factor Injection High Q 2500.68 kW 1183.14 kVars 0.904

Power Factor Calculations

Circuit	Dipole	F-Quad	Rest of Site	D-Quad	F-Sext	D-Sext	Klystron
D.C. Voltage	485	378		115	296	56	
D.C. Current	1424	1021		423	481	171	
RF (kW)							135
Trans Sec Volts	485	485		198	340	104	
Cos(alpha)	0.74	0.58		0.43	0.64	0.40	
Trans Imped. %	6	6		5	5	5	•
A.C Power (kW)	723.03	404.04	2375	51.04	149.17	10.05	371.25
A.C. KVars	655.73	571.44	1520	107.09	176.80	23.10	92.8125
415V Correction					300 ((kVars)	
11kV Correction		1200	(kVars)				
Sub-total Power		3502.07			210.26		371.25
Sub-total KVars		1547.17			6.98		92.81
Power Factor		0.91			1.00		0.97

Total Site Power Total Site KVars Site Power Factor 2 GeV High Q 4083.58 kW 1646.96 kVars 0.927

Circuit
D.C. Voltage
D.C. Current
RF (kW)
Trans Sec Volts
Cos(alpha)
Trans Imped. %
A.C Power (kW)
A.C. KVars
415V Correction
11kV Correction
Sub-total Power
Sub-total KVars
Power Factor

Dipole	F-Quad	Rest of Site	D-Quad	F-Sext	D-Sext	Klystron
128	66		31	48	11	
403	193		116	75	31	
					Ì	11
485	485		198	340	104	
0.20	0.10		0.12	0.10	0.08	
6	6		5	5	5	·
54.00	13.34	2375	3.77	3.77	0.36	30.25
270.91	131.62	1520	32.31	35.87	4.55	7.5625
				50	(kVars)	
	800	(kVars)				
	2442.34			7.90		30.25
	1122.53			22.74		7.56
	0.91			0.33		0.97

Total Site Power Total Site KVars Site Power Factor Injection Low Q 2480.49 kW 1152.83 kVars 0.907

SRS Switch

4

Power Factor Calculations

D.C. Voltage		F-Quad	Rest of Site	D-Quad	F-Sext	D-Sext	Klystron
	485	224		102	146	28	_
D.C. Current	1424	655		382	246	86	
RF (kW)							135
Trans Sec Volts	485	485		198	340	104	i
Cos(alpha)	0.74	0.34		0.38	0.32	0.20	
Trans Imped. %	6	6		5	5	5	
A.C Power (kW)	723.03	153.60	2375	40.88	37.63	2.53	371.25
A.C. KVars	655.73	421.88	1520	99.02	112.16	12.41	92.8125
415V Correction					200 (kVars)	
11kV Correction		1200	(kVars)				
Sub-total Power		3251.63			81.04		371.25
Sub-total KVars		1397.61			23.60		92.81
Power Factor		0.92			0.96		0.97

Total Site Power Total Site KVars Site Power Factor 2 GeV Low Q 3703.92 kW 1514.02 kVars 0.926

Appendix Three

Specification for the 415V Power Factor Correction Capacitors

Specification for Automatic 415V Power Factor Correction Capacitors

The following specification is for 415V, 50Hz power factor correction capacitors to be installed as shown on the attached electrical distribution diagram. Please quote for both Option A and Option B.

Option A

One 300 kVAr automatic capacitor assembly equipped with 6 x 50 kVAr contactor switched stages, selector switches and stage lamps.

Each stage shall be fitted with series detuning reactors and there will be an integral stage reactive control relay complete with digital power factor indication.

There should also be a forced cooling system and over temperature cutout if required.

Option B

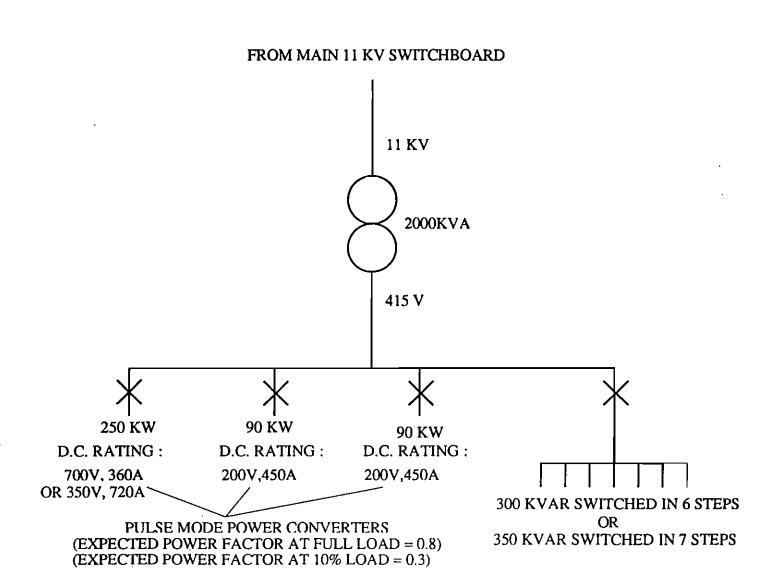
One 350 kVAr automatic capacitor assembly equipped with 7 x 50 kVAr contactor switched stages, selector switches and stage lamps.

Each stage shall be fitted with series detuning reactors and there will be an integral stage reactive control relay complete with digital power factor indication.

There should also be a forced cooling system and over temperature cutout if required.

Both options should be supplied in a sheet steel enclosure complete with lockable front access door, and appropriate monitoring devices to allow automatic power factor correction. Tenderers should state the size of the capacitor enclosure and the cable entry details.

ELECTRICAL DISTRIBUTION FOR NEW D.C. POWER CONVERTERS AND AUTOMATIC POWER FACTOR CORRECTION CAPACITORS



Appendix Four

Specification for the 11kV Power Factor Correction Capacitors

Specification for 11kV Power Factor Correction Capacitors.

Introduction.

Daresbury Laboratory provides facilities for government funded experimental research. Due to upgrading of plant, new sets of D.C. rectifying equipment are being installed and as a result the overall site power factor will require further correction.

This specification covers the design, manufacture, delivery and commissioning of suitable static equipment for this purpose. It must be noted that harmonic problems must be taken into account in the design of the power factor correction equipment.

Site Electrical Supplies.

Electrical power to the site is via two 11kV feeders from the local Regional Electricity Company (REC) with a supply capacity of 6.5MVA. These incoming feeders supply the site main 11kV switchboard comprising twenty-one outgoing circuit breakers, with a board fault level of 250MVA. See Figure 1 for electrical distribution diagram.

New Equipment.

New thyristor controlled rectification plant is to replace existing regulator controlled rectifier systems. The new plant rated at two units of 750kW each will be supplied at 11kV via rectifier transformers. As a result power factor correction equipment will be required to improve the overall site power factor to a minimum of 0.928 lag.

Details.

Three main site load parameters shall be considered when specifying the power factor equipment:-

 Rectifiers turned off and site running at low level base load conditions.

Site parameters as seen by REC:-

11kV 3 phase 50Hz

1.7MW at 0.88 lag

 Rectifiers operating at low load and site running at full load conditions.

Site parameters as seen by REC:-

11kV 3 phase 50Hz

2.5MW at 0.88 lag

 Rectifiers operating at full load and site running at full load conditions.

Site parameters as seen by REC:-

11kV 3 phase 50Hz

4.0MW at 0.88 lag

* Note - These are calculated figures and take into account the existing 600kVAr of power factor correction capacitors connected to the 11kV system. These capacitors are not de-tuned and it is therefore assumed they will not be suitable in their present form for continued operation on the system when the new rectifier units are operating and generating harmonics.

Correction.

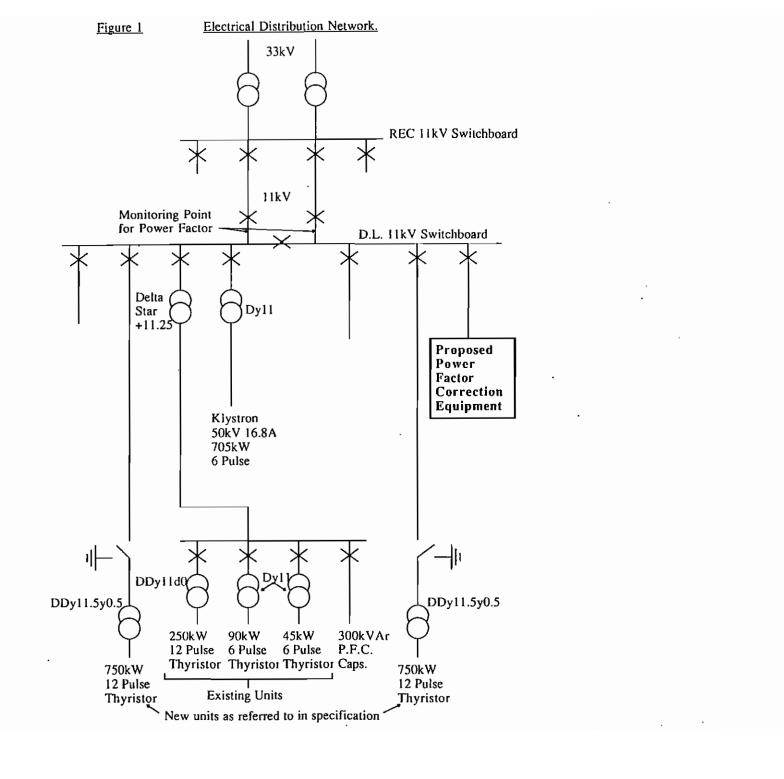
All correction will be achieved by static capacitors automatically switched in the minimum number of stages possible to ensure the site power factor remains between 0.928 lag and unity.

Harmonics,

The Daresbury Laboratory site must comply with the Engineering Recommendation G 5/3 under all load conditions and once delivered to the site a representative of the contractor will be required to commission the equipment and carry out measurements to prove that the harmonic levels in G 5/3 are not exceeded.

Uninterruptible Power Supplies.

In the future it is possible that an unknown amount (probably 200 - 500kW) of UPSs will be installed, and the design of the power factor correction equipment should take this into account.



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