

**USAID / SOUTH ASIA
REGIONAL INITIATIVE FOR ENERGY
(SARI/ENERGY)**

26th July to 8th August, 2010

**Central Institute for Rural Electrification
of**

**Rural Electrification Corporation Ltd
(A Govt. of India)**

Hyderabad, Andhra Pradesh, India

**CAPACITY BUILDING
PROGRAM ON
DISTRIBUTION SYSTEM LOSS
REDUCTION
FOR
AFGHANISTAN POWER
EXECUTIVES**

Reactive Power Management in Distribution Systems

INTRODUCTION:

- Reactive Power appears in every AC power system .
- Many loads consume active and reactive power also.
- Electric network itself consumes and produces reactive power.
- Transmission and distribution of electric power involves reactive power losses.

- Reactive power losses in the network are due to :
 - 1) Series Inductance of Transformers
 - 2) Overhead Lines
 - 3) Underground Cables
- Lines and cables of High System Voltages also generate reactive power due to their shunt capacitance

- There is a strong coupling between the reactive power balance of a power system and the voltages.
- If the balance is not proper, unacceptable voltages prevail.
- Excess reactive power means High Voltages.
- Deficit reactive power means Low Voltages.
- Reactive power imbalance, in some cases influences the power system stability.

MEANS OF REACTIVE POWER COMPENSATION:

- Shunt compensation: straight forward reactive power compensation method
- Series compensation: line reactance compensation method.
- Earlier means of furnishing reactive power:
 - Synchronous motors and condensers
 - Shunt capacitors
- In EHT Lines: Shunt reactors
 - Series capacitors
- Latest Development: Thyristor controlled static compensator.

- Reactive power is produced by over excited synchronous machines and capacitors
- Reactive power is consumed by under excited synchronous machines ,inductors etc.
- Composite loads of a power system vary with the time of the day, day of the week, and the season of the year and may also grow from year to year.

Network component characteristics:

- Two winding transformer: Series reactance
0.05 to 0.15 p.u
- Magnetizing reactive power may also increase rapidly with the voltage level
- Overhead lines and underground cables have series resistance, series inductance and shunt capacitance distributed uniformly along their length

- The reactive power generated due to the capacitance, the charging reactive power, is practically independent of the power transmitted.
- Reactive power loss due to the inductance varies with the power transferred.

Surge Impedance:

- Under surge impedance loading conditions, the reactive power loss due to the line inductance is equal to the reactive power generated by the line capacitance.

- $$P_o = \frac{U^2 (b)^{1/2}}{X} \text{ MW}$$

where U= Voltage , line-line kV

b= susceptance -mho/km

X= reactance -ohm/km

Overhead line characteristics at 50Hz

Operating Voltage (kV)	SIL (MW)	Line Charging (Mvar /km)	X (ohms/km)	X/R
0.4	-	-	0.4	0.5
10	-	-	0.4	0.5
130	50	0.05	0.4	3
220	130	0.14	0.4	6
400	550	0.6	0.33	15
750	2200	2.3	0.28	30

X/R ratio increases rapidly with the system voltage.

Underground cable characteristics at 50Hz

Operating Voltage (kV)	SIL (MW)	Line Charging (Mvar /km)	X (ohms/km)	X/R
0.4	-	-	0.07	0.3
10	3	0.01	0.10	0.4
130	500	2	0.15	2
220	1000	4	0.18	6
400	3200	13	0.20	7

Except for low voltage cables ,the SIL is usually much larger than the thermal rating.

Relationship of voltage with reactive power:



- The scalar voltage difference (the voltage drop) is defined by

$$U = |U_1| - |U_2|$$

- Approximately $U = RI \cos \phi + XI \sin \phi$

$$U = (RP + XQ) / U_2$$

- For transformers, R can be disregarded.
 - For transmission lines and cables, X is usually much larger than R .
- ▲
- There is greater influence on U , per kvar of reactive power than per kW of active power transmitted.

- Three major methods of power system voltage control
 - 1) Varying the excitation of the generators by means of their excitation systems.
 - 2) Varying the turns ratio of transformers by means of their on-load tap changers.
 - 3) Varying the shunt compensation , where applied.
- Drawing reactive power → affects voltage reduction
- Injection of reactive power → affects voltage rise

Series Compensation:

- By series compensation is meant, partial compensation of the line series reactance by means of a fixed capacitor in series with the line, thus reducing the effective reactance and the voltage difference.
- Nowadays, series compensation is employed on long EHV lines only.
 - 1) To improve the transient stability
 - 2) To obtain a desired load division among parallel circuits.

Relationship of losses and thermal loading of network components with reactive power :

$$i = \frac{(P^2 + Q^2)^{1/2}}{U_2}$$

$$P_{\text{loss}} = \frac{(P^2 + Q^2)}{U_2^2} R$$

- Transfer of reactive power means a higher current and thereby higher losses and higher thermal loading.
- The latter may influence the ratings of transformers and cables.
- Ideally, a reactive power balance should be affected within each region of a power system, within each transmission system and within each distribution system.

Reactive Power Compensation in transmission systems :

- It is advantageous to operate the transmission parts of a power system
 - 1) With a fairly flat voltage profile.
 - 2) With a relatively little supply of reactive power into the distribution system.
 - 3) With reactive power reserves available

HVDC Terminal Stations:

- HVDC converters always consume reactive power when in operation. The reactive power consumed is normally around 50% of the active power converted, which means that the terminal stations need large reactive power supplies.
- Most of the shunt capacitors, if not all of them, in a terminal station, form integral parts of the necessary A.C filters, which means that these shunt capacitors perform the dual tasks of reactive power production at fundamental frequency and filtering of current harmonics.

Reactive Power Compensation in Distribution Systems:

- Distribution Systems need supply of reactive power:
 1. To equalize the reactive power consumption of the load.
 2. To compensate for the net reactive power losses of the distribution network itself.
- The required reactive power is supplied from:
 1. Transmission system
 2. Shunt capacitors
 3. Static compensators

Average power factor values for the most commonly-used equipment and appliances

Equipment and appliances		cos ϕ	tan ϕ
Common load at induction motor	0%	0.17	5.80
	25%	0.55	1.52
	50%	0.73	0.94
	75%	0.80	0.75
	100%	0.85	0.62
Incandescent lamps		1.0	0
Fluorescent lamps (uncompensated)		0.5	1.73
Fluorescent lamps (compensated)		0.93	0.39
Discharge lamps		0.4 to 0.6	2.29 to 1.33
Ovens using resistance elements		1.0	0
Induction heating ovens (compensated)		0.85	0.62
Dielectric type heating ovens		0.85	0.62
Resistance-type soldering machines		0.8 to 0.9	0.75 to 0.48
Fixed 1-phase arc-welding set		0.5	1.73
Arc-welding motor-generating set		0.7 to 0.9	1.02 to 0.48
Arc-welding transformer-rectifier set		0.7 to 0.8	1.02 to 0.75
Arc furnace		0.8	0.75

- Power factor correction by means of fixed and switched shunt capacitors is much used in many urban, residential and rural systems.
- Active power loss $\rightarrow I^2R$
- Reactive power loss $\rightarrow I^2X$

Location of shunt capacitors in distribution systems :

- As close to the loads as possible.
- At places where we can postpone the reinforcement of the network otherwise needed.
- Install low voltage fixed capacitors to such an extent so that they equal the yearly minimum reactive load of the system.
- Remaining by installing switchable shunt capacitors

Maximum voltage change, when switching a bank shall not exceed 2% for hourly switching, 3% for daily switching and 5% for seasonal switching .

High power Industrial systems

- Induction motors are common loads.
- Consume reactive power of 0.6 to 1.1 kVAR/KW at rated outputs.
- Primary voltage control : by means of OLTCs.
- Power factor corrections : by means of switched and shunt capacitors.

Recommended size of capacitor for direct connection to Induction motors of different speeds to improve the power factor to 0.95 or better at all loads.

Motor HP	3000	1500	1000	750	600	500 R.P.M.
2.5	0.5	1	1	1.5	1.5	1.5
5.0	1	1.5	1.5	2.5	3	3
7.5	1.5	2.5	2.5	3	4	4
10	2.5	3	3	4	5	5
12.5	3	4	4	5	6	6
15	3	4	4	6	6	6
17.5	4	5	5	6	8	8
20	5	6	6	6	8	10
22.5	5	6	6	8	8	10
25	6	6	6	8	10	12
27.5	6	8	8	10	10	12
30	6	8	8	10	12	14
32.5	6	8	8	10	12	14
35	8	8	10	12	14	14
37.5	8	8	10	12	14	16
40	8	10	10	14	14	16
42.5	8	10	12	14	14	16
45	8	10	12	14	16	18
47.5	10	10	12	14	16	18

Motor HP	3000	1500	1000	750	600	500 R.P.M.
50	10	12	14	16	18	18
55	10	12	14	16	18	20
60	12	12	14	18	20	22
65	12	14	16	18	20	24
70	12	14	18	18	22	24
75	14	16	18	20	22	26
80	14	16	20	20	24	28
85	14	18	20	22	24	28
90	16	20	22	24	26	30
95	16	20	24	24	28	30
100	18	22	24	26	28	32
105	18	22	24	26	30	32
110	18	24	26	28	30	34
115	20	24	26	28	32	34
120	20	26	26	28	32	36
125	22	26	28	30	34	36
130	22	26	28	30	34	38
135	24	28	28	30	34	38
140	24	28	30	32	36	40
145	26	28	30	32	36	40
150	26	28	30	32	36	42
155	26	30	30	34	38	44

Motor HP	3000	1500	1000	750	600	500 R.P.M.
160	28	30	32	34	38	46
165	28	30	32	36	40	48
170	30	32	32	36	40	48
175	30	32	34	38	42	50
180	30	34	34	38	44	50
185	30	34	34	38	44	52
190	32	34	36	40	46	52
195	32	34	36	42	46	54
200	32	36	36	44	46	54
205	32	36	38	44	48	56
210	34	36	38	46	48	58
215	34	36	38	46	50	58
220	34	36	38	48	50	60
225	36	38	40	48	52	62
230	36	38	40	50	52	62
235	36	40	42	50	54	64
240	38	40	42	52	56	66
245	38	40	42	52	56	66
250	40	42	44	54	58	68

Arc Furnace Loads :

- Low P.F
- Unbalance
- Rapid active and reactive power fluctuations.
- Current harmonics
- Voltage fluctuation at the point of common coupling should lie below 0.3 %.
- Remedial measure : Static compensator

Ratings of capacitors bank for power factor correction of arc furnace

Rating of Arc Furnace Transformer MVA	Rating of Capacitor Bank MVAR
6	1.5 – 2.0
12.5	4 – 5
25 - 30	7.5 – 12.0
50 - 60	15 – 25
100	40 – 45
150	60 - 70

- Notes: (1) The recommended ratings of capacitor banks are for guide lines only intended to achieve a p.f. of 0.95 and above at peak load periods.
- (2) The arc furnace manufacturers normally give the rating and specifications of any capacitor bank required.

Reactive power compensation devices :

- Generators :
 - Produce reactive power when over excited
 - absorbs reactive power when under excited
- Shunt compensating devices

Synchronous condensers :

- Used in transmission systems at the receiving end of long transmissions and in conjunction with HVDC inverter stations.
- Have high short – time over load capability.
- Absorption capacity is normally of the order of 60% of MVA rating.

- Losses : 10 w/kvar at rated output.
- Present day application : HVDC inverter stations only, where the short circuit capacity has to be increased.

Shunt reactors

- Absorbs reactive power
- Applied in conjunction with long EHV overhead lines.
- Applied in conjunction with under ground cables in large urban areas.

Shunt Capacitors

Produce reactive power.

- Construction of a shunt capacitor bank is flexible
- Low over all cost
- High application flexibility
- Improvement of the voltage at the load
- Better voltage regulation
- Reduction of losses
- Postponement of investment in transmission

Disadvantage : Provide the least support when most needed because Q is proportional to V^2

Losses : 0.2 to 0.6 watts/KVAr.

Thyristor controlled static compensators

- First came as an alternative to synchronous condenser.
- Main application : Reduction of voltage fluctuations caused by arc furnaces.

Series capacitors :

- It is not a reactive power compensation device but a reactance compensation device.
- Greatly influence reactive power conditions of transmission systems.

Application:

- To increase the transmission load capability as determined by transient stability limits.
- To obtain a desired load division among parallel circuits.

- Reactive Power generated in a series capacitor increases with increasing transmitted load i.e, a self regulating device.
- Degree of compensation usually lies between 20 and 70% as referred to line inductive reactance.
- Choice of location requires special study in each case (about one third of the length from the receiving end)

Where to Install correction capacitors?

➤ Global compensation

The capacitor bank is connected to the busbars of the main LV distribution board and remains in service during the period of normal load. Capacitor KVAR per KW determined from the formula $KVAR/KW = \tan \phi 1 - \tan \phi 2$

Initial Power factor	Compensation required to improve upto				
	0.8	0.85	0.90	0.95	1.00
0.20	4.15	4.28	4.42	4.57	4.90
0.22	3.68	3.84	3.95	4.10	4.43
0.24	3.30	3.43	3.56	3.72	4.04
0.26	2.96	3.09	3.23	3.39	3.71
0.28	2.68	2.81	2.94	3.10	3.43
0.30	2.43	2.56	2.70	2.85	3.81
0.32	2.21	2.34	2.48	2.63	2.96
0.34	2.02	2.15	2.28	2.44	2.77
0.36	1.84	1.97	2.11	2.26	2.59
0.38	1.68	1.81	1.95	2.11	2.43
0.40	1.54	1.674	1.81	1.96	2.29
0.42	1.41	1.54	1.68	1.83	2.16
0.44	1.29	1.42	1.56	1.71	2.04
0.46	1.18	1.31	1.45	1.60	1.93
0.48	1.08	1.21	1.34	1.50	1.83
0.50	0.98	1.11	1.25	1.40	1.73
0.52	0.89	1.02	1.16	1.31	1.64

Initial Power factor	Compensation required to improve upto				
	0.8	0.85	0.90	0.95	1.00
0.54	0.81	0.94	1.07	1.23	1.56
0.56	0.73	0.86	1.00	1.15	1.48
0.58	0.65	0.79	0.92	1.08	1.41
0.60	0.58	0.71	0.85	1.00	1.33
0.62	0.52	0.635	0.78	0.94	1.27
0.64	0.45	0.58	0.72	0.87	1.20
0.66	0.39	0.52	0.65	0.81	1.14
0.68	0.33	0.46	0.59	0.75	1.08
0.70	0.27	0.40	0.54	0.69	1.02
0.72	0.21	0.34	0.48	0.61	0.96
0.74	0.16	0.29	0.43	0.58	0.91
0.76	0.10	0.24	0.37	0.53	0.59
0.78	0.05	0.18	0.32	0.47	0.50
0.80	-	0.13	0.27	0.42	0.745
0.82	-	0.08	0.21	0.37	0.70
0.84	-	0.03	0.16	0.32	0.635
0.86	-	-	0.11	0.27	0.59
0.88	-	-	0.06	0.21	0.54
0.90	-	-	-	0.16	0.48
0.92	-	-	-	0.10	0.43
0.94	-	-	-	0.03	0.36
0.96	-	-	-	-	0.29
0.98	-	-	-	-	0.20

Where to Install correction capacitors? (contd.)

➤ Compensation by Sector

Recommended when the installation is excessive where the load / time pattern differs from one part of the installation to another.

➤ Individual Compensation

When the power of motor is significant with respect to the power of the installation

The KVA_r rating of the capacitor bank is in the order of 25% of the KW rating of the motor.

Significant reactive currents no longer exist in the installation.

Active-power capability of fully-loaded transformers, when supplying loads at different values of power factor.

tan ϕ	cos ϕ	Nominal rating of transformers (in kVA)											
		100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.00	1	100	160	250	315	400	500	630	800	1000	1250	1600	2000
0.20	0.98	98	157	245	309	392	490	617	784	980	1225	1568	1960
0.29	0.96	96	154	240	302	384	480	605	768	960	1200	1536	1920
0.36	0.94	94	150	235	296	376	470	592	752	940	1175	1504	1880
0.43	0.92	92	147	230	290	368	460	580	736	920	1150	1472	1840
0.48	0.90	90	144	225	284	360	450	567	720	900	1125	1440	1800
0.54	0.88	88	141	220	277	352	440	554	704	880	1100	1408	1760
0.59	0.86	86	138	215	271	344	430	541	688	860	1075	1376	1720
0.65	0.84	84	134	210	265	336	420	529	672	840	1050	1344	1680
0.70	0.82	82	131	205	258	328	410	517	656	820	1025	1312	1640
0.75	0.80	80	128	200	252	320	400	504	640	800	1000	1280	1600
0.80	0.78	78	125	195	246	312	390	491	624	780	975	1248	1560
0.86	0.76	76	122	190	239	304	380	479	608	760	950	1216	1520
0.91	0.74	74	118	185	233	296	370	466	592	740	925	1184	1480
0.96	0.72	72	115	180	227	288	360	454	576	720	900	1152	1440
1.02	0.70	70	112	175	220	280	350	441	560	700	875	1120	1400

Example: (see Fig. 1.18)

An installation is supplied from a 630 kVA transformer loaded at 450 kW (P_1) with a mean power factor of 0.8 lagging. The apparent power $S_1 = \frac{450}{0.8} = 562$ kVA

The corresponding reactive power

$$Q_1 = \sqrt{S_1^2 - P_1^2} = 337 \text{ kvar}$$

The anticipated load increase $P_2 = 100$ kW at a power factor of 0.7 lagging.

The apparent power $S_2 = \frac{100}{0.7} = 143$ kVA

The corresponding reactive power

$$Q_2 = \sqrt{S_2^2 - P_2^2} = 102 \text{ kvar}$$

What is the minimum value of capacitive kvar to be installed, in order to avoid a change of transformer?

Total power now to be supplied:

$$P = P_1 + P_2 = 550 \text{ kW}$$

The maximum reactive power capability of the 630 kVA transformer when delivering 550 kW is:

$$Q_m = \sqrt{S^2 - P^2} \quad Q_m = \sqrt{630^2 - 550^2} = 307 \text{ kvar}$$

Total reactive power required by the installation before compensation:

$$Q_1 + Q_2 = 337 + 102 = 439 \text{ kvar}$$

So that the minimum size of capacitor bank to install:

$$Q_{\text{kvar}} = 439 - 307 = 132 \text{ kvar}$$

It should be noted that this calculation has not taken account of load peaks and their duration.

The best possible improvement, i.e. correction which attains a power factor of 1 would permit a power reserve for the transformer of $630 - 550 = 80$ kW.

The capacitor bank would then have to be rated at 439 kvar.

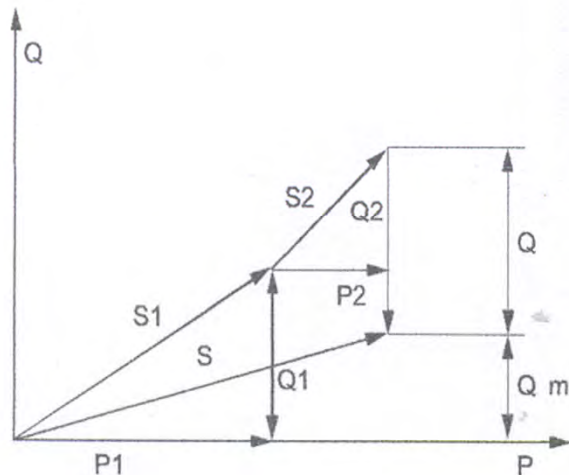


Fig. 1.18: Compensation Q allows the installation-load extension S_2 to be added, without the need to replace the existing transformer, the output of which is limited to S

- The installation of a capacitor bank can avoid the need to change a transformer in the event of a load increase.

Effect of Permanently Connected Capacitor on Voltage:

The effect of connecting a capacitor across transformer terminals is to cause a voltage rise at those terminals. A simplified expression for determining the voltage rise is:

$$\text{(Percent) voltage rise} = \frac{Q}{P} \times X_T$$

Where

Q = output of capacitor in KVAR

P = rating of transformer in KVA

X_T = reactance of transformer in percentage.

Example:

Transformer rating $P = 100 \text{ KVA} - 11/0.415 \text{ KV}$

Capacitor rating $Q = 6 \text{ KVAR}$

Fault level on the 11 KV

bus or transformer terminal = 100 MVA

$$\text{system reactance on 100 KVA base} = \frac{100 \times 100}{100 \times 1000} = 0.1\% \text{ (neglect)}$$

Therefore, percentage voltage rise at transformer

$$\begin{aligned} \text{secondary terminals} &= \frac{6 \times 4}{100} = 0.24\% \text{., assuming the} \\ \text{percentage reactance of the T/F} & \\ \text{is } &4\% \end{aligned}$$

Installation, Commissioning, Operation and Maintenance of Capacitor Banks:

- Life of capacitors is greatly affected by the operating temperature, which in turn is influenced by installation and operating conditions.

Installation:

Consideration to be given to:

- Fire hazard
- Explosive hazard
- Ambient temperature
- Ventilation of heat
- Lightning arresters and grounding to be taken care of.

Commissioning of Capacitor Banks:

- Continuous current rating of all the associated equipment should be 1.43 times the normal current for HT capacitors.

Commonly used Circuit Breakers:

- BOCBs
- MOCBs
- ABCBs
- VCBs
- SF6CBs
- Circuit Breakers for high voltage capacitors should be restrike free.

Making Current Capacity:

- Making current capacity at the encountered high frequency is of importance.
- In doubtful situations, advisable to deploy series reactors to limit inrush currents.

Protection:

- Shunt capacitors are subject to failure from external and/or internal causes.
- Protection generally consists of
 1. Fuse Protection
 2. System Protection by over current relays
 3. Bank Protection by relays

Secondary Bank Protection:

Single star capacitor Banks :

➤ **Neutral grounded :**

through CT

through PT

➤ **Neutral ungrounded :**

neutral displacement relay

Voltage differential relay

Double Star Capacitor Banks:

Neutral ungrounded Bank with neutral CT protection :
Neutral ungrounded with out - of - balance protection

- Method of connection depends on
 - System Neutral grounding
 - Bank location
 - Fusing practices
 - Possible inductive interference with communication circuits
 - Economic consideration

Generally large banks on transmission, sub transmission and distribution substation busbars are star connected.

Grounded Star Banks:

➤ Advantages:

Reduced recovery voltage on circuit breakers for normal repetitive capacitor switching duty

- Better surge protection
- Comparatively reduced over voltage phenomena

➤ Disadvantages:

- Necessity of recalculating zero sequence currents of the system
- Allows triple harmonic currents to flow freely, which causes interference with telephone communication circuits
- In case of banks having only one series group per phase, the flow of fault current in the event of short circuiting of any unit is very high.

If the short circuit current exceeds 4000 Amps, it may be advisable to leave the capacitor bank neutral ungrounded.

All the pre-commissioning tests on the capacitors and the associated equipment viz., circuit breaker, CT, RVT, neutral CT, L.A. and the testing of relays is to be carried out before energizing the capacitor bank

Control of Capacitor Banks at industrial loads:

- Manual Switching
- Automatic control with :
 - VAR sensitive without or with power factor control.
 - Current sensitive
 - Voltage Sensitive
 - Time switches

Operation:

- Conditions responsible for over loading of capacitors:
 - Operating voltage
 - Harmonics
 - Transient inrush currents

Operating Voltage:

Operation on	Voltage factor (multiple of rated voltage)	Maximum Duration	Observation
Power Frequency	1.00	Continuous	-
do	1.10	12 hrs in every 24 hrs	System voltage regulation and fluctuations
Do	1.15	30 min in every 24 hrs	System voltage regulation and fluctuations
do	1.20	5 min	Voltage rise at light load
do	1.30	1 min	-

Harmonics:

- Cause: Excessive currents and thermal overloading.
Internal partial discharges and rapid deterioration of dielectric.
- Harmonics are generated by:
 - Non-linear devices such as thyristors, rectifiers, SCR drives; Magnetic devices with non-linear B-H curves such as motors, generators when the magnetic circuit is saturated.

Resonance:

- The presence of harmonics may sometimes cause resonance with the system reactance.
- Fifth harmonic is the most important to be considered.

One method of preventing resonant conditions where capacitors are connected on the same bus as harmonic current generating equipment is employing series reactors.

Transient inrush currents:

- If the inrush current exceeds the capability of the breaker or the capacitors themselves, it becomes necessary to deploy current limiting reactors.

Reduction of inventory:

- Standardization of all the associated equipment is essential.

Maintenance of Capacitor Banks:

- Checking for fuse operation indication.
- Checking capacitance of individual units.
- Checking for bulging of capacitor container.
- Checking for leakage of liquid from the container.
- Cleaning of bushings.
- Maintenance of all other equipment associated with the capacitor banks.

Monitoring possible abnormal operating conditions of capacitor banks:

- Checking up voltage across the neutral displacement relay.
- Checking up neutral CT current.
- Checking up reactor temperature.
- Checking up any unusual noise from the reactors.

Thank You



ZWANI.COM