Module-4

REACTIVE POWER COMPENSATION AND VOLTAGE CONTROL

Introduction:

A power system engineer has been encountering in the distribution & transmission of power, a variety of problems such as voltage variations with load, poor power factor, large losses, electromagnetic and electromechanical oscillations followed by disturbances, supply voltage distortions due to harmonics generated by non-linear loads, interference with communications and so on. Their intensities may differ but all these problems exist in the main transmission, sub-transmission and distribution networks. The undertakings strive to provide un-interruptible supply with quality, minimize losses to conserve energy [31] and operate the system with timely actions in an attempt to overcome the adverse effects due to internal defects and external causes. In recent times the complexities in operation and control have increased due to a large variety of highly non-linear loads and electronic controllers. The primary concern in the thesis work undertaken is related to reactive power compensation, voltage control and energy conservation in a distribution system. In this chapter the conventional methods employed for reactive power compensation, their relative merits and demerits, desirable features of an advanced compensator in a distribution system are highlighted.

VAR Compensation:

Reactive power compensation by appropriate means has become the most economically attractive and effective solution technically for both traditional and new problems at different voltage levels in a power system. VAR compensation near load centre has gained more importance in recent times. It limits the flow of load reactive current in lines and feeders, boosts the voltage, reduces KVA demand and leads to both energy conservation and cost savings. Fig 3.1(a) & (b) show a typical distribution transformer feeding inductive loads and three a winding transformer at a receiving station requiring shunt reactive power COMPENSATION.

The desirable characteristic features of a shunt compensator are as mentioned below.

- Reactive power compensation of the load for power factor improvement.
- Stepless control of reactive power continuously matching with the prevailing load requirements from time to time.
- Maintenance of rated voltage at the point of common coupling within a narrow range irrespective of the load acting during the day.
- Reduction in the main line / feeder current, the losses and to conserve energy, throughout the day.
- Capacity to absorb line charging KVAr in very high voltage system under light load conditions.
- In case the loads introduce harmonics, the compensator should provide bypass paths for dominant harmonics and reduce the distortion levels.
- Under disturbed conditions the compensator is expected to act fast enough and damp out the oscillations.

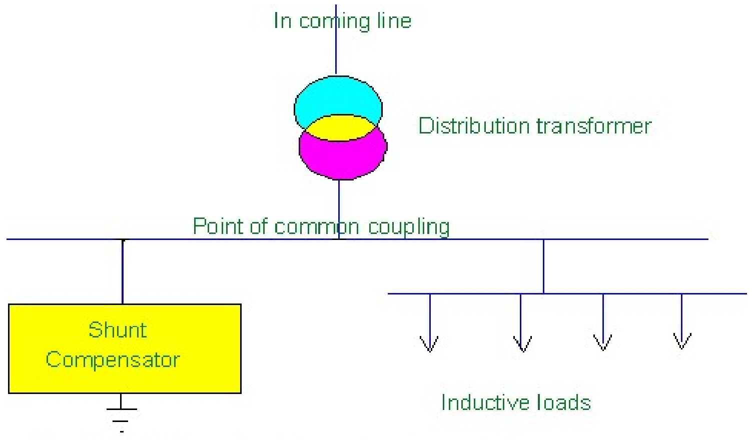

Fig. 3.1 (a) Schematic diagram showing a shunt Compensator on a distribution transformer

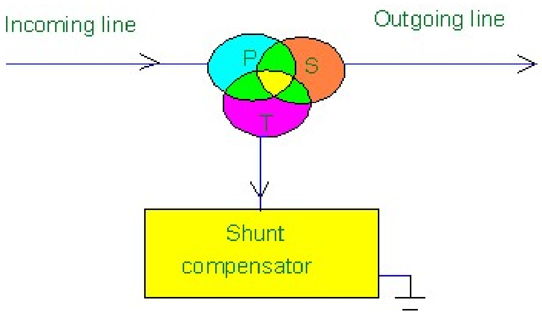

Fig. 3.1 (b) shunt compensator at a receiving station

Traditional Methods of VAR Compensation:

This section deals with the conventional methods employed for reactive power compensation and voltage control.

Synchronous Phase Modifier:

This is an ideal source having the capacity either to absorb or inject reactive power. However, it has got number of limitations as pointed out in section 1.5 (performance requirement). There are proven alternative methods of compensation available which are practically equivalent to SPM at low cost, more reliable, fast in response and giving trouble free service.

Shunt Capacitors:

The use of shunt capacitors in conventional way through mechanical switches has the following advantages:

- Overall cost is very low.
- The installation is simple requiring no strong foundations.
- Incur negligible losses
- Less maintenance problems
- More reliable in service with long life.

However, notable short coming are:

- Not possible to vary reactive power matching with load demand continuously (only step variation).
- There exist a possibility for harmonics, if present, to get amplified.
- There also exists a scope for series / parallel resonance phenomenon to occur, which requires to be investigated prior hand.

Hence the choice of a suitable compensator scheme calls for detailed study and careful design before implementation.

Series Capacitors:

A capacitor bank can be interposed is a line to partially neutralize the line reactance. Such an arrangement has the following attractive features.

- It automatically provides reduction in line voltage drop with increased loads.
- It increases the power handling capacity of a line by reducing the transfer reactance.
- It reduces voltage flicker and damp out transient oscillations.
- Quite effective in maintaining the voltage profile.

However, it poses serious problems during faults, prone for resonance phenomenon, complexity in control and likely to give rise to sub-synchronous oscillations. Hence the series capacitors can be installed after careful study only. They are employed widely in HV lines and somewhat uneconomical for distribution networks, as the requirements in both cases differ widely.

Static VAR Compensator:

This essentially consists of capacitor bank in suitable steps (operated through mechanical switches / thryristors) and thyristor controlled reactor across it of the size of minimum step. This combination yields step less variation of reactive power over the entire range. When SVC is applied at a receiving station it is possible to absorb line charging KVAr produced under light load conditions. This will enable to avoid over voltage phenomenon under light loads. The main theme of this thesis work is application of multilevel advanced static VAR compensator with a closed loop controller on a distribution transformer. The notable features of SVC are[32, 33]

- Close matching of load reactive power
- Maintenance of power factor near unity
- Voltage control and reduction in losses

However, SVC has the following limitations.

- Switching of capacitor bank steps require appropriate coordination.
- Complexity in the control of TCR.
- Generation of harmonics through TCR control

Harmonic Filters:

Most loads consume reactive power, highly non-linear and generate harmonics. The twin problems, reactive power compensation and harmonics reduction are carried out using shunt passive filters. These are tuned LC circuits to provide low impendence paths for dominant harmonics. They are quite effective in reducing the total harmonic distortion levels. An appropriately designed filter scheme can provide low impendence paths for harmonics and inject reactive power at fundamental frequency. The tuning reactor in every filter also serves the purpose of limiting inrush / outflow currents during switching operations. A filter scheme consisting of 2/3 selectively tuned filters for lower order dominant harmonics and a high pass filter can meet the most commonly encountered requirements in LT and HT applications. It is possible to choose the appropriate filter scheme at the point of common coupling depending on the load, its pattern of variation, harmonics present, reactive power compensation at fundamental frequency so as to improve the power factor, relieve the system from adverse effects due to harmonics and improve the quality of power supply.

The advantages of shunt passive filters are:

- These are of relatively low cost, less complex, easy to operate and reliable.
- Reduction in total harmonic distortion levels and improvement in the quality of power supply.
- These have long life compared to active filters.
- Reactive power compensation and associated benefits similar to the use of shunt capacitors.
- Reduction in metering errors, communication interference, and heating of electrical apparatus.

The limitations in their application are:

- Capacitors and Reactors are to be specially designed.
- Every filter in the scheme has to be provided with protection and control arrangement.
- The scope for possible series / parallel resonance exists and should be avoided by careful study before implementation.
- These do not offer 100% solution for harmonic suppression similar to active filters.

- Their performance is subject to parameter variations, ageing etc. and precise tuning not possible.

Advanced Compensators:

The conventional techniques of reactive power compensation have been dealt in the above sections. As seen, each method has its own merits and limitations. Number of improvement have been brought out over the years with the increased usage of high power rated thyristors and advanced control techniques. There has been a growing tendency to increase the number of functions to be carried out by a compensator, either series, shunt or hybrid type. This section deals with the requirements of a compensator and reviews the advances that have taken place in the recent past.

: Role of series / shunt Compensator:

Consider a transmission line with sources at either end, provided with shunt and series compensator separately.

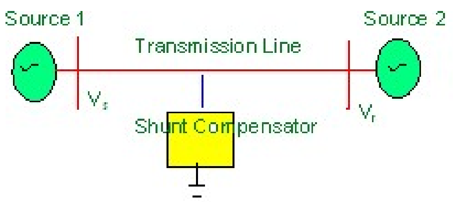

Fig 3.2 (a) Shunt Compensator

Fig 4.2 (b) Series Compensator

A shunt compensator provided say at the middle of a line (Fig. 3.2 (a)) if effectively controlled can maintain the voltages V_s and V_r equal irrespective of the directions of P & Q flows. This type of ideal compensator doubles the power handling capability, improves the power factor and maintains good voltage profiles. However, it is difficult to practically realize fully such a condition of operation. It is quite effective in providing reactive power compensation, improves steady state performance and damps out the transient oscillations during disturbances. It is usually a fast acting static VAR compensator.

On the other hand a series compensator interposed in the transmission line as shown in fig. 3.2 (b) either at sending end or somewhere in the line is quite effective to provide partial neutralization of line impedance and to reduce the voltage drop in the line. This improves the power handling capability of the line and damps out electromagnetic oscillations. However, as compared to shunt compensator, series compensator is complex to control and protect, costly and must be carefully designed to avoid sub synchronous oscillations. Both the methods have their own attractive features and limitations. It has been established that a combination of shunt and series compensators called hybrid scheme works out well. To have a understanding of the advanced compensator in the modern power systems, consider the following case as shown in fig. 3.3

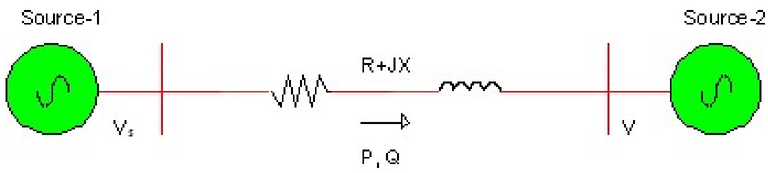

Fig - 3.3 Simplified Schematic Diagram of a Line between Two Sources

Under simplify conditions of operation (neglecting shunt paths). It is well known that, the relative magnitude difference between $|V_s|$ and $|V_r|$ determines the direction and magnitude of reacting power flow in the line. On the other hand the relative phase angle displacement between V_s and V_r will determine the direction and magnitude of real power flow. For example, if $|V_s| > |V_r|$ and V_s leads V_r then both P & Q flow from source-1 to source-2. If $|V_s| < |V_r|$ and still leads V_r then P flows from soucr-1 to source-2 and Q flows from source-2 to source-1. This clearly indicates that the magnitude of P & Q and their directions of flow depend on the voltage magnitudes and their phase angles. To have an understanding of the influence of voltage control in its magnitude and direction, consider a situation with nominal values of V_s, V_r and P_0, Q_0 in the line subject to incremental changes in voltage deviation and phase angle difference. This obviously gives rise to four quadrant operation with coordinate axis around 'O' point corresponding to the nominal values. Fig 3.4 and table 3.1 gives the four quadrant operation for incremental values in $\Delta|V|$, $\Delta\delta$, ΔP, ΔQ.

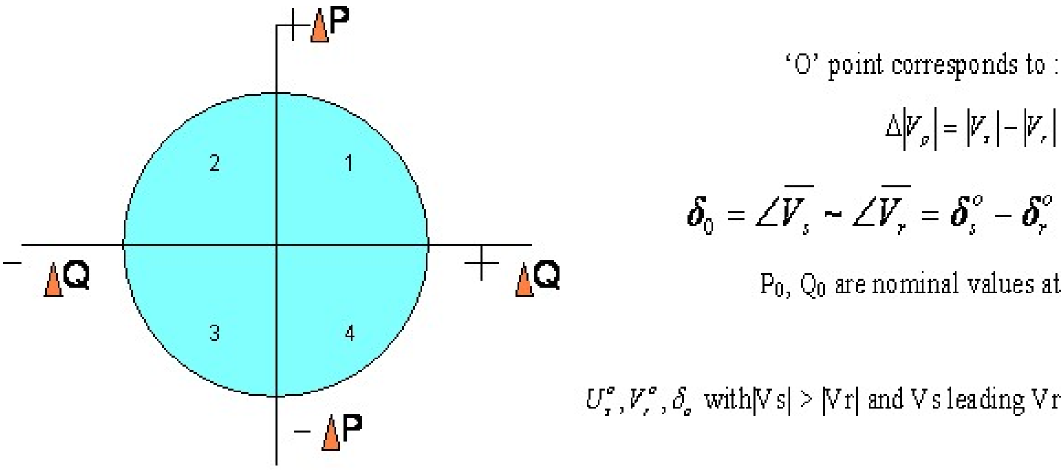

Fig - 3.4 Four Quadrant Operations For Incremental P & Q

Quadrant	$\Delta\lvert V_1\rvert$	$\Delta\delta$	ΔP	ΔQ
1	+	+	→	→
2	-	+	→	←
3	-	-	←	←
4	+	-	←	→

Table 3.1. Four quadrant operation for incremental changes in $\Delta\lvert V\rvert$, $\Delta\delta$ and the corresponding changes in ΔP and ΔQ.

A variety of compensating devices both in series and shunt forms have been developed over the years to achieve complete control on a voltage profile, the magnitude and directions of both P and Q flows. The schemes in vogue are STATCOM, power conditioners, energy sourced inverters, in phase and quadrature boosters and so on. The detailed treatment of this advanced compensators is outside the scope of present work.

Requirements of Advanced Compensator for distribution Systems:

In recent years lot of developments have taken place in FACT devices (flexible AC transmission) for their applications in interconnected power systems[34, 35]. However, that much attention was not paid to the compensators in the distribution system. It is in this perspective attempt is made to develop an advanced shunt compensator as could be made applicable on mass scale for the distribution transformers. The work proposed aims at developing a static VAR compensator with the following technical features:

- To design a static VAR compensator with capacitor bank in five binary sequential steps.
- To design a thyristor controledl reactor of KVAr capacity equal to the lowest size of capacitor bank step.
- To design an electronic feedback controller with high gain and low time constant for fast response.
- To sense the reactive power requirement as per the prevailing load, at periodical intervals.
- To coordinate the switching ON and OFF operations of the capacitor bank steps with permissible time delays from OFF state to ON state.
- To initiate operation through feedback controller for obtaining reactive power from the compensator.

- To continuously monitor the reactive power injection, voltage condition and to maintain the power factor near unity.

The advantages contemplated with the use of above mentioned static VAR compensator on a distribution transformer are as mentioned below:

- Control of voltage and maintenance of power factor
- Reduction in feeder losses and conservation of energy
- Relief in tariff and reduction in maximum demand.
- Flexibility in control and reliability in operation.
- Limited generation of harmonics from TCR and reduction in phase unbalance.
- Minimization of neutral currents / potentials.
- Improvement in the quality of power supply.

Transformer Tap Changer effect on Reactive Power

6.1 In line with IEGC clause 6.6.5 & 6.6.4, the transformer tap positions on different 765kV, 400kV & 220kV class ICTs & GTs shall be changed as per requirements in order to improve the grid voltage. RLDCs shall coordinate and advise the settings of different tap position of ICTs in their region. And any change in their positions shall be carried out after consultation with RLDC only. Normally tap position of all the ICTs shall be reviewed/changed at every three month interval.

6.2 Transformers with tap-changing facilities constitute an important means of controlling voltage throughout the system at all voltage levels. Coordinated control of the tap changers of all the transformers interconnecting the subsystems is required if the general level of voltage is to be changed.

6.3 As per CEA Manual on Transmission Planning Criteria, in planning studies all the transformers may be kept at nominal taps and On Load Tap Changer (OLTC) may not be considered. Hence the effect of the taps should be kept as operational margin for system operator.

6.4 The OLTC allows voltage regulation and/or phase shifting by varying the turns ratio under load without interruption. Large power transformers are generally equipped with ―voltage tap changers,‖ sometimes called ―taps‖ with tap settings to control the voltages either on the primary or secondary sides of the transformer by changing the amount and direction of reactive power flow through the transformers. Transformer taps can be controlled automatically based on local system conditions or manually.

6.5 **Generating Transformer:** - Power generated at generating station (usually at the range of 11kV to 25kV) is stepped up by generating transformer to the voltage level of 220, 400, 765kV for transmission. It is one of the important and most critical components of power system. They are generally provided with off circuit tap changer with a small variation in voltage because the voltage can always be controlled by the field of generator. Generating Transformer with OLTC also used for reactive power control.

6.6 **Interconnecting Transformer: -** Normally autotransformers are used to interconnect two grid/systems operating at two different voltage levels (i.e.400 and 220kV). They are normally located between generating transformer and receiving end transformer. In autotransformer there is no electrical isolation between primary and secondary. Some volt-amperes are conductively transformed and some are inductively transformed.

REACTIVE POWER

Reactive power is defined for AC systems only. Reactive power is produced when the current waveform is out of phase with the voltage waveform due to inductive or capacitive loads. Current lags voltage with an inductive load and leads voltage with a capacitive load. Only the component of current in phase with voltage produces real or active power that does real work like running motors, heating etc. Current is in phase with voltage for a resistive load like an incandescent light bulb. Reactive power is necessary for producing the electric and magnetic fields in capacitors and inductors.

Reactive power is present when the voltage and current are not in phase, one waveform leads the other, Phase angle not equal to zero and power factor less than unity. It is measured in volt-ampere reactive (VAR). It is produced when the current waveform leads voltage waveform (Leading power factor). Vice versa, consumed when the current waveform lags voltage (lagging power factor).

The additional current flow associated with reactive power can cause increased losses and excessive voltage sags. Transmission system operators have to ensure that reactive reserves are available to handle system contingencies such as the loss of a generator or transmission line because increased current flow after the occurrence of contingencies can produce greatly increased reactive power absorption in transmission lines.

The transmission lines generate VARS under No load or less loaded conditions and consume VARS under loaded conditions. At any given point of time the power system can experience different voltage levels at various locations.

In general, under peak load conditions, voltages are high at reactive source points and are low at load points and the direction of reactive power flow is from source to the load, whereas, under the off peak conditions, the reactive power flow is from load points to source.

The transmission of VARS over transmission elements during peak load conditions further burdens the transmission elements and as a result, the voltages at the load end become further less. Hence it is desirable to meet the reactive power requirement locally and necessary planning of reactive compensation to be carried out. Even at nominal frequency and satisfactory voltage operating conditions, voltage collapse cannot be ruled out as voltage is a local phenomenon.

System voltage levels are directly related to the availability of reactive power. System events, such as the loss of a transmission line, create an instantaneous change in the reactive power demand. Shunt capacitors are not able to switch fast enough to supply the increase in demand and prevent further voltage decline.

VOLTAGE MANAGEMENT

3.3.1 Control of voltage levels is accomplished by controlling the production, absorption, and flow of reactive power at all levels in the system. Unlike
system frequency, which is consistent throughout an interconnected system in the steady state, voltages experienced at points across the system form a "voltage profile" which is uniquely related to local generation and demand at that instant, and is also affected by the prevailing network arrangements.

3.3.2 Controlling the voltage is a local problem. In other words,the voltage control problems need to be solved separately by each control area. This can be achieved by providing sufficient reactive power sources for controlling voltage level as specified in

IEGC. The voltage controlling problems can be divided into two situations, which are normal situation and emergency situation.

3.3.3 Voltage changes continuously according to the varying electrical demand, transmission lines utilization etc. Reactive power (VAR) is required to maintain the voltage to deliver active power (watts) through transmission lines. When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines.

VOLTAGE STABILITY

a) Voltage stability‖ is the ability of the power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to disturbance. A system enters steady voltage instability when a disturbance (An increase in load demand, or change in system conditions) causes a progressive and uncontrolled drop in voltage.

b) A system is voltage unstable, if for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection in the same bus is increased.

c) ‗Voltage Instability‖ is basically caused by non-availability of reactive power support in some nodes of the network, where the voltage uncontrollably falls. Lack of reactive power may essentially have two origins,

i. Gradual increase of power demand where the reactive requirement at some buses cannot be met.

ii. Sudden change of network topology redirecting the power flows
in such a way that the reactive power cannot be delivered at some buses.

d) The increased load is always accompanied by a decrease of voltage except in the case of a capacitive load. When the loading is further increased, the maximum loadability point is reached, from which no additional power can be transmitted under those conditions.

In case of constant power loads, the voltage in the nodes become uncontrollable and rapidly decreases.

VOLTAGE COLLAPSE:

a) When voltages in an area are significantly low or blackout occurs due to the cascading events accompanying voltage instability, the problem is considered to be a voltage collapse phenomenon. Voltage collapse normally takes place when a power system is heavily loaded and/or has limited reactive power to support the load.

PROCEDURES FOR CONTROLLING VOLTAGE AND REACTIVE POWER:-

a) The control of voltage level is accomplished by controlling the production, absorption and flow of reactive power at all levels in the system. (Refer Table –1 for sources and sinks of reactive power.)

b) **Primary Voltage Control**: RLDCs shall control primary voltage by providing specific voltage levels to generators according to the requirement. The generators shall adjust the AVR which will vary the excitation of generating units in order to achieve the specified voltage levels. For other voltage control equipment such as SVCs or automatic tap changing transformers, they are considered to be a part of primary voltage control.
The maximum and minimum values in the above table are the outer limits and all the regions shall endeavour to maintain the voltage level within the above limits. The steady state voltage is maintained within the limits given in above table. However, the step change in voltage may exceed the above limits where simultaneous double circuit outage

of 400 kV lines are considered. In such cases, it may be necessary to supplement dynamic VAR resources at sensitive nodes.

c) SLDC/RLDC may direct a wind farm to curtail its VAr drawal/Injection on considering system security or safety of personnel/equipments.

d) The control centers shall apply the following mechanism for voltage control in general.

i) Generating units of all the region shall keep their Automatic Voltage Regulators (AVRs) in operation and power system stabilizers (PSS) in AVRs shall be tuned in line with clause 5.2(k) of IEGC.

ii) The transformer tap positions on different 765kV, 400kV & 220kV class ICTs & GTs shall be changed as per requirements in order to improve the grid voltage.

Switching off of the lines in case of high voltage:-

i) In the event of persistent high voltage conditions when all other reactive control measures as mentioned earlier including opening of redundant HT lines within the state system by the concerned SLDCs have been exhausted, selected 400 / 230 / 220 / 132 / 110 KV lines shall be opened for voltage control measures.

ii) The opening of lines and reviving them back in such an event would be carried out as per the instructions issued by RLDC/NLDC in real time and as per the standing instructions issued from time to time. While taking such action, RLDC/NLDC would duly consider that to the extent possible the same does not result in affecting ISGS generation as well as the system security & reliability is not affected.

h) **VAR Exchange by regional constituents for Voltage and Reactive Control:**

i. Each constituent shall provide for the supply of its reactive requirements including appropriate reactive reserves, and its share of the reactive requirements to support safe and secure power transfer on interconnecting transmission circuits.

ii. The RLDC and constituent states shall take action in regard to VAR exchange with the grid looking at the topology and voltage profile of the exchange point. In general, the beneficiaries shall endeavour to minimize the VAR drawl at interchange point when the voltage at that point is below the nominal value and shall not inject VARs when the voltage is above the nominal value. In fact, the beneficiaries are expected to provide local VAR compensation so that they do not draw any VARs from the grid during low voltage conditions and do not inject any VARs to the grid during high voltage conditions.

i) **VAR generation / absorption by generating units: -** In order to improve the overall voltage profile, the generators shall run in a manner so as to have counter balancing action corresponding to low/high backbone grid voltage and to bring it towards the nominal value. In order to achieve the same, all generators shall generate reactive power during low voltage conditions and absorb reactive power during high voltage conditions as per the capability limit of the respecting generating units.

Load Management for controlling the Voltage:- All the regions shall identify the radial feeders in their areas in consultation with SLDCs which have significant reactive drawls and which can be disconnected in order to improve the voltage conditions in the event of voltage dropping to low levels. The details of all such feeders shall be kept ready in the respective control rooms of RLDC/SLDC and standing instruction would be given to the operating personnel to ensure the relief in the hour of crisis by disconnecting such feeders.

k) **Following corrective measures shall be taken in the event of voltage going high / low:-**

1. In the event of high voltage (when the bus voltage going above 410 kV), following specific steps would be taken by the respective grid substation/generating station at their own, unless specifically mentioned by NLDC/RLDC/SLDCs.

i) The bus reactor be switched in

ii) The manually switchable capacitor banks be taken out

iii) The switchable line/tertiary reactors are taken in.

iv) Optimize the filter banks at HVDC terminal

v) All the generating units on bar shall absorb reactive power within the capability curve.

vi) Operate synchronous condensers wherever available for VAR absorption.

vii) Operate hydro generator / gas turbine as synchronous condenser for VAR absorption wherever such facilities are available.

viii) Bring down power flow on HVDC terminals so that loading on parallel EHV network goes up resulting in drop in voltage.

ix) Open lightly loaded lines in consultation with RLDC/SLDC for ensuring security of the balanced network.

2. In the event of low voltage (when the bus voltage going down below

390kV), following specific steps would be taken by the respective grid substation/generating station at their own, unless specifically mentioned by NLDC/RLDC/SLDCs.

i) Close the lines which were opened to control high voltage in consultation with RLDC/SLDC.

ii) The bus reactor be switched out

iii) The manually switchable capacitor banks are switched in.

iv) The switchable line/tertiary reactor are taken out

v) Optimize the filter banks at HVDC terminal**.**

vi) All the generating units on bar shall generate reactive power within capability curve.

SYSTEM FREQUENCY & VOLTAGE CONTROL:-

i) This option is rarely used say for example when two islands has to be synchronized and voltage has to be controlled at the end where line has to be synchronized.

ii) Voltage of the large interconnected grid can also be controlled by controlling the system frequency. As per Modern Power Station Practice, System Operation Volume-I (2), the general synchronous machine equations shows that voltage levels are directly proportional to frequency and for good voltage control extremes of system frequency must be avoided.

$E=4.44\phi f N$. Where: E is the EMF Generated; f is the Frequency, ø the flux.

iii) Times of low frequency are usually associated with plant shortage. The reactive capability is low as the units are running at rated MW capacity; any increase in reactive power would only be at the cost of reduction in MW output, something that is not usually allowed as per the Indian Electricity Grid Code section 6.6 Para 6.

ADVERSE WEATHER CONDITIONS AND VOLTAGE CONTROL

As per Modern Power Station Practice, System Operation Volume-L [2], Fog or other conditions of high humidity give an increased risk of insulation flashover which can be minimised by reducing voltage levels. However under critically loaded conditions, it is judged that the risk of running with reduced voltage levels outweighs.