The total control system incorporates a status processor and cathode ray tube (CRT) display/data entry terminal in the control system.

The primary functions of the status processor are the monitoring of the control circuits in operation for any alarm or trip conditions and the execution of control commands and adjustments of operating parameters by the operator.

The status processor also includes diagnostic software routines accessible by maintenance personnel *via* the CRT terminal on the SVC control panel aid trouble shooting and system checkout. A detailed status history is also maintained by the status processor which can be displayed on the CRT terminal.

This capability has provided to the extremely useful and a flexible tool in diagnosing control and thyristor valve related problems.

49

Interconnected Power Systems

Introduction — System configuration and Principle of Interconnection — Merits — Limitations — Tie-line Power — Obligation of Participating System — Relative priority — Correlation between Real Power Generation, Tie-line Power Flow and Load Frequency Control — Control of Tie-line Power in 2 Area System and 3 Area System — Scheduled Interchange and Actual Interchange — Tie-line Bias Control — Basic Equations — Actions by operators — Phase shifting Transformers — SCADA Systems — National Grid of India.

49.1. INTRODUCTION

During the early years small local generating stations supplied power to respective local loads. Each generating station needed enough installed capacity to feed the local peak loads. Gradually, the merits of interconnected AC power systems were recognised.

The interconnection of individually controlled AC networks gives several advantages such as :

— Lesser spinning reserves
— Lesser installed capacity
— Better use of energy reserves
— Economic generation
— Minimise operational costs, maximise efficiency
— Better service to consumers.

Modern power system (Network) is formed by interconnecting several individually controlled AC networks. Each individually controlled AC network has its own generating stations, transmission and distribution systems, loads and a load control centre. The regional load control centre controls the generation and in its geographical region to maintain the system frequency within targeted limits (50.5 – 49.5 Hz). The exchange of power (Import/Export) between neighbouring AC networks is dictated by the National Load Control Centre. Thus the entire AC network is an interconnected network called National Grid. Even neighbouring National Grids are interconnected to form a Super Grids. (*e.g.* USA Canada; European Grid ; UK-France). Interconnections between India-Pakistan, India-Shri Lanka, India-Nepal etc. are in initial planning stage (1997).

The main task of an interconnecting transmission system is to transfer adequate power from one AC system to the other AC system during normal conditions and also during emergency condition and maintain system security. Traditionally AC lines have been used for interconnection. However, HVDC links give asynchronous interconnection and have a distinct superiority over AC links for the application of system interconnection. HVDC system interconnection may have a transmission line/cable or it may be in the form of a back-to-back convertor station without a transmission line. HVDC links are also used for interconnection between AC systems having different frequencies *e.g.* 50 Hz to 60 Hz. The choice of voltage of EHV-AC or HVDC Inter-connection link is decided by the economic studies related with power transfer and distance.

Present HVDC interconnections are with two terminals. Recently multi-terminal HVDC systems have been executed (1987). With multi-terminal HVDC systems, several AC systems can be interconnected. Back-to-back HVDC stations are preferred for interconnecting adjucent AC systems to provide Asynchronous tie.

Inter-connection has significant influence on load-frequency control, short-circuit levels, power system security and stability, power system protection and control, energy management, financial accounting etc.

Energy management EM has received due attention during recent years and the Interconnections have received greater importance.

49.2. SYSTEM CONFIGURATION AND PRINCIPLE OF INTERCONNECTION

Fig. 49.1 gives a schematic diagram of a Group of Interconnected Power Systems (called National Grid in Indian Context).

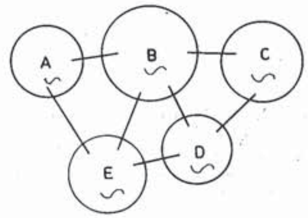


Fig. 49.1. Interconnected Power systems.

A, B, C, D, E are interconnected by Tie Lines. Each Area has its individual load-frequency controls which controls the total generation of the Area to match the load, losses and the net interchange. The generation control is by AGC (Automatic Generation Control System). Total control of

Each individual AC system (A, B, C) etc. called Regional Grid has its own Regional load control centre for its Automatic Generation Control (AGC) such that the load-frequency is controlled and frequency is maintained within target limits.

49.2.1. Individual System (Region or Area).

Each individual system generates enough power equal to the Regional load plus losses, plus required net interchange with adjacent systems *via* the tie-lines (interconnectors).

Total Generation = Total area load+Total net interchange by area

$$P_{GA} = \Sigma P_{LA} + \Sigma P_{iA} \quad ...(49.1)$$

where P_{GA} = Total Generation of Area A, MW

ΣP_{LA} = Total load on Area A, including losses, MW

ΣP_{iA} = Total net interchange by Area A, MW

By maintaining the balance between RHS and LHS in Eqn. 49.1; the frequency of area A is maintained within targetted limits. This condition is fulfilled by *Automatic Generation Control* (AGC) performed by the Regional Load Control Centre (of area A). Thus each area has to fulfil the following obligation :

Total generation = Total load plus losses + Net interchange

$$\left.\begin{aligned} \Sigma P_{GA} &= \Sigma P_{LA} + \Sigma P_{iA} \\ \Sigma P_{GB} &= \Sigma P_{LB} + \Sigma P_{iB} \\ \Sigma P_{GC} &= \Sigma P_{LC} + \Sigma P_{iC} \\ &\dots \quad \dots \quad \dots \\ \Sigma P_{GN} &= \Sigma P_{LN} + \Sigma P_{iN} \end{aligned}\right\} \quad ...(49.2)$$

where ΣP_{NG} = Total Generation of N_{th} Area

ΣP_{LN} = Total load plus losses of N_{th} Area MW

ΣP_{iN} = Total net interchange by N_{th} Area.

49.2.2. Total Generation in Interconnected Systems (National Grid)

Total Generation of the Group of Interconnected systems (called the National Grid) is equal to the total load plus total losses, the algebraic sum of net interchanges becomes zero *i.e.*

$$\Sigma \text{Imports} = \Sigma \text{Exports}$$

$$\Sigma P_G = \Sigma P_L + \Sigma P_i \quad ...(49.3)$$

$$\Sigma P_G = \Sigma P_L, \ \Sigma P_i = 0 \quad ...(49.4)$$

where ΣP_G = Total generation of all areas in the National Grid, MW

ΣP_L = Total load of all Areas, plus total losses in all Areas, MW

ΣP_i = Total algebraic sum of net interchanges of all Areas.

Note : Total net interchange (ΣP_i) in the Grid is the algebraic sum of interchange by all individual Area *i.e.*

$$\Sigma P_i = \Sigma P_{iA} + \Sigma P_{iB} + \dots + \Sigma P_{iN}$$

$$\Sigma P_i = 0 \quad ...(49.5)$$

The algebraic sum of interchange of all areas is zero.

This has been explained in Sec. 49.9.

For stable frequency.

$$\Sigma P_G = \Sigma P_L.$$

$$\Sigma P_s = \Sigma P_L$$

This condition is fulfilled by the control by National Load Despatch Centre. National Load Control Centre Instructs Regional Load Control Centres to export/import scheduled power so as to satisfy Eqn. 49.5.

If total Generation in Grid is lesser than total load on the Grid, the frequency of entire grid starts falling. Fall of frequency causes increase power inflow from neighbouring region.

If total Generation is more than total load, frequency starts rising.

National load control centre determines the total generation requirement and allocates the amount of generation to each Area for fulfilling the requirements of interchange.

Load-frequency control is automatic. The generation in each Area is made equal to the load plus net tie-line exchange so as to maintain the frequency within the targetted limits.

This is achieved by two actions :

1. Primary load frequency control : by Governor action of each turbine generator.

2. Secondary control : by enough interchange of power between Regional Grids as per instructions of Load Control Centre.

49.3. MERITS OF INTERCONNECTED POWER SYSTEM

Interconnections offer several advantages subject to the conditions mentioned in Sec. 49.5. Limitations of Interconnections have been mentioned in Sec. 49.6. Due to tremendous advantages, Interconnections have been accepted universally by various National Networks and also between neighbouring National Networks (*i.e.* between USA and Canada ; between England and France ; several Nations in Europe ; Sweden/Denmark etc.).

Main advantages include the following :

1. **Reduced Overall Installed Capacity.** Interconnected Power Systems reduce the overall requirement of installed capacity.

Peak loads in individual areas occur during different clock-times of the day depending upon the working hours and daily load cycles and sleeping habits in that geographical area/city.

Installed capacity of the power system should be adequate to meet the peak demand of consumers.

With interconnection between adjucent power systems, peak demand in an area is met by importing power from neighbouring area. Thus the installed capacity of each Area can be selected to meet the average demand. This results in tremendous reduction in overall installed capacity and reduction in investment and yet better fulfilment of peak demand.

2. **Better utilization of Hydro Power.** During rainy season, the hydro stations are loaded fully and thermal stations lightly. The flow rate of rivers and water reservoirs fluctuates with rains. Wastage of water during rainy season can be avoided by interconnection between hydro and thermal plants. During summer, the hydro power can be minimised and thermal power enhanced. *Interconnection enables useful Hydro-thermal co-ordination.*

3. **Better utilization of Energy Reserves.** By better coordination between hydro, thermal, nuclear and other energy sources, *the energy conservation can be planned for optimum utilization.* This has long term benefits for the nation. Modern interconnected systems have total automatic EMS (Energy Management System).

4. **Reduction in operating costs and better efficiency.** Different plants have different operating costs, efficiencies. By interconnections, economic loading can be achieved and overall efficiency enhanced. *Energy can thereby be supplied to consumers at lowest cost.*

5. **Higher Unit Size Possible.** Generating units of higher unit capacity (200 MW, 500 MW etc.) can be installed and operated economically.

6. **Higher System Security.** The overriding factor in the operation of power system is to maintain System Security. The simple definition of power system security is as follows :

System Security is defined as the ability of the power system to continue to supply power through alternative transmission path in the event of a fault in a line or a generating unit.

Interconnections contribute to higher system security. In isolated power system, a fault in a generating station results in black out in the local region.

In interconnected system, the power is imported from adjucent area so as to continue to supply power to the consumers. This increases security of power supply.

7. **Improved Quality of Voltage and Frequency.** By interconnection, the frequency can be easily held within targetted limits by appropriate generation control and interchange. Isolated systems have higher frequency fluctuations with change in load cycle. *With more interconnections, the system becomes stronger and influence of load fluctuations is reduced.*

49.4. LIMITATIONS OF INTERCONNECTED POWER SYSTEMS

— Interconnection assumes that some areas have surplus generation/installed capacity/spinning reserves. *This does not apply to many developing countries where load growth is more rapid than the growth of installed capacity.* In absence of surplus power, the merits of interconnection cannot be accrued.

— With synchronous tie, the frequency disturbance of one area are transferred to adjacent areas, resulting in overall disturbance.

— Cascade trippings and overall black-outs occur in large interconnected systems.

— Each Regional Load Control Centre should fulfil its obligations and cooperate with the Master Load Control Centre. This may not occur if each Regional Load Control Centre seeks greater autonomy.

— Larger interconnections require more investments for Load control centres and automatic control.

— Technical problems of larger interconnected systems regarding planning, operations and control etc. are more complex.

— Large interconnections require more automation. Reliability and security of each system should be high.

49.5. OBLIGATIONS OF EACH INTERCONNECTED SYSTEMS

While deriving benefits of interconnections, each participant power system has to fulfil its obligations inluding :

— Each Area should have its load control centre with sufficiently advanced Automatic Generation Control, load-frequency control, reliable protection system etc.

— Each area should plan its installed capacity and should maintain adequate spinning reserves.

— Each area should have efficient voltage control and reactive power compensation to ensure voltage stability.

— Each Area should cooperate with National Load Control Centre with regard to interchange of power as per the instructions of National Load Control Centre. The levels should be respected.

— Control principles and requirements of parallel operations, overall load frequency control, steady state/emergency and post emergency stability should be maintained.

— Each Region should have a strong system analysis group and system operation group with trained man power.

49.6. OBJECTIVES OF AUTOMATIC GENERATION CONTROL AND TIE-LINE POWER FLOW CONTROL

Automatic Generation Control (AGC) and automatic control of Tie-line power Flow are essential for smooth and effective operation of Interconnected Power Systems. A multiple area interconnection has several Areas and several tie-lines. The main objectives of the AGC are the following :

Objective 1. Total generation in the entire interconnected system should be matched at continuously with total prevailing consumer demand plus losses. This objective is achieved by AGC primary and Secondary Load Frequency Control (Sec. 45.3 and 45.4).

$$\Sigma P_{GN} = \Sigma P_{LN} \qquad \text{...(49.6)}$$

ΣP_{GN} = Total generation of all the generating stations in the Network at an instant of time.

ΣP_{LN} = Total load plus losses in entire Network at that time.

G = Generation, L = Load, N = Number of Areas

— Inertia and favourable characteristics of large rotating machines provide self-regulating forces to satisfy Eqn. 49.6 during momentary load fluctuations (Sec. 45.2).

— The action of turbine governor (Primary frequency control adjusts the speed of each turbine-generator unit to prevailing synchronous speed (Sec. 45.3).

— The setting of turbine governor is determined on the basis of the prevailing requirement of generation. The requirement is allocated by Load Control Centre/Control Room. (Secondary frequency Control Sec. 45.4).

Refer Sec. 44.5 — Load frequency control of a Grid.

Objective 2. Total generation of the interconnected system should be allocated among the participant Areas is accordance with the requirements of load in each area and the scheduled interchange *i.e.*

$$\begin{aligned}\Sigma P_{GN} = \Sigma P_{GA} + \Sigma P_{GB} + \ldots\ \Sigma P_{GN'}\\ + \Sigma P_{iA} + \Sigma P_{iB} + \ldots\ \Sigma P_{iN'}\\ + \Sigma P_{LA} + \Sigma P_{LB} + \ldots\ \Sigma P_{LN'}\end{aligned}$$

— This applies to Multi-Area Interconnected System.

— Each area has allocated generation.

— This allocation is done by National Load Control Centre.

— The implementation of Generation in the Area is the responsibility of Regional Load Control Centre.

— The scheduled tie-line exchange is decided by National Load Control Centre.

Objective 3. Each Area generates allocated power. The Regional Load Control Centre of that Area allocates the total area generation among various generating stations in accordance with the following :

— Principles of economic load despatch — Primary frequency control by governor action

— Secondary frequency control in accordance with allocation by the National Load Control Centre.

Relative Priority Between Frequency Control and Economic Loading

Electrical energy cannot be stored in large quantities. The load varies, the total generation should be matched with total load so that service to customer at specified frequency is continued. This objective (1) is given higher priority than priority for economic loading of individual generating stations objective (3).

Therefore, priority is given in order of objectives 1, 2, 3. Thus in the automatic generation control, the load frequency control is given higher priority over the economic load despatch.

49.7. OVERALL OBJECTIVE AND CO-RELATION BETWEEN REAL POWER AND REACTIVE POWER CONTROL AND TIE-LINE POWER FLOW

The overall objective of the Power supply company is to supply required electrical power to all the consumers at all times at

— Specified frequency — Specified voltage

This ideal objective is not possible to be achieved in practice because

— Load changes continuously resulting in continuous change in Real Power Flow (*P*) and Reactive Power Flow (*Q*).
— With change in load (Real Power *P*). The frequency tends to change.
— With change in load (*P*) reactive drop (*IX*) changes thereby the voltages of buses change.
— With increase in generation, the net interchange from an area increases.

(*a*) **Real Power** (*P*). The total generation of electrical power should match with total load and the mismatch between the prevailing generation is judged by the measurement of prevailing frequency (*f*) and rate of change of frequency (df/dt). Sec. (45.11).

(*b*) **Reactive Power** (*Q*). The change in real power flow causes change in flow of reactive power through lines, transformers and generators etc. change in *Q* causes change in voltages of buses (Ref. Sec. 45.16).

System governing deals with total generation with total load by joint action of the following :

— National load control centre
— Regional load control centre
— Control Rooms in power stations

Section 46.22 gives further details about function of each :

(A) **Load frequency Control.** When the system load changes, corresponding changes are brought about in generation in following steps.

Increased System load. Increase in load, ΣP_G increased.

— Stored energy, decreases
— Decrease in the spinning energy in the rotating machines decrease of system speed or frequency.
— Frequency (*f*) : Decreases

Change in effective load. The drop in frequency brings about drop in effective load, because of frequency bias *K* (Refer Sec. 45.2). The factor *K* called system frequency Bias (or coefficient) in the amount of power generation required to change the frequency by one cycle.

This factor co-relates the rates real power *P* (in MW) with frequency *f* (Ref. Sec. 46.3).

Change in Generation (increase). The change in frequency brings about governor action (primary frequency control) and increases (Sec. 45.3) the input to generator-turbines and increase in generator outputs.

This results in :

— Change in generation of area : Increase
— Consequent change in frequency : Increase

Fig. 49.2(*a*) illustrates the above steps for increased load. Fig. 49.2(*b*) illustrates the steps for decreased load.

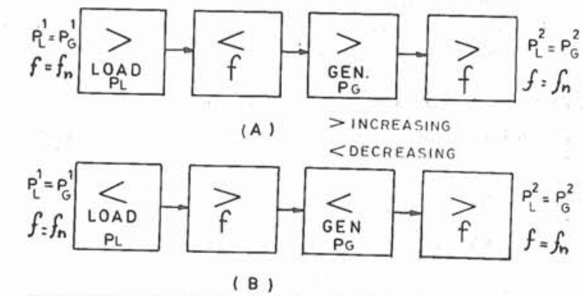


Fig. 49.2. Sequence of actions in Automatic Generation Control (AGC) and Load frequency control.

(A) Increasing load (B) Decreasing load
P_L = Load f = Frequency P_G = Generation > Increase < Decrease
P_L^1, P_G^1 = Initial condition P_L^2, P_G^2 = New condition

(B) **Voltage Control.** The change in load brings about change in *IX* drop in transmission lines, power transformers, generators, rotating machines, etc. Whereas real power follows the equation :

$$\Sigma P_G = \Sigma P_L ;$$

the voltage is controlled by reactive power flow (VAr flow) and the control is achieved by following :

— Generator excitater control, AVR control
— Shunt reactor or static VAR sources at substation buses
— Shunt capacitors near loads and receiving substations.

Further details have been given in Sec. 45.14.

(C) **Control of Tie-line Power Flow.** The overall generation is matched with overall load.

The generation gets allocated between the various generating units in proportion to the inputs to their turbines. Total system generation of all the areas in the interconnected system is equal to total load on the entire system.

$$\Sigma P_{GN} = \Sigma P_{LN} + \Sigma P_{iN}$$

Since $$\Sigma P_{iN} = 0$$

$$\Sigma P_{GN} = \Sigma P_{LN}$$

where LHS for generation on RHS for loads and losses.

The net algebraic sum of power interchange of all the interconnected systems is zero. But interchange through individual tie-lines is not zero.

Power transfer through tie-lines depends on the sharing of generation and load by Areas and the basic equation of power flow through a tie-line (Eqn. 44.1)

$$P_{AB} = \frac{V_A \cdot V_B}{X} \sin \delta$$

where δ = Power angle

X = Reactance of Interconnector

V_A, V_B = Voltages magnitudes at sending and receiving end.

Details of tie-line power flow control is described in the following sections.

Following means are available for controlling the power flow through the tie-lines.

— Increase in generation by area which is exporting power and reduction by generation by Area which imports power.

— Use of phase shifting transformer

— Line Switching.

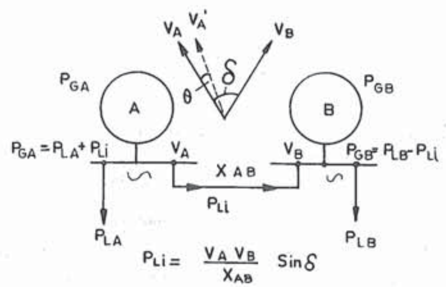
— HVDC interconnection, long distance

— HVDC Back-to-Back interconnection

— Flexible AC Transmission line

49.8. TIE-LINE POWER FLOW CONTROL IN 2-AREA SYSTEM

Fig. 49.3 co-relates Fig. 44.1(*a*) with Fig. 45.1 with respect to control of power flow through tie-line *AB*.



P_{GA}, P_{GB} = Generation in area *A*, *B*

P_{LA}, P_{LB} = Area loads plus losses in *A*, *B*

P_{Li} = Tie–line power flow between *A*, *B*

Fig. 49.3. Tie-line power flow control in 2-area system.

Area *A* generates P_{GA} and feeds local load P_{LA}

$$P_{GA} = P_{LA} + P_{iAB} \qquad ...(49.7)$$

P_{GA} = Generation of Area *A*

P_{LA} = Load of Area *A*

P_{iAB} = Tie–line power flow between area *A*, *B*.

In 2-Area system, Tie-line power flow from station *A* is equal to the algebraic difference between the Generation and load of Area *A*.

$$P_{GA} + P_{GB} = P_{LA} + P_{LB} + P_{LI}$$

As generation of station *A* is increased, the voltage vector advances such that angle δ increases. This results in increased power flow through the tie-line (P_{iAB}).

Eqn. 49.11 is satisfied by Primary load-frequency control (Governor Action) in station *A* and station *B*.

The Eqn. 49.8 and 49.9 are satisfied by action of load control centre which instructs control room of station *A* to generate P_{GA} and station *B* to generate P_{GB} such that exchange P_{iAB} takes place.

Thus, the phase shifting transformer is not essential for achieving power flow through the interconnector AB between two areas A and B in case of a 2-Area System.

49.9. TIE-LINE POWER FLOW IN 3-AREA SYSTEM

Refer Fig. 49.4. The net power outflow or inflow of *Nth* area is decided by the equation

$$P_{GN} = P_{LN} \pm P_{iN}$$

If load of area *N* is more than generation of area *N*, there will be *inflow* of power in Area *N*, *i.e.* Area *N* imports.

If generation of Area *N* is more than load of area *N*, area *N* exports power.

Assuming total generation of all the areas is equal to total load of all areas by action of load-frequency control, the *power flow through tie-lines is decided by the difference between load and generation and also paths available for power flow between areas.*

Actual net interchange of all areas is zero.

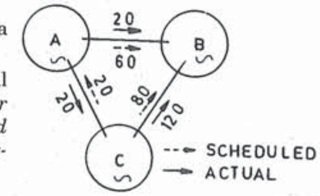


Fig. 49.4. 3-Area interconnected systems [Algebraic sum of net interchange

Consider area *A* exporting P_{GA}. This will flow through all the tie-lines emanating from *A*.

$$P_{iA} = \pm P_{i1} \pm P_{i2} + P_{i3} \qquad ...(49.12)$$

The net interchange by area *A* is given by

$$P_{GA} - P_{LA} = P_{iA} \qquad ...(49.13)$$

P_{GA} = Generation of area A

P_{AL} = Load on Area A

P_{iA} = Net interchange from area A

The magnitudes and directions of power flow through tie-lines from *A i.e.*, Pi_1, Pi_2, Pi_3 etc. is determined by basic circuit equations, following Ohms law.

From area *A*, power may flow to area *B* entirely through tie-line *AB* or partly through tie-line *AB* and through tie-lines *BC* and *CD*. Thus it may be noted that the net interchange of all areas is zero. *The paths of interchange of power are decided by circuit conditions and cannot be exactly matched. There occurs a difference between scheduled tie-line flow and Actual tie-line flow.*

From this analysis, it is clear that the total net interchange of all areas in a system is zero. The actual interchange between Areas *via* the Tie-lines differs from scheduled values. The total generation in entire system is equal to total load in entire system. This basic principle is applicable to multi-area interconnected system.

For increasing power flow through tie-line *AB*, the direction of power flow is decided by export/import conditions in areas *A* and *B*. If area *A* has to export, it should increase its generation over its load. Simultaneously area *B* should reduce its generation between its load. Thereby power with flow naturally from area *A* to area *B*.

The phase angle of voltage vectors V_A and V_B will follow Eqn. 49.6 such that angle δ gets adjusted to new value corresponding to P_{AB}. This is the basic principle behind power flow through tie-lines.

49.10. Alternative Principles of Control and the Tie-line Bias Control

(Ref. Sec. 45.11 and Sec. 46.23).

Various types of control principles have been developed for achieving effective area regulation of interconnected power systems consider the following two alternatives :

1. In one control principle, one area is assigned the task of controlling the system frequency while the other areas are assigned with the task of holding the tie-line power flow at fixed levels. This principle is used in interconnection between a very large Area with a very small Area.

2. In another control principle, one area is assigned the task of controlling system frequency while the other areas are asked to vary the tie-line power in accordance with the system frequency.

Both the above principles had limitations in Multi-Area systems and resulted in improper distribution of regulation requirements and inter-area oscillations of power flow. The above principles are however used in certain specific cases.

The above principles may still be used for two-area system such as interconnection between a large system and a small system. The large system controls the frequency and the smaller system controls the tie-line power flow within assigned limits.

With possibility of HVDC tie-lines and HVDC back-to-back coupling stations the above limitations may be overcome further.

According to the universally adopted control principle for large interconnected system, each participant area regulates its net tie-line power flow so as to regulate its own frequency such that the net tie-line power flow (net interchange) may depart from scheduled interchange within predetermined limits. With this principle, there is a difference between scheduled tie-line flow and actual tie-line flow ; scheduled interchange and actual net interchange as described in Fig. 49.4, Tables *A*, *B*. With this control principle, the following control tasks can be achieved.

1. Under normal operating conditions each area is able to execute its control tasks. Load changes in the area are absorbed by the same area. Tie-line power flow is maintained near scheduled level within predetermined departure from scheduled flow.

The control of system frequency should be all the areas and normal frequency is maintained.

2. Under abnormal or emergency condition, one or two Areas may be in trouble and may not be able to fulfil their control task. The area continues to remain interconnected and in synchronism. Under such conditions, the Emergency Control Mode takes over. All the other Areas automatically assist the area in trouble.

The Tie-line power flows are readjusted in magnitude and direction such that the assistance is provided to the Area in trouble.

Such an automatic control of interconnected systems is called *Tie-line Bias Control.*

In the Tie-line Basic control each area controls its own generation to match its load and the required net tie-line interchange. The power flow through each tie-line is adjusted to required scheduled level with permissible departure limits. As each Area controls the frequency, the task of controlling system frequency is shared by all the areas.

Principle of Tie-line Bias Control

— Each area generates power equal to its own load plus or minus net interchange so as to maintain frequency.

— Actual tie line flow departs from scheduled tie-line flow within certain limits.

— System frequency remains within target limits.

— Algebraic sum of net interchange of all areas is zero.

— Algebraic sum of total generation is equal to algebraic sum of total load plus total losses of all areas in the interconnected system.

49.11. EQUATIONS OF TIE-LINE POWER FLOW CONTROL REVIEWED

Refer Sec. 45.11, Sec. 46.23.

Let f = System frequency, Hz.

P_i = Actual tie-line power, MW

P_{io} = Scheduled tie-line power flow, MW

ΔP = Deviation in P_i, MW

f_o = Target frequency

K = System frequency bias MW/Hz

e = Area requirement correction MW

Δf = System frequency deviation

ΔP = Net deviation of power exchange through tie-lines, MW

$K\Delta f$ = Power change required to achieve target frequency.

Consider the power generation in an area (Region). The task of the power system network controller in the load control centre is to maintain the power exchange through the tie-lines with neighbouring regions at the desired values, and simultaneously to control the system frequency f.

The network controller compares the action sum of Tie-line power P_i with scheduled sum of Tie-line power P_{io} to calculate the deviation ΔP.

$$\Delta P = \sum_{1}^{n} (P_i - P_{io})$$

where ΔP = Deviation of actual power transfer through tie-lines from targeted values.

1, 2, ... n = No. of Tie-lines with neighbouring regions

P_i = Tie-line Power Flow, MW

P_{io} = Scheduled Tie-line Power Flow, MW

Thus
$$\Delta P = \sum_{1}^{n} (P_i - P_{io})$$

gives total deviation of power exchange with interconnected areas from the scheduled exchange.

It means, the generation in the area under the control of the network controller should be changed by to meet targeted exchange.

Next, the network controller has to control the system frequency.

Let Δf be the frequency deviation *i.e.*

$$\Delta f = f - f_0$$

where Δf = frequency deviation ; f_0 = target frequency, Hz C/s ; f = actual frequency, Hz C/s

A factor K called System Frequency Bias is introduced.

The system frequency bias K is amount of power generation required to change the system frequency by one cycle. Thus,

K = System Frequency Bias MW/Hz.

Thus to correct the frequency deviation Δf the amount of power charge would be

$$K\Delta f \text{ ... MW}$$

Combining (1) and (2), the area requirement e is given by

$$e = \Delta P + K\,\Delta f$$

Thus the network controller determines area Requirement (e), where

$$\boxed{e = \Delta P + K\Delta f}$$

e = Area Requirement Correction MW

P = Deviation in power exchange through Tie-lines MW

K = System Frequency Bias

Δf = System Frequency Deviation

$K\Delta f$ = Power change required to achieve target frequency, MW

This area requirement correction is transformed into output signals by the network controller. These output signals for correcting conditions are set to various generating stations under automatic control (Block 1.2 in Fig. 46.13). The primary load frequency control in response to automatic governor action to achieve target frequency is faster (a few seconds). This corrects the input to turbines within set limits of turbine to control the frequency.

The secondary load-frequency control (in response to instructions from network controller) is slower (once in say 5 minutes). It adjust the governor settings.

Refer Fig. 46.14 illustrating load frequency controls of generating unit.

Turbine Governor Gate valve is adjusted by the servo-motor in the closed loop system of frequency control system. The turbine input gets adjusted to maintain required frequency and to give economic loading. Turbine-governor setting can be changed by operator or by automatic SCADA.

49.12. ACTIONS BY THE CONTROL ROOM OPERATORS TO CHANGE TIE-LINE POWER

— Change in turbine setting within permissible limits so as to

1. Increase the input to overcome fall in frequency.
2. Decrease the input to overcome rise in frequency.

— Adjusting interchange of tie-line power flow by the above mentioned action.

— Adjusting phase shifting transformer to force power through alternative tie-lines.

— Appropriate switching of transmission line paths.

— Load shedding at distribution level.

49.13. ACTIONS BY CONTROL ROOM OPERATORS FOR VOLTAGE CONTROL

These are taken at each power station and sub-station.

— Change in exciter settings to change generator terminal voltage.

— Change of tap position of on load tap changer.

— Switching in shunt reactors during low loads and switching off during high loads.

— Switching in shunt capacitors during heavy loads and switching off during light loads.

49.14. CONTROLLING TIE-LINE POWER BY MEANS OF PHASE SHIFTING TRANSFORMER (REGULATING TRANSFORMERS)

In simple two terminal interconnected transmission line, power flows from surplus area to deficit area automatically. By increase in generation above the own load, the area forces the power through the tie-line. The load angle δ gets automatically adjusted. (Fig. 49.3) to allow the exchange of power to follow equation.

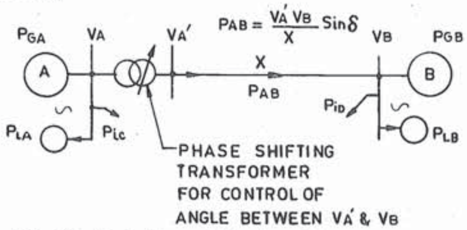


Fig. 49.5. Illustrating need for phase shifting transformer for forcing power P_{AB} through tie-line AB.

[By increasing generation in area A and reducing generation in area B, power flow through tie lines is changed. But the exact power flow through tie line A_B is determined by phase angle between V_A and V_B. This can be controlled by means of phase shifting transformer in case of AC tie line. In

$$P_{AB} = \frac{V_A\, V_B}{X} \sin \delta$$

Refer Sec. 45.16 $|V_A| - |V_B| = \Delta V = \dfrac{XQ}{V_B}$

and $$\delta \propto \frac{XP}{V_B}$$

For forcing the power flow P through a tie-line, angle δ between terminal voltages V_A and V_B of that tie line should be changed.

In multi-area system having meshed interconnections, parallel lines, loop circuits etc. increased generation may not increase tie-line power flow through the desired path. For adjusting the tie line power flow through a particular tie-line, angle δ between terminal voltage vectors of that line should be adjusted. This can be achieved by means of phase shifting transformer connected in series with the tie line at one of the terminals. Real power flow through the tie-line P_{AB}, is adjusted by controlling phase angle δ between V_A' and V_B by means of phase shifting transformers.

$$P_{AB} = \frac{V_A' \cdot V_B}{X} \sin \delta$$

By changing angle δ and keeping magnitudes of V_A and V_B within permissible limits, the power flow is changed. Angle δ is kept within about 30° considering the transient stability limit. Increase in δ gives increase in tie-line power flow. The magnitude of V_A and V_B are controlled by controlling reactive power flow Q.

$$|V_A| - |V_B| = \Delta V = \frac{XQ}{V_B}$$

By changing reactive power flow Q (by shunt compensation), the voltage difference ΔV is changed. (Refer Sec. 45.16).

ΔV can be changed by means of

1. Tap-changing 2. Reactive power injection

Phase angle can be changed by

1. Increasing generation above load.
2. *Use of phase shifting transformer* (Voltage Regulating Transformer).

49.15. PHASE SHIFTING TRANSFORMER (REGULATING TRANSFORMER)

Figs. 49.5 and 49.2 illustrates the function of a phase shifting transformer. The phase shifting transformer brings about the phase shift in line voltage (V_A to V_B by angle θ). Thereby, the load angle can be changed and power flow through tie-line AB can be changed. For increasing power flow angle δ is increased by adjusting angle θ. *This adjustment is in addition to control of angle θ by controlling the difference between generation and load.*

Fig. 49.5 illustrates the principle of voltage control by phase shifting transformer. Only one phase is shown for simplicity. By using the phase shifting transformer, the phase angle between the input side and output side voltage vectors two can be changed. In the phase shifting transformer, voltage from other phases (Y, B) is stepped down and injected into the first phase R.

Thus the output voltage of phase R becomes ... V_R'

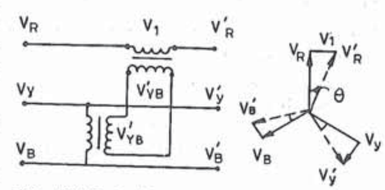


Fig. 49.6. Principle of Phase shifting transformer.

[Only one phase shown for simplicity. Voltage V_1 is injected in series with the line

The phase shifting transformer has two sets of windings, one connected between two phases and the other one in series with line phase. Thus by injecting voltage V_1 in series with V_R the vector V_R' is shifted in phase by angle θ. The magnitude of V_R is varied by means of tap-changing on the shunt winding. Phase shifting transformers are three-phase units though only one phase has been shown in Fig. 49.6 for simplicity.

49.16. TYPES OF INTERCHANGES IN INTERCONNECTED SYSTEM

Interconnections are generally for obtaining economic benefits and other bonus advantages mentioned in Sec. 49.3. Power systems are interconnected for any of the following significant purposes :

1. **Capacity Interchange.** Normally, a power system adds to its installed generation capacity to meet the predicted increased peak load plus surplus reserve for taking care of outages.

Instead of adding to the installed capacity, the power system may enter into capacity interchange agreement with an adjacent power system having surplus capacity. In such interchange; the adjacent system supplies power during peak load hours as per schedule in the agreement.

2. **Diversity Interchange.** Both the interconnected systems may not have same peak load hours. Peak loads may generally occur at different clock hours of the day. One system may lag behind the other by say 2 hours due to the difference in working hours, sleeping habits etc. Such system can have daily diversity interchange covering operating areas having different time zones.

3. **Energy Banking Arrangement.** A power system having predominantly hydro power, may be interconnected to another system having predominantly thermal power to have energy banking arrangement.

The purpose of such interconnection is to utilize hydro energy during monsoon periods and feed it to predominantly thermal area. During low water levels, the generation of hydro stations is reduced and thermal stations increased.

During Monsoon : Predominantly Hydro system exports power.

During low water : Predominantly thermal system exports power.

The purpose of such interconnection is better utilization of energy resources.

4. **Emergency Power Interchange.** The power system are interconnected mainly to support each other under emergency condition. The rate of power for such an interchange is generally very high.

5. **Inadvertant Power Interchange.** The interchange due to error by the operator or the control system is called inadvertant Interchange.

Hydro-thermal Co-ordination. During monsoon, the water level of reservoirs is high and excess water is wasted. Each hydro scheme has different capacity and load pattern. An area has some hydro-electric power stations and some thermal power stations. The hydrothermal co-ordination deals with interchange of power between predominantly hydro area and predominantly thermal area.

The schedule of exchange between predominantly thermal area ; and predominantly hydro-area depends on capacity of each area and requirement of load throughout the year. Generally, during rainy season, the Hydro-area does maximum generation and exports power. During low water level, the Thermal area does maximum generation and exports power.

If hydro-area has enough reservoir capacity throughout the year, the exchange is based on economics of power interchange.

General Pattern. Modern interconnected systems have various types of generating stations *viz.* thermal hydro, nuclear, gas-turbine, diesel, electric, wind power, solar power, geo-thermal power etc. In addition, energy storage schemes like pumped stored (hydro) ; compressed air storage, battery storage etc. are also used for limited capacity.

The generating stations are divided into three categories :

— Base-load stations

— Midrange load stations

— Peak load stations.

Large generation (thermal/hydro/nuclear) are generally used for base load stations.

Heavy duty thermal stations are used for midrange stations. Gas-turbine stations are quick to start and flexible and are preferred for peak loads. Hydro stations are used as base load stations during rainy season and peak load stations during summer. Wind power plants are used as energy

displacement plants. These are installed very near the load points. The system planners explore many types of generating stations available and select the suitable types for base, midrange and peak loads. The choice depends upon economics and variable energy resources.

49.16.1. Control of Power Flow through Interconnector

Three types of interconnectors are used in todays power systems. These are :

— 3 Phase AC lines

— HVDC lines or HVDC cables

— HVDC Back-to-Back coupling stations

The functional requirements are rapid and accurate control of power flow from one AC network to the other. In AC transmission system, the power flow through the tie-line is controlled by increasing generation in one system and reducing the generation in the other. However, this is a slow process.

Recently, Flexible AC Transmission Systems (FACT) have been introduced. In HVDC systems, the power flow can be rapidly controlled by changing delay (α) of converters.

49.17. NATIONAL GRID AND GROWTH OF POWER SYSTEM IN INDIA

Fig. 49.7 indicates the Regional Zones in the National grid of India.

Fig. 49.7. Power Map of India.
Indicating National and Regional Load Control Centres.

Refer Ch. 56, Sec 56.21 for India's Power Plans.

India, like other developing Nations is on the verge of perpectual Energy Crisis. The loadgrowth is faster than the growth of power system. The energy resources and status of power sector are covered in Sec. 56. 21. The summary is as follows :

Table 49.1. Growth of Installed Capacity in India

5 year Plan	1	2	3	4	5	6	7	8	9
Span Start	1951	1956	1961	1966	1972	1978	1984	1990	1995
End	1955	1960	1965	1971	1977	1983	1989	1979	2000
Installed Capacity by End Year of plan									
$\times 10^3$ MW	3.4	5.7	10.1	14.7	23	30	42	92	132

Approximate Break-up (1997)

Hydro (Renewable)	30%
Coal Thermal	65%
Nuclear	4%
Gas Turbine and Noconventional	1%

Approximate Contribution of Regional Grids in Installed Capacity 1997

Western	*Nothern*	*Southern*	*Eastern*	*North-Eastern*
30%	*28%*	*25%*	*15%*	*2%*

Landmarks in India's Power Sector

1955 - First 132 kV Transmission Line Commissioned

1961 - First 220 kV Transmission Line Commissioned

1965 - National Grid and regional grids identified

1966 - First nuclear power plant commissioned

1975 - First 400 kV AC transission line commissioned

1978 - First 500 MW Generator Unit Commissioned

1979 - SF_6 and Vacuum Circuit-Breakers introduced

1985 - SF_6 GIS Introduced

1989 - First HVDC Back-to-Back Coupling Station Commissioned (Vindhyachal Back to Back, Northern Grid - Western Grid)

1991 - First Long Distance Bipolar HVDC Link Commissioned Rihand (UP) to Delhi (Dadri)

1992 - First Wind Turbine generator unit commissioned.

SUMMARY

Interconnected power systems have been established all over the world. The interconnection is by 3 phase AC line or by Back to Back HVDC link or by Multi terminal HVDC. National Load Control Centers ensures that : Total power generated = Total load + Losses.

Regional Control Centre controls generation/Load balance in the region plus Import/Export requirement as per instructions of national control centre. Recent Renewable energy power plants either stand alone or grid-connected depending on location.

50

Operation and Control of Interconnected Power Systems, AGC and SCADA

50.1. INTRODUCTION

The role of Master Control Centre, Regional Control Centres, Control Rooms in power stations in the supervision, operation and control of power system has been illustrated in Fig. 46.1. Chapter 46 and also in Sec. 46.22.

The principles of interconnected power systems and tie-line power flow have been described in Chapter 49.

The object of the power supply company is to generate and supply required amount of electrical power at specified voltage and frequency to all the consumers at all times. The extensive growth of interconnected power system has resulted in complex operation and control requirements.

AGC refers to Automatic Generation Control. AGC involves maintaining generation in each area at such a value as to keep the frequency in the area within targetted limits and to keep the net interchange with adjacent interconnected areas within scheduled limits.

SCADA refers to Supervisory Control and Data Aquisition Systems. SCADA systems are essential in the operation of todays large interconnected systems. Basis equipments required in SCADA systems have been mentioned in Sec. 46.3.

Most SCADA equipment operate in scanning mode providing continuous monitoring of several large power stations and substations. SCADA requires two way communication between Master Station (A) and remote outstations (B) which are usually at the sub-station level.

The various aspects of power system operation and the inter-relation between control functions has been reviewed in this chapter.

50.2. MAIN TASKS IN POWER SYSTEM OPERATION

The main tasks in power system operation at different levels are divided into following categories (Table 46.1).

1. Planning of operations
2. Operation control
3. Operation follow-up and accounting.

The functional responsibilities in performing the above tasks are shared by the following (Table 46.1).

1. National Grid Control Centres
2. Regional Load Control Centres
3. Power Station Control Rooms
4. Major Substation Control Rooms.

Tables 46.1 and 46.2 in Sec. 46.1 cover the responsibilities and tasks.