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INSTRUCTION No. TI/JN/002

111-2

Rev-0 **MASTER COPY** मूल प्रति

Addendum & Corrigendum Slip No. 1 (Jan.1997) to "Guidelines for design of shunt compensation for Improving power factor at 25kV Traction substation(Sept.1996)"

The existing matter in paras 3.4 & 3.5 may be replaced by the following:

3.4 Thyristor switched capacitors (TSC):

If the load at the traction substation fluctuates considerably and there are prolonged periods of light load, the fixed shunt capacitor bank would be ineffective in providing desired improvement in power factor, though the improvement in M.D. would still take place. Thyristor switched capacitor banks (Fig.10) can in such cases be used with advantage. In this scheme 2 or 3 capacitor banks each controlled by thyristors connected in anti parallel is adopted so that capacitor banks are in circuit during both positive and negative half cycles. All switching on should take place when the voltage across the thyristors is zero to obtain almost transient free switching. As the capacitor while switching off is left with a trapped charge, the voltage across thyristors will alternate between zero and twice the peak phase voltage. Besides the capacitors will start discharging when switched off. A transient free switching will therefore, require two conditions to be met -

i) The thyristors must be gated at a positive or negative crest of supply voltage and

ii) The capacitors must be precharged or topped up for the loss of charge with the same polarity.

[The pre- charged voltage = $\dfrac{n^2}{n^2 - 1} . Vp$

Where $n = \sqrt{\dfrac{XC}{XL}}$, Vp - Peak phase voltage

Xc = Capacitor reactance, and

Xl = Reactance of damping reactor used for keeping di/dt within capability of thyristors.]

Appropriate circuitary to precharge the discharged capacitor has also to be provided to avoid large switching transients and premature failure of capacitors.

Disconnection is affected by withdrawing the firing pulses at natural current zero. The current is sinusoidal and contains no harmonics.

The degree of flexibility with given number of parallel branches (i.e. maximum number of steps) is maximum if no two capacitor bank branches have equal value however on grounds of economy equal values of capacitance is only adopted. The response time of such an arrangement is quite good (roughly about 2 cycles) but the compesation is in discreet steps as large number of banks if provided in parallel would complicate the schemes and add to a very high cost of the installation.

3.5 Thyristor controlled reactor with fixed capacitor banks:

In this scheme (Fig.2.0) two oppositely poled thyristors conduct on alternate half cycles of the supply frequency. If thyristors are gated into conduction precisely at the peaks of the supply voltage, full conduction results in the reactor and the current is the same as though the thyristor controller were short circuited. The current is essentially reactive, lagging the voltage by nearly 90 degree. If gating in delayed by equal amounts on both thyristors a series of current wave forms is obtained. By varying the conduction angle, the amount of lagging reactive power can be controlled. Equal conduction angles of the two oppositely poled thyristors, introduces odd harmonics will also get introduced. Therefore, such a scheme has to incorporate harmonic filters to keep the total harmonic distortion within limits. During light loads the capacitive power requirement would be very less, therefore, the reactor would be working with almost full conduction resulting into considerable energy losses. The arrangement would however give a stepless control of the reactive power with a very high response time of the order of 1.5 cycles. Combination of TSC and TCR can also be used to suit the appalication.

Guidelines for design of fixed shunt compensation for improving power factor at 25 kV, 50 Hz Traction substation

1.0 Introduction:

The traction load unlike the industrial loads is of frequently and rapidly varying nature, the variations ranging from no load to short time overloads. The traction system is also subjected to frequent short circuit primarily due to earth faults. The harmonics generated by the electric locomotives particularly the thyristor locomotives are quite high with odd harmonics dominating and producing a severe distortion of voltage wave. The instantaneous power factor of traction loads (electric locomotives) is usually lagging -- being poorer at light loads. The average power factor being generally in the range of 0.7 and 0.8 lagging.

The lagging power factor of the traction loads is not welcomed by the State Electricity Boards and in the recent past the trend has been to raise the penalty level for poor power factor from 0.8 to 0.9. On account of the stiff penalty being imposed by the supply authorities for power factor below this level, it has become essential for the Railways to take measures for improving the power factor of the traction loads. Drawal of leading kVAR to compensate/partially compensate the lagging kVAR of traction loads by providing shunt compensation is by far the most common method employed. While the best place for installation of power factor compensation equipment is at the load itself, some compensation at the traction substation becomes inevitable particularly since most of locomotives of Indian Railways are not provided with any such compensation.

2.0 Chargeable power factor and metering arrangement:

The overall chargeable power factor over the billing period as calculated by the Electricity Boards is different from the instantaneous power factor reflected at the point of metering which is continuously varying. This chargeable power factor not only depends on instantaneous power factor but also on the method of calculating the chargeable power factor from the metering registers installed at the traction substations.

A fixed shunt compensation which continuously draws a leading kVAR reduces the cumulative kVAh by reducing the net (lagging) kVAR of the load. Thus as long as this is true an improvement in chargeable power results. However, during periods of prolonged no load/low load, the leading kVARh drawn by capacitor bank will get recorded in different fashions depending upon the type of metering systems installed. The electronic meters now available have facility of recording the leading kVARh and lagging kVARh separately and therefore depending upon whether the advantage of drawing the excess leading kVARh by the consumers(Railways) has to be reflected in calculating the chargeable power factor will depend upon the method used for calculating the chargeable power factor. Three possible methods for calculating the chargeable power factor can be employed:

The most common method of calculating the chargeable power factor is :-

$$\text{Chargeable power factor} = \frac{\Sigma kWh}{\Sigma kVAh}$$

(The kVAh meter rotates in same direction irrespective of drawal of leading or lagging kVARh)

OR

Where separate registers for leading & lagging kVARh are provided.

$$\text{Chargeable power factor} = \frac{\Sigma kWh}{\sqrt{(\Sigma kWh)^2 + (\Sigma \text{lagging } kVARh)^2 + (\Sigma \text{leading } kVARh)^2}}$$

As excessive leading kVARh increases the denominator, a reduction in chargeable power factor could result with excessive compensation. This method of calculating chargeable power factor. therefore discourages drawal of excessive leading kVARh.

II) $$\text{Chargeable power factor} = \frac{\Sigma kWh}{\sqrt{(\Sigma kWH)^2 + (\Sigma \text{lagging } kVARh)^2}}$$

OR

Where kVARh meter stops rotating while drawing leading kVARh

$$\text{Chargeable power factor} = \frac{\Sigma kWh}{\Sigma kVAh}$$

This method of calculating chargeable p.f. neither penalises nor gives benefit for drawal of excessive leading kVARh.

III) Chargeable power factor

$$= \frac{\Sigma kWh}{\sqrt{(kWh)^2 + (\Sigma \text{lagging } kVARh)^2 - (\Sigma \text{leading } kVARh)^2}}$$

OR

Where kVAh meter rotates in opposite direction while drawing leading kVARh.

$$\text{Chargeable power factor} = \frac{\Sigma kWh}{\Sigma kVAh}$$

This method of calculating chargeable power factor gives benefit for drawing excessive leading kVARh.

3.0 Methods used for improving power factor:

3.1 Fixed shunt capacitor:

The simplest and the most common method employed at present is to install fixed shunt compensation equipment at the traction substation. The compensation improves power factor by reducing the net lagging kVAR drawn by traction load thus avoiding the payment of low power factor penalty.The other incidental benefit acrued are by way of reduction in maximum demand charges.improvements in the voltage and reduction in transformer losses.

3.1.1 Problems associated with fixed shunt compensation:

(i) Traction load is continuously varying, the compensation has to be therefore truely dynamic which fixed capacitor can not provide thus resulting into under/over compensation at times.

(ii) Excessive compensation may sometimes (depending upon the extent of overcompensation) lead to deteriorate in chargeable power factor if chargeable power factor is calculated according to method I.

iii) Changing the capacity to meet changed requirement of compensation disturbs the capacitor bank configuration & is therefore not always possible to implement. In larger bank using series reactor this may not be possible at all from consideration of rating of existing equipment and resonance.

To overcome some of the above drawbacks it is suggested that:

a) Bank rating should be fixed on the basis of load pattern over the billing period instead of average load.

b) While it is possible to improve chargeable power factor to desired value of method II & III is followed. it may some times be not possible to improve the chargeable power factor to desired value particularly in lightly loaded traction substation if chargeable power factor is calculated by method I. in which case one of the following two alternative may be considered.

A) As changing the rating of fixed shunt compensation could be tricky, smaller capacitor bank (around 500 kVAR) without series reactor could be tried in the interim period till the load fully builds up at the traction substation.

B) If penality limits of p.f. are too stringent e.g. 0.95 & load pattern at traction substation is likely to change, use of dynamic compensation may be resorted to.

3.2 Switched shunt capacitors:

Where load pattern at a traction substation is fairly stable and has rather fixed periods of no load/low load, the chargeable p.f. can still be improved even if calculated using method I provided the shunt capacitors are switched off during such no load/ low load periods. Such switching off/on has to be limited to not more 1-2 operation/day if reliability of capacitors is not to be launched. Such switching On/off can be activated either automatically using a combined time of the day/load current check or done manually through RCC.

3.3 Multistage switching of shunt capacitors:

Changing the kVAR rating of the capacitor bank by switching in/out branches of capacitor bank is not suitable for traction application as traction load fluctuates widely & is rather difficult to predict. The switching operation may also be too large for reliability of compensation equipment & the system. Moreover, on account of increased in rush current while switching on a parallel branch of capacitor, the circuit breaker shall be subjected to very heavy duty particularly if the polarity of the branches are in opposition. Considering these aspects it is considered that this current will not be suitable for traction application.

3.4 Thyristor switched capacitor:

3.5 Thyristor control reactor:

4.0 Calculation of rating of fixed shunt compensation:

4.1 Based on average load:

A rough method for calculating the requisite rating for a fixed compensation for a heavily loaded traction substation involves calculation of an average demand which can be approximated as:

$$\text{Average demand in kW} = \frac{\text{Monthly average energy consumed}}{\text{Number of hours in a month}}$$

The rating of the shunt compensation for getting a desired power factor is given by:-

$$\text{Capacitive kVAR} = \text{Average demand in kW} \; (\tan\phi_1 - \tan\phi_2)$$

where, ϕ_1 = initial power factor angle
ϕ_2 = improved power factor angle

While this method gives the reasonable idea of the compensation needed in case of heavily loaded traction substation, the method is likely to give quite eroneous result for traction substations which are very lightly loaded where excess leading KVAR drawn by the shunt compensation would complicate the metering. Therefore in order to take the varrying nature of traction load into account and whether the chargable power factor is to be calculated over the billing period, it is necessary to take the above aspects into consideration for fixing the load of the shunt compensation.

4.2 Based on load pattern and method of calculating chargeable power factor:

As illustrated in para 5.0 the calculation of rating of shunt compensation on tthe basis of average loads could even lead to power factor poorer than before. It is herefore essential that the rating is related to the load patterns and not with average load. It must be understood that a particular KVAR rating of fixed shunt compensation is best suited only for the designed load pattern. If the load pattern changes markedly particularly in regard to periods of no load/ low load and peak loads. the rating may become unsuitable for getting the desired compensation. The shunt compensation therefore can be employed with advantages only in cases where the load patterns are reasonably stable and traction substation is well loaded. Where these conditions are not met with a fixed shunt compensation may not give the desired results and may even lead to poor chargeable power factor.

The procedure takes into account the fluctuating traction load, varying instantaneous power factor and simulates the reading which may get recorded in different registers of different metering system on the basis of which chargeable power factor is calculated for working out the optimum rating of the shunt compensation a number of iterations have to be performed on the load pattern. This procedure therefore, necessarily requires calculations by computer. A programme module in C++ has been designed to help enable this calculation being performed by persons not familiar with computer working by following simple screen prompts.

5.0 Illustrative examples:

To illustrate the above aspects two examples -one relating to load pattern (I) for typically lightly loaded traction substation and another for load pattern (II) for a reasonably loaded traction substation has been considered. It is assumed that these load patterns are representative of the entire billing period. If this is not, so several representative load patterns prevailing in the billing period can also be considered in the simulation. The following data has been entered for the purpose of above illustrations.

i) Load pattern over the billing period for all the days in a month.........Pattern (I)

ii) Load pattern over the billing period for all the days in a month.........Pattern (II)

ii) Desired power factor 0.9

The result of the simulation for the two load patterns is tabulated below:

LOAD PATTERN (I) (LIGHTLY LOADED TRACTION SUBSTATION)

Existing chargeable power factor = 0.79

TABLE - I

Methodology for calculating chargeable power factor	Optimum rating of fixed shunt compensation	Likely actual chargeable power factor after installation of compensation.	Remarks
I	100 kVAR	0.802 lagging	Not possible t improve chargeable p.f.beyon 0.80 by fixed shunt compensation.
II	400 kVAR	0.90 lagging	Chargeable p.f will improve beyond 0.90 wi increase in rating beyond 400 kVAR.
III	1000 kVAR	0.90 lagging	Chargeable p.f will improve beyond 0.90 wi increase in rating beyond 1000 kVAR.

As against these if capacitor rating is designed based average load the chargeable power factor with differe methodlogy will be as under:

TABLE - II

Methodology for calculating chargeable power factor	Optimum rating of fixed shunt compensation	Likely actual chargeable power factor after installation of compensation.	Remarks
I	400 KVAR	0.78 lagging	Chargeable p.f. will deteriorate below 0.78 with increase in rating beyond 400 kVAR.
II	400 kVAR	0.90 lagging	Chargeable p.f. will improve beyond 0.90 with increase in rating beyond 400 kVAR.
III	400 kVAR	0.84 lagging	Chargeable p.f. will improve beyond 0.84 with increase in rating beyond 400 kVAR.

Table-II gives an idea of how the chargeable power factor will look like if rating of fixed shunt compensation is increased. When chargeable power factor is being calculated on the basis of method I. From this it will be seen that the chargeable power factor deteriorates from the existing chargeable power factor with increased rating of shunt compensation. This explains the deterioration of power factor reported by some Railways at some of the traction substation where a over rated shunt compensation has been installed.

Similar information for the loaded traction substation [Pattern (II)] is shown in Table-III. From this it would be seen that there is an improvement in power factor with increased rating of shunt compensation.

LOAD PATTERN : II : (REASONABLY LOADED TRACTION SUBSTATION)

Existing chargeable power factor = 0.62

TABLE : III

Mothodology for calculating chargeable power factor	Optimum rating of fixed shunt compensation	Likely actual chargeable power factor after installation of compensation.	Remarks
I	1800 kVAR	0.90 lagging	Chargeable power factor will improve beyond 0.90 with increase in rating beyond 1800 kVAR.
II	1450 kVAR	0.90 lagging	Chargeable power factor will improve beyond 0.90 with increase in rating beyond 1450 kVAR.
III	1800 kVAR	0.90 lagging	Chargeable power factor will improve beyond 0.90 with increase in rating beyond 1800 kVAR

6.0 Harmonics:

Percentage of individual current harmonics present in the traction system as measured during 1990-1992 is given below:-

Percentage current harmonic

Zone	Eastern		Northern		Central		Southern		Western	
Harm. No.	A	B	A	B	A	B	A	B	A	B
3rd	18	18	19	17	19	17	19	19	18	18
5th	8	8	9	7	9	8	8	8	9	9
7th	4	4	5	4	6	5	8	7	5	5
9th	3	2	3	3	4	3	4	3	4	4
11th	2	2	3	3	-	-	2	2	3	2

A - Load current range 200-300 A ; B - Load current range 300-400 A

Typical value of current harmonics for the load current range 200 - 400 A has been considered for designing the capacitor bank:

3rd harmonic		20%
5th	"	10%
7th	"	8%
9th	"	4%
11th	"	3%

In addition to the above 20 % safety margin has also been taken into account while designing the actual rating of capacitor bank.

7.0 Rating of the shunt capacitor bank:

Considering reasonably loaded traction substation as indicated in load pattern (II) and the methodology for calculating chargeable power factor as II the optimum rating of fixed capacitor bank is 1450 KVAR.

Assuming 10% extra for the future growth of load. kVAR capacity of the capacitor bank at 25 kV = 1.1 x 1450 = 1600 kVAR.

Capacitive reactance of 1600 kVAR capacitor bank at 25 kV

$$= \frac{1000 \times kV^2}{kVAR}$$

$$X_c = \frac{kV^2 \times 1000}{KVAR.}$$

= 390.63 ohm. ✓

7.1 Series reactor rating:

In order to avoid resonance at all odd harmonics, the minimum value of series reactor reactance (XL) should to be 13% of the capacitive reactance (Xc).

Moreover, to keep the effective capacitive reactance same as 390.63 ohm, the capacitive reactance of capacitor bank should be increased by the same amount of the series reactor reactance.

The value of series reactor reactance. XL = 0.13Xc

and (Xc - XL) = 390.63 ohm

$$\therefore X_c = \frac{390.63}{(1-0.13)}$$

$$= 449 \text{ ohm.}$$

$$\text{and } X_L = 0.13 \times 449 \text{ ohm.}$$

$$= 58.37 \text{ ohm.}$$

7.2 Actual rating of capacitor bank with series reactor:

Taking into account the fluctuations of incoming supply volatage and the voltage rise at no load due to capacitor, the voltage class of the capacitor bank should be calculated taking the bus voltae as 28 kV.

Current drawn by capacitor - reactor circuit at fundamental frequency

$$= \frac{28000}{(X_c - X_L)}$$

$$= \frac{28000}{(449 - 58.37)}$$

$$= 71.68 \text{ Amps.}$$

Voltage across the capacitor bank at fundamental frequency.

$$V_{cf} = I_{cf} \times X_c$$

$$= 71.68 \times 449$$

$$= 32184 \text{ Volts.}$$

Taking the average load current of 336 A corresponding to th load pattern (II) (8.39 MVA load), the individual harmoni current is:

Harm No.	Harmonic current (In)	Distribution factor(pc)	Actual harmonic current through capacitor bank
3	I3 - 80.64 A	0.46	Ic3 - 37.10 A
5	I5 - 48.38 A	0.134	Ic5 - 5.36 A
7	I7 - 32.26 A	0.126	Ic7 - 4.06 A
9	I9 - 16.13 A	0.119	Ic9 - 1.92 A
11	I11 - 12.10 A	0.115	Ic11- 1.39 A

7.2.1 Voltage rise due to harmonic currents:

i) 3rd harmonic voltage across the capacitor bank:

$$V_{c3} = \frac{X_c}{3} \times I_{c3}$$

$$= \frac{449}{3} \times 37.1$$

$$= 5552.6 \text{ Volts.}$$

ii) 5th harmonic voltage across the capacitor bank.

$$V_{c5} = \frac{X_c}{5} \times I_{c5}$$

$$= \frac{449}{5} \times 6.48$$

$$= 581.9 \text{ Volts}$$

iii) 7th harmonic voltage across the capacitor bank.

$$V_{c7} = \frac{X_c}{7} \times I_{c7}$$

$$= \frac{449}{7} \times 4.06$$

$$= 260.4 \text{ Volts.}$$

) 9th harmonic voltage across the capacitor bank.

$$Vc9 = \frac{Xc}{9} \times Ic9$$

$$= \frac{449}{9} \times 1.92$$

$$= 95.8 \text{ Volts}$$

i) 11th harmonic voltage across the capacitor bank.

$$Vc11 = \frac{Xc}{11} \times Ic11$$

$$= \frac{449}{11} \times 1.39$$

$$= 56.74 \text{ Volts.}$$

otal harmonic Voltage across tho capacitor bank.

$$= \sqrt{Vc3^2 + Vc5^2 + Vc7^2 + Vc9^2 + Vc11^2 +}$$

$$= \sqrt{(5552.6)^2 + (581.9)^2 + (260.4)^2 + (95.8)^2 + (56.74)^2}$$

$$= 5590.22 \text{ Volts.}$$

Final voltage across the capacitor bank,

$$Vcf + Vchar. = 32184 + 5590.22$$

$$= 37774.22 \text{ Volts, say 40 kV}$$

kVAR capacity of the capacitor bank at 40 kV

$$= \frac{kV^2 \times 1000}{Xc} = \frac{(40)^2 \times 1000}{449}$$

$$= 3564 \text{ kVAR}$$

.3 Rating of the series reactor:

Voltage across the series reactor.

$$VLmax = XL \times \sqrt{Icf^2 + 9\,Ic3^2 + 25\,Ic5^2 + 49\,Ic7^2 + 81\,Ic9^2 + 121\,Ic11^2}$$

$$= 58.37 \times \sqrt{(71.68)^2 + 9(37.1)^2 + 25(6.48)^2 + 49(4.06)^2 + 81(1.92)^2 + 121(1.39)^2}$$

$$= 58.37 \times 141.12$$

$$= 8237.32 \text{ VOlts.}$$

$$Icmax = \sqrt{Icf^2 + Ic3^2 + Ic5^2 + Ic7^2 + Ic9^2 + Ic11^2}$$

$$= \sqrt{(71.68)^2 + (37.1)^2 + (6.48)^2 + (4.06)^2 + (1.92)^2 + (1.39)^2}$$

$$= 81.108 \text{ A}$$

kVAR rating of the series reactor $= VL\,max \times Ic\,max \times 10^{-3}$

$$= 8237.32 \times 81.108 \times 10^{-3}$$

$$= 668 \text{ KVAR.}$$

Inductance of the series reactor.

$$L = \frac{XL}{2\pi f} = \frac{58.37}{100\pi} \times 10^{3} \text{ mH} = 185.8 \text{ mH}$$

8.C Resonant Frequency:

i) Source reactance, Xs

Assuming 30 fault level on 132 kV side of traction substaion 2000 MVA.

∴ Source reactance on 132 kV side = $(132)^2 / 2000 = 8.71$ ohm.

∴ Loop reactance on 132 kV side = 2 x 8.71 ohm.

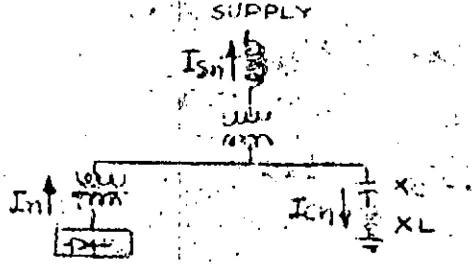
∴ Reflected reactance on 25 kV side, $Xs = 17.42 \times (27/132)^2$
$= 0.625$ ohm

ii) Transformer Impedance:

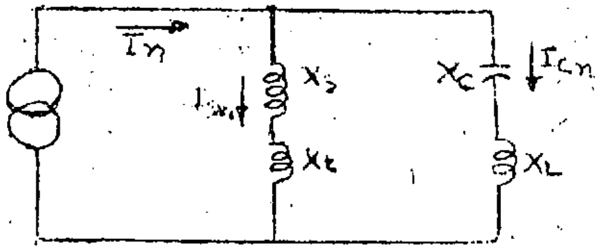
132/25 kV, 13.5 MVA transformer with 12% impedance has reactance value:

$$Xt = \frac{12 \times (27)^2}{100 \times 13.5}$$
$$= 6.48 \text{ ohms.}$$

iii) Equivalent circuits of traction power supply circuit:



(Traction power supply circuit



Harmonic source Supply Capacitor (equivalent circuit)

Where,

In - Harmonic current at nth harmonic.
Xs - Source reactance.
Xt - Transformer reactance.
Xc - Capacitive reactance.
XL - Series reactor reactance.
Icn- Capacitor current at the nth harmonic
Isn- Supply current at the nth harmonic.
Ps,Pc - Distribution factors.

In = Icn + Isn

$$Icn = \frac{(Xs + Xt)}{(Xs + Xt + XL) - Xc/n^2} . In = pc.In$$

$$Isn = \frac{(XL - Xc/n^2)}{(Xs + Xt + XL) - Xc/n^2} . In = ps.In$$

Capacitor bank will have two types of reactances:

i) Parallel resonance will occur at.

$(Xs + XL + XL - Xc/n^2) = 0$

i.e. $n^2 = \sqrt{\dfrac{Xc}{(Xs + St + XL)}}$

$= \sqrt{\dfrac{449}{(0.825 + 6.48 + 58.37)}}$

$= \sqrt{449/65.475}$

$= 2.62$

$f0 = 2.62 \times 50 = 131$ Hz.

ii) Series resonance will occur at:

$(XL - Xc/n^2) = 0$

i.e. $n = \sqrt{Xc/XL}$

$= \sqrt{448/58.37}$

$= 2.77$

$f0 = 2.77 \times 50 = 138.50$ Hz.

Harmonic current distribution between supply and capacitor bank

n	Ps	Pc
1	1.0185	0.0185
2	1.152	0.152
3	0.544	0.456
4	0.81	0.19
5	0.85	0.15
6	0.866	0.134
7	0.874	0.126
8	0.878	0.122
9	0.881	0.119
10	0.883	0.117
11	0.885	0.115

It is clear from the enclosed graph for harmonic current distribution to supply circuit and capacitor bank circuit V/s frequency. that when harmonic current distribution factor Ps is less than 1. higher harmonic current is decreased by capacitor bank and when it is more than 1.higher harmonic current is amplified with the shunt capacitor bank.

Therefore. the resonant frequency of the capacitor bank with the system should be in the range between 50 Hz and 140 Hz to avoid amplification of harmonic current at 3rd and other higher harmonics.

Therefore. it is recommended to use 13 to 15% reactor in series with capacitor bank to make the capacitor reactor bank inductive in the frequency area above the 3rd harmonics.

It is also recommended that whenever a capacitor unit is found defective. it is necessary to cut of the whole capacitor bank from the circuit with the help of circuit breaker instead of removing the defective unit and putting the capacitor bank with reduced capacity again into service. This is required because the total capacitive reactance Xc will increase. and the resonant frequency will become higher and this will cause the amplification of high harmonic current.

8.0 Capacitor bank inrush currents:

The energizing of a capacitor by closing a circuit breaker produces an inrush current which is a function of the applied voltage. the capacitances of the circuit. the values and location of the inductances in the circuit. the charges on the capacitor at the time the circuit is closed and the damping of the switching transients. The inrush current can be calculated by knowing the network impedances and calculations of inrush current are usually made on the assumptions that the capacitor bank has no initial charge and that the circuit is closed at a time which produces the maximum inrush current.

(a) Connection of a single bank:

$$i = \sqrt{2}\, U \sqrt{C_1 / (L_0 + L1)}$$

$$f = 1 / \{2\pi\sqrt{C1\,(Lo + L1)}\}$$

(b) Connection when one bank is already connected:

$$i = \sqrt{2}\, U \sqrt{\frac{C1C2}{(C1 + C2)(L1 + L2)}}$$

$$f = \frac{1}{2\pi\sqrt{\frac{C1C2\,(L1 + L2)}{(C1 + C2)}}}$$

$$S = \sqrt{2}\, U / (L1 + L2)$$

here. U - system voltage
$\hat{i}$ - inrush current peak
f - inrush current frequency
S - inrush current rate-of-rise
Lo- source inductancce including transformer
L1- inductance in series with switched cap. bank 1
L2- inductance in series with switched cap. bank 2
C1- capacitance of switched capacitor bank 1
C2- capacitance of switched capacitor bank 2

The value of the overcurrents due to switching operations should be limited to a maximum of 100 times the rated current(rms value) of the capacitor bank.

9.0 Maximum permissible switching voltages

The residual voltage on a capacitor bank prior to energization shall not exceed 10% o the rated voltage of the capacitor bank. The energization of a capacitor bank by a restrike-free circuit breaker usually causes a transient overvoltage, the first peak of which does not exceed 2 /2 times the applied voltage (rms value) for a maximum duration of 1/2 cycle. However the switching surge voltage should not normally exceed 70 kV peak.

10.0 Restrike-free circuit breakers:

Circuit breakers suitable for capacitor switching i.e. restrike-free circuit breakers shall be used for controlling the capacitor banks. While selecting the circuit breaker, it should be ensured that the circuit breaker can take a minimum of 140% of the capacitor bank current continuously.

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ANNEXURE-I

LOAD PATTERN -(1)

TIME	kW	P.F.
00 00	1220.0	-.7
00 10	1800.0	-.7
00 20	1950.0	-.7
00 30	3000.0	-.75
00 40	3500.0	-.8
00 50	2000.0	-.75
01 00	900.0	-.7
01 10	50.0	-.7
01 20	50.0	-.7
01 30	50.0	-.7
01 40	50.0	-.7
01 50	50.0	-.7
02 00	50.0	-.7
02 10	50.0	-.7
02 20	50.0	-.7
02 30	50.0	-.7
02 40	50.0	-.7
02 50	50.0	-.7
03 00	50.0	-.7
03 10	50.0	-.7
03 20	50.0	-.7
03 30	50.0	-.7
03 40	50.0	-.7
03 50	50.0	-.7
04 00	50.0	-.7
04 10	200.0	-.7
04 20	1000.0	-.7
04 30	50.0	-.7
04 40	50.0	-.7
04 50	50.0	-.7
05 00	50.0	-.7
05 10	1000.0	-.7
05 20	5000.0	-.8
05 30	4500.0	-.8
05 40	6000.0	-.8
05 50	8000.0	-.8
06 00	7000.0	-.8
06 10	9000.0	-.8
06 20	12000.0	-.85
06 30	11000.0	-.85
06 40	13000.0	-.85
06 50	18000.0	-.85
07 00	2000.0	-.75
07 10	50.0	-.7
07 20	50.0	-.7
07 30	50.0	-.7
07 40	50.0	-.7
07 50	50.0	-.7
08 00	50.0	-.7
08 10	1000.0	-.7
08 20	1500.0	-.7
08 30	2000.0	-.75
08 40	500.0	-.7
08 50	500.0	-.7
09 00	50.0	-.7
09 10	50.0	-.7
09 20	50.0	-.7
09 30	50.0	-.7
09 40	50.0	-.7
09 50	50.0	-.7
10 00	50.0	-.7
10 10	50.0	-.7
10 20	50.0	-.7
10 30	50.0	-.7
10 40	50.0	-.7
10 50	50.0	-.7
11 00	50.0	-.7
11 10	500.0	-.7
11 20	2500.0	-.75
11 30	500.0	-.7
11 40	50.0	-.7
11 50	50.0	-.7
12 00	50.0	-.7
12 10	50.0	-.7
12 20	50.0	-.7
12 30	50.0	-.7
12 40	50.0	-.7
12 50	50.0	-.7
13 00	50.0	-.7
13 10	1000.0	-.7
13 20	1000.0	-.7
13 30	800.0	-.7
13 40	250.0	-.7
13 50	1000.0	-.7
14 00	50.0	-.7
14 10	50.0	-.7
14 20	50.0	-.7
14 30	50.0	-.7
14 40	50.0	-.7
14 50	50.0	-.7
15 00	50.0	-.7
15 10	50.0	-.7
15 20	50.0	-.7
15 30	50.0	-.7
15 40	50.0	-.7
15 50	50.0	-.7
16 00	50.0	-.7
16 10	4000.0	-.8
16 20	3000.0	-.75
16 30	4000.0	-.8
16 40	2500.0	-.75
16 50	7000.0	-.8
17 00	1000.0	-.7
17 10	500.0	-.7
17 20	1000.0	-.7
17 30	500.0	-.7
17 40	50.0	-.7
17 50	50.0	-.7
18 00	1220.0	-.7
18 10	1800.0	-.7
18 20	1950.0	-.7
18 30	3000.0	-.75
18 40	3500.0	-.8
18 50	2000.0	-.75
19 00	900.0	-.7
19 10	50.0	-.7
19 20	50.0	-.7
19 30	50.0	-.7
19 40	50.0	-.7
19 50	50.0	-.7
20 00	50.0	-.7
20 10	50.0	-.7
20 20	50.0	-.7
20 30	50.0	-.7
20 40	50.0	-.7
20 50	50.0	-.7
21 00	50.0	-.7
21 10	50.0	-.7
21 20	50.0	-.7
21 30	50.0	-.7
21 40	50.0	-.7
21 50	50.0	-.7
22 00	50.0	-.7
22 10	200.0	-.7
22 20	1000.0	-.7
22 30	50.0	-.7
22 40	50.0	-.7
22 50	50.0	-.7
23 00	50.0	-.7
23 10	1000.0	-.7
23 20	5000.0	-.8
23 30	4500.0	-.8
23 40	6000.0	-.8
23 50	8000.0	-.8

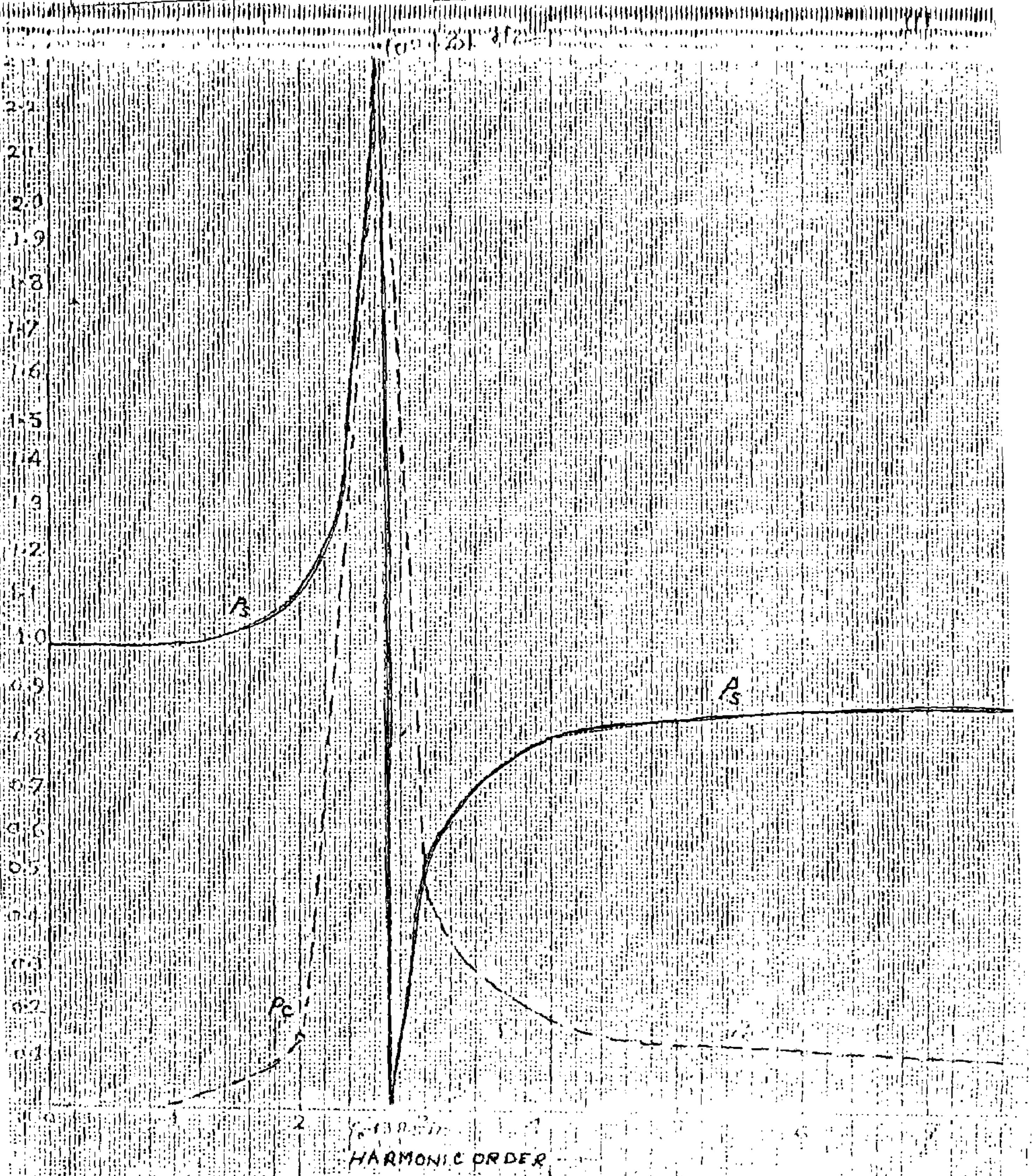
Page [illegible] of [illegible] Pages	Effective From [illegible]

LOAD PATTERN - [redacted] Instruction

No: TI/MI[illegible] Rev. [illegible]

ANNEXURE

TIME	KW	P.F.
00 00	5000.0	-.8
00 10	9000.0	-.8
00 20	10000.0	-.85
00 30	12000.0	-.85
00 40	5000.0	-.8
00 50	8000.0	-.8
01 00	10000.0	-.85
01 10	8000.0	-.8
01 20	9000.0	-.8
01 30	10000.0	-.85
01 40	5000.0	-.8
01 50	3000.0	-.75
02 00	1000.0	-.7
02 10	500.0	-.7
02 20	50.0	-.7
02 30	4000.0	-.8
02 40	5000.0	-.8
02 50	10000.0	-.85
03 00	8000.0	-.8
03 10	10000.0	-.85
03 20	12000.0	-.85
03 30	10000.0	-.85
03 40	5000.0	-.8
03 50	7000.0	-.8
04 00	10000.0	-.85
04 10	5000.0	-.8
04 20	5000.0	-.8
04 30	8000.0	-.8
04 40	10000.0	-.85
04 50	8000.0	-.8
05 00	5000.0	-.8
05 10	6000.0	-.8
05 20	8000.0	-.8
05 30	10000.0	-.85
05 40	5000.0	-.8
05 50	6000.0	-.8
06 00	2000.0	-.75
06 10	1500.0	-.7
06 20	50.0	-.7
06 30	50.0	-.7
06 40	4000.0	-.8
06 50	8000.0	-.8
07 00	10000.0	-.85
07 10	5000.0	-.8
07 20	8000.0	-.8
07 30	10000.0	-.85
07 40	15000.0	-.85
07 50	12000.0	-.85
08 00	8000.0	-.8
08 10	9000.0	-.8
08 20	10000.0	-.85
08 30	5000.0	-.8
08 40	8000.0	-.8
08 50	10000.0	-.85
09 00	5000.0	-.8
09 10	7000.0	-.8
09 20	8000.0	-.8
09 30	10000.0	-.85
09 40	5000.0	-.8
09 50	6000.0	-.8
10 00	10000.0	-.85
10 10	10000.0	-.85
10 20	8000.0	-.8
10 30	6000.0	-.8
10 40	1000.0	-.7
10 50	1000.0	-.7
11 00	50.0	-.7
11 10	50.0	-.7
11 20	8000.0	-.8
11 30	10000.0	-.85
11 40	12000.0	-.85
11 50	10000.0	-.85
12 00	5000.0	-.8
12 10	9000.0	-.8
12 20	10000.0	-.85
12 30	12000.0	-.85
12 40	5000.0	-.8
12 50	8000.0	-.8
13 00	10000.0	-.85
13 10	8000.0	-.8
13 20	9000.0	-.8
13 30	10000.0	-.85
13 40	5000.0	-.8
13 50	3000.0	-.75
14 00	1000.0	-.7
14 10	500.0	-.7
14 20	50.0	-.7
14 30	4000.0	-.8
14 40	5000.0	-.8
14 50	10000.0	-.85
15 00	8000.0	-.8
15 10	10000.0	-.85
15 20	12000.0	-.85
15 30	10000.0	-.85
15 40	5000.0	-.8
15 50	7000.0	-.8
16 00	10000.0	-.85
16 10	5000.0	-.8
16 20	5000.0	-.8
16 30	8000.0	-.8
16 40	10000.0	-.85
16 50	8000.0	-.8
17 00	5000.0	-.8
17 10	6000.0	-.8
17 20	8000.0	-.8
17 30	10000.0	-.85
17 40	5000.0	-.8
17 50	6000.0	-.8
18 00	2000.0	-.75
18 10	1500.0	-.7
18 20	50.0	-.7
18 30	50.0	-.7
18 40	4000.0	-.8
18 50	8000.0	-.8
19 00	10000.0	-.85
19 10	5000.0	-.8
19 20	8000.0	-.8
19 30	10000.0	-.85
19 40	15000.0	-.85
19 50	12000.0	-.85
20 00	8000.0	-.8
20 10	9000.0	-.8
20 20	10000.0	-.85
20 30	5000.0	-.8
20 40	8000.0	-.8
20 50	10000.0	-.85
21 00	5000.0	-.8
21 10	7000.0	-.8
21 20	8000.0	-.8
21 30	10000.0	-.85
21 40	5000.0	-.8
21 50	6000.0	-.8
22 00	10000.0	-.85
22 10	10000.0	-.85
22 20	8000.0	-.8
22 30	6000.0	-.8
22 40	1000.0	-.7
22 50	1000.0	-.7
23 00	50.0	-.7
23 10	50.0	-.7
23 20	8000.0	-.8
23 30	10000.0	-.85
23 40	12000.0	-.85
23 50	10000.0	-.85



DISTRIBUTION FACTORS Vs HARMONIC ORDER

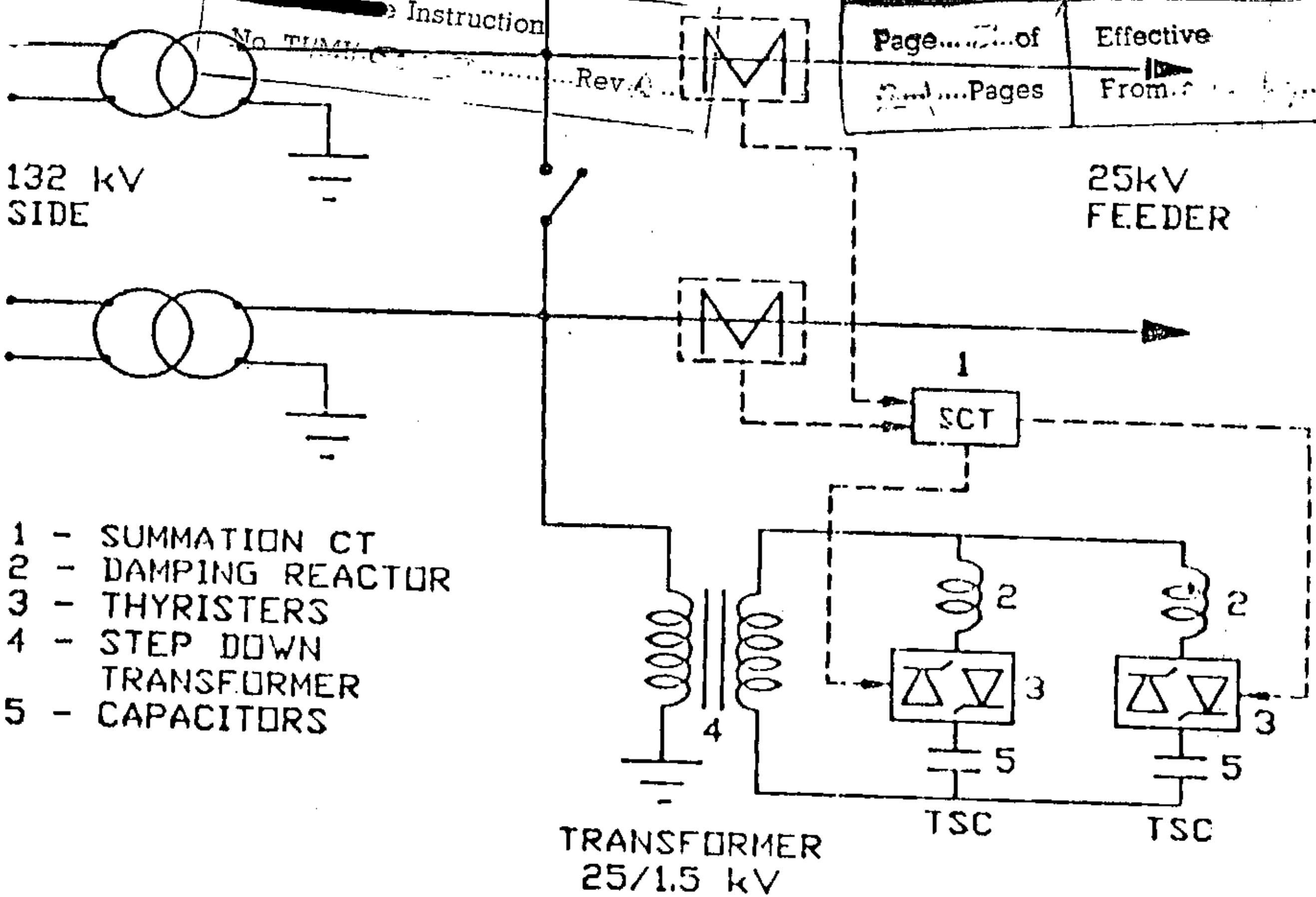


FIG. 1.0 THYRISTOR SWITCHED CAPACITOR

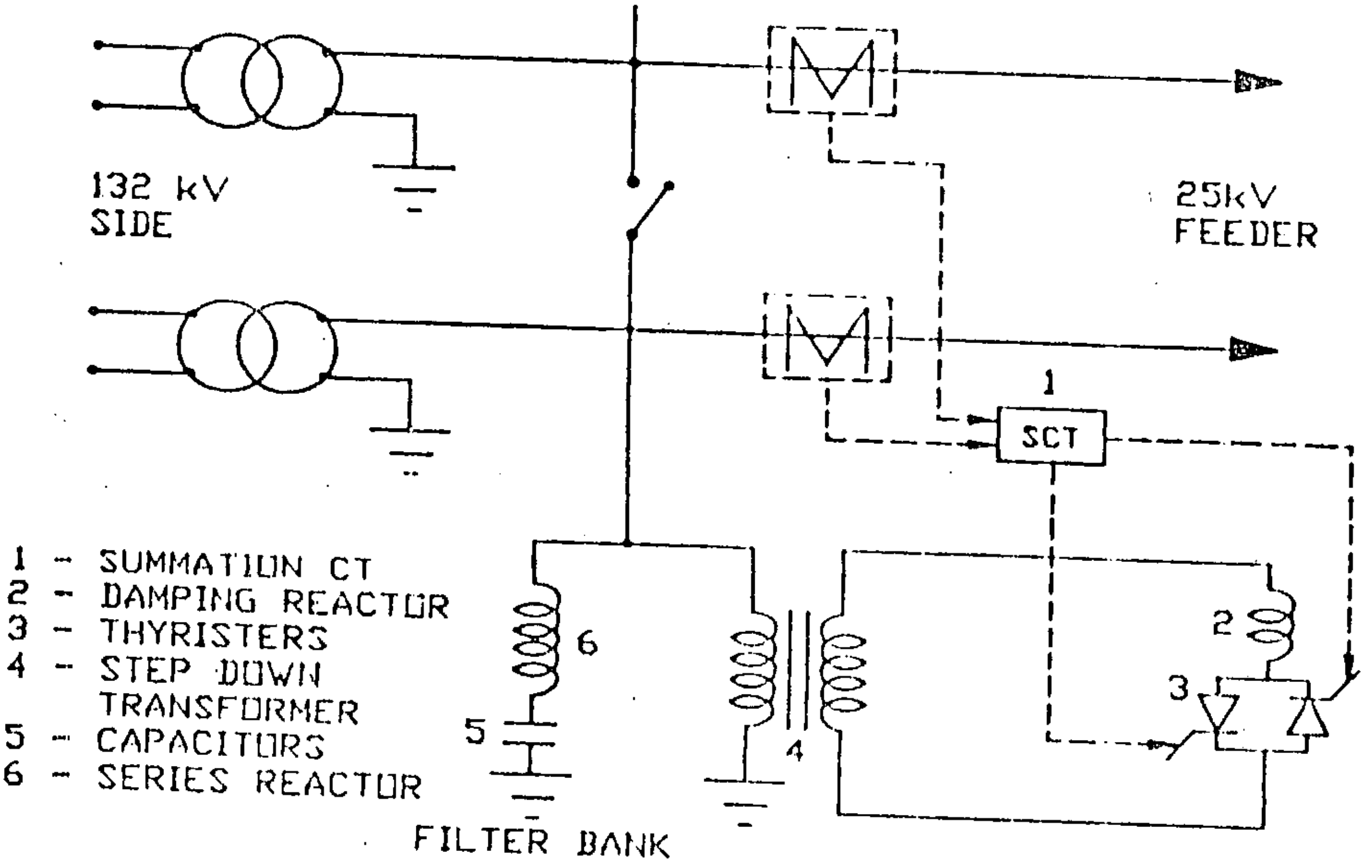


FIG. 2.0 THYRISTOR CONTROLLED REACTOR