52

Improving Dynamic Stability by Flexible AC Transmission System (FACT) and HVDC Systems

Inter-relationship between P, Q, V. δ — Concept of Dynamic Stability — Tasks in Power System Operation — Network phenomena and associated problems — Methods of Improvement — Dynamic Stability — Power Swings — First Swing — Oscillations — Damping Control — FACT Systems. HVDC Systems with Damping Control Feature.

52.1. INTER-RELATIONSHIP BETWEEN VOLTAGE, ACTIVE POWER, REACTIVE POWER, POWER ANGLE, OSCILLATIONS AND VARIOUS TYPES OF STABILITIES

Various types of stabilities have been defined in Sec. 44.21. Voltage control and reactive power compensation has been covered in Chapter 45-B. Static VAr Sources (SVS) and their application for dynamic compensation has been covered in Sec. 48.28. We will now take an overall integrated view of various methods being used presently and in near future for improving voltage profile and the dynamic stability of power system.

52.1.1. Review of Concepts of Power System stability and Basic Equations

Power system stability is generally explained by means of the following well known power equations :

1. **For a Single Machine against Infinite Bus :**

$$P = \frac{EV}{X_S} \sin \delta \qquad \text{...(1)... Ref. Eqn. (44.3)}$$

2. **For AC Transmission System :**

$$P = \frac{V_S \cdot V_R}{X} \sin \delta \qquad \text{...(2)... Ref. Eqn. (44.1)}$$

where, E and V, V_S, V_R are magnitudes in rms volts

From these equations the co-relation between the following variables is identified.

For Single Machine System

P = Active power flow from generator to infinite bus
E = Induced e.m.f., rms Volts.
V = Terminal voltage, rms Volts
δ = Phase angle between E and V, are called power angle or load angle.
X_S = Synchronous reactance.

For AC Transmission System :

P = Active power flow from V_S to V_R
V_S = Sending-end voltage, rms Volts.
V_R = Receiving-end voltage, rms Volts.
X = Series reactance of the line
δ = Load **angle or power** angle, **the angle between vectors V_S** and V_R.

During dynamic operating conditions P, V_S, V_R, δ undergo violent swings and stability is endangered.

In the above equations, the term reactive power flow (Q) is not appearing. However, the voltages V, V_S, V_R are influenced by the reactive power flow (Q) as visualised from the following equations :

Complex power S is given by :

$$S = P + jQ \qquad \text{...(3)}$$

Power angle δ between V_S and V_R of a transmission line is given by approximate equation

$$\delta = \frac{XP - RQ}{|V_R|} \qquad \text{...(3) ... Ref. Sec. (45.15)}$$

If $X \gg R$,

$$\delta = \frac{XP}{|V_R|} \qquad \text{...(4) ... Ref. Sec. (45.15)}$$

In equations (1) to (4) the voltages at the buses of generation station, sending and receiving-ends of transmission lines are influencing the load angle δ and the power flow P. Hence the magnitude difference ΔV between sending-end voltage V_S and receiving-end voltage V_R of a transmission line is given by the equation.

$$\Delta V = |V_S| - |V_R| = \frac{XQ}{|V_R|} \qquad \text{...(5) ... Ref. Sec. (45.16)}$$

Hence reactive power flow Q determines the voltage difference ΔV between the sending-end bus and the receiving-end bus.

52.2. PARAMETERS FOR DYNAMIC CONTROL

By co-relating Equations (1) to (5) given above we can visualise the following :

1. **Active Power Flow *P*.** This determines the load angle δ and *vice versa*. As the voltage must be maintained within specified limits, no much variation in active power flow can be achieved by varying voltages.

Instead, the phase angle (δ) between voltages is varied to change P.

2. **Load Angle** δ. The load angle δ between generator e.m.f. E and generator bus voltage V is increased by increasing the input to the turbines.

The load angle δ between sending-end voltage $|V_S|$ and receiving-end voltage $|V_R|$ of a transmission system is varied by increasing the generation or by reducing the load.

Other methods to achieve the change in power flow through a tie-line include

1. Use of phase shifting transformer in series (Sec. 49.15).
2. Use of Flexible AC Transmission (FACT) (Fig. 52.2).
3. Use of HVDC Transmission (Sec. 47.2.10).

3. **Bus Voltages and Reactive Power Consumption.** Various methods of controlling the bus voltages have been reviewed in Table 45-B-1. Bus voltages are controlled by controlling reactive power Q, and by tap-changing transformers. *Voltage Stability* is related with bus voltages and reactive power compensation. (Ch. 45 C) *Generator Stability* improvement by AVR and Excitation System is covered in Ch. 45 D.

4. **Steady State Stability Limit and Transient Stability Limit.** Various methods are described in Ch. 44.

5. **Oscillations in Power Angle δ and Power Swings.** Refer Sec. 44.21 – Clause 13. During disturbance the power angle δ oscillates. The first swing is generally largest. By various means, the swing of δ is minimised.

6. **Dynamic Stability.** The instability caused by insufficient damping torque is called *Oscillatory instability.*

A transmission system is said to be *Dynamically stable* if it recovers its normal stable condition following a sudden specified minor disturbance.

7. **Transient stability.** A transmission system is said to be transiently stable if following a sudden *large disturbance,* it regains its normal stable condition. Various methods of improvement in transient stability have been reviewed in Ch. 44.

52.3. FUNDAMENTAL REQUIREMENTS OF AC TRANSMISSION SYSTEM

— Voltages at sending and receiving ends should be within specified limits and should not be allowed to collapse during steady state, transient state; under the various conditions of dynamic stability. This is called voltage stability. Voltage instability occurs due to reactive power unbalance. SVS systems are necessary to avoid voltage instability.

— Stability should be maintained under steady, transient and dynamic conditions.

— Power flow through transmission lines should be controllable. This is particularly required for an interconnected line due to the reasons described in Sec. 49.9.

52.4. TIME RANGES OF ABNORMAL CONDITIONS AND DISTURBANCES

The disturbance and damping are related with time-rate of change of variables. The abnormal conditions and disturbances may occur during sub-transient, transient, or steady-state periods (Ref. Sec. 3.5). Some very fast transient may be within a period of a few microseconds. Table 52.1 gives the time ranges of various phenomena.

Table 52.1. Time Range of Power System Phenomena, Disturbances and Abnormal Conditions

Phenomenon or Happening	*Time-Range (Approximate)*
1. Lightning surges	10 μs — 100 μs
2. Very fast switching surges	2 μs — 10 μs
3. Switching surges	100 μs — 3000 μs
4. Line faults and fault clearing primary back-up (Ref. Table 44.1)	1 — 2 cycles 2 — 3 cycles
5. Transient stability and Dynamic Stability	40 millisce — 40 sec
6. Steady State Voltage control	20 cycles — 1 min
7. Steady state stability	20 cycles — 1 min
8. Load-frequency disturbance and prime-mover response.	3 sec — 1 hr
9. Load cycle and Thermal Overloads	5 min — 24 hrs

Note : 1–3 Sub-transient state happening.
4–5 transient state happening.
6–9 Steady state happening.

52.5. ENTER THYRISTOR CONTROL

Traditionally the only means available for protective and control switching operations of circuit-equipments such as reactors, lines, capacitors etc. were circuit-breakers which operate under transient state (Fig. 3.7) and require approximately 3 cycles (60 milli-sec.). Thyristors used for power switching operate within a few milli-seconds including control time. During 1980's the rate and capabilities of thyristors have increased manyfold. Single thyristors are now available for rated forward current upto 4000 A and rated voltage upto 1.5 kV. A thyristor can be triggered by a short-duration pulse (100 μs) of a few milli-ampere gate current. When used in AC circuits, the gate current pulses can be phased so as to fire the thyristor at desired phase angle within each positive half-cycle thereby producing phase control. Several thyristors can be connected in series to form a 'Valve' for high voltage convertors.

By means of power thyristors, and associated controls it has been possible to obtain switching of power circuits components within a few milli-seconds during every cycle, thus giving effective means of dynamic control.

This application has been successfully used for

— HVDC Convertors (Sec. 47.5)
— Flexible AC Transmission (FACT)
— Excitation Systems and AVR.
— SVS Systems (Sec. 48.28)
— AC harmonic filters.

52.6. FIRST SWING PERIOD AND OSCILLATORS PERIOD

Fig. 52.1 illustrates the oscillations in P, V_R and δ during a sudden disturbance in a transmission system or connected AC networks.

The *first swing* period refers to the time for the first half oscillation of the rotor angle(s) or synchronising power swing(s) following a large disturbance such as a fault or a small disturbance such as opening a line. *Typical time range of first swing period is 0.5 to 1 sec.* In this period the synchronous machines are characterised by constant flux linages behind machines transient reactance. First swing period is usually critical for maintaining transient stability.

Oscillatory period follows the first swing period. *During oscillatory period, significant cyclic variation in voltage, currents, active and reactive power flow, power angle δ take place.* Synchronizing power swings caused by synchronous machine rotor angles may last for 3 to 20 sec after a severe fault.

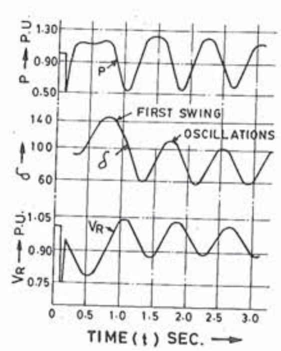


Fig. 52.1. First Swing and Subsequent Oscillations in an AC Transmission System (Without dynamic oscillation.)

By adopting SVS, FACT, HVDC System with damping control, fast response excitation systems of synchronous generators, first swing peak is reduced and subsequent oscillations are damped. Dynamic stability is improved.

For improving transient stability and dynamic stability the flow of reactive power and damping of voltage oscillations is helpful. This technique is possible by using the following means :

— SVS Systems
— HVDC transmission with damping control*.
— FACT Systems*

52.7. REVIEW OF POWER SYSTEM PROBLEMS AND METHODS FOR IMPROVEMENT

Switchgear, Protection, Power System, Automation and Controls perform the tasks by a teamwork of various equipments and associated controls.

Table 52.2 gives the review.

* Refer book 'EHV-AC and HVDC TRANSMISSION PRACTICE.'

Table 52.2. Review of Power System Problems and Methods/Equipments for Improvement

Tasks ↓ / Methods →	*Increase transmission voltage*	*Increase No. of Lines in parallel*	*Transformer Tap-changing*	*Slow AV Control*	*Fast AV Control*	*Fast turbine valving*	*Rapid line switching operations, reclosing of circuit breakers*	*Breaking resistors*	*Shunt reactor (switched/ unswitched/linear/non-linear*	*Shunt Capacitor*	*Series reactor*	*Series capacitor*	*Synchronous condenser*	*Thyristor controlled reactor*	*Thyristor switched capacitor*	*Static VAr sources (SVS)*	*Short circuit limiting coupling (or Fault current limiter)*	*Flexible AC Transmission (FACT)*	*HVDC System with Damping Control*
1. To improve steady-stage stability	*	*		*								*	*	*	*	*		*	*
2. To improve dynamic stability					*								*	*	*	*		*	*
3. To improve transient stability	*	*			*	*	*					*	*	*	*	*		*	*
4. To limit rapid voltage decline					*		*			*			*	*	*	*		*	
5. To limit slow voltage decline			*	*						*			*	*	*	*		*	
6. To limit rapid voltage increase					*		*		*				*	*	*	*		*	
7. To limit slow voltage increase			*	*					*				*	*	*	*		*	
8. To limit fast wavefront overvoltages due to lightning, switching etc.								*	*					*		*			
9. To give reactive power support at dc converter terminals										*			*	*	*	*			
10. To increase short circuit level												*	*						
11. To decrease short circuit level										*	*						*		*

Table 52.3 gives the comparison of various methods. In traditional protective systems the protective and control functions are almost independent. In recent microprocessor based protective and control devices the functions are integrated.

Table 52.3
Comparison of Various Methods
for Improving Voltage, Reactive Power Flow, Dynamic Stability

Method	*Advantages*	*Disadvantages*
1. Shunt reactor (Switched)	Simple principle and construction	Fixed in value. Switching of large reactors is difficult, gives transients.
2. Shunt capacitor (Switched)	Simple principle and construction, can be arranged in Banks.	Fixed in value. Switching takes about 3 cycles.
3. Series capacitor (Fixed)	Simple principle. Performance relatively insensitive to location. Improves steady state stability limit.	Requires overvoltage protection and subharmonic filters. Limited overload capability. Power flow cannot be changed.
4. Synchronous condenser	Has useful overload capability, Fully controllable. Low harmonics. Step-less control.	High maintenance cost. High initial cost. Slow control response. Performance sensitive to location.
5. Thyristor-controlled reactor (TCR). Gives shunt compensation.	Fast response. Fully controllable. No effect on fault level. Can be rapidly repaired after failures.	Generates harmonics. Perfomance sensitive to location. Requires harmonic filters
6. Thyristor-switched capacitor (TSC). Gives shunt compensation.	Can be rapidly repaired after failures. No harmonics.	No inherent absorbing capability to limit overvoltages. Complex buswork and controls. Low frequency resonances with system. Performance sensitive to location.
7. Static VAr Source (SVS)	Stepless control. Combination of 5, 6.	Requires harmonic filters. Combination of 5, 6 above
8. Flexible AC Transmission (FACT).	Less costly and simpler than HVDC. Damps oscillations and improves dynamic stability. Power Flow can be controlled. Improves transient and dynamic stability.	Needs intermediate substations at an interval of 250 to 350 km along the long line. In initial stage of development.
9. Fast circuit breakers, Protective relaying, Auto-reclosing.	Improves the transient stability limit.	Does not help in damping oscillations and improving the dynamic stability.
10. HVDC System with Damping Control	Power flow can be controlled rapidly. Power Flow can be reversed rapidly. Damping of power swings effective.	Very costly Very complex.

The various techniques are reviewed in following paragraphs :

1. **Switched Shunt Reactors.** Shunt reactors are connected to long transmission lines at sending-end, receiving-end and in intermediate sub-station. Large shunt reactors are difficult to switch-off due to high inductive energy and current chopping in circuit-breakers. Hence fixed unswitched shunt reactors are being used presently for EHV-Transmission systems. Shunt reactors provide *fixed* shunt compensation to line capacitance to earth.

2. **Switched Shunt Capacitors.** These are used at receiving end, in intermediate substation and near load points. They are switched on during heavy loads and switched-off during low loads for voltage control. Modern SF_6 and vacuum circuit-breakers have overcome the problems of restrike phenomena and the switching overvoltages occurring with earlier oil circuit-breakers. However circuit-breakers cannot be operated repeatedly and their operating time is about 3 cycles.

3. **Series Capacitors** are used for long EHV-Transmission systems for improving power transfer ability and stability limit. They are located in sending-end, receiving-end and intermediate sub-stations. They compensate the inductive series reactance of long transmission lines. They have inherent limitations of subsynchronous resonance and limited overload capacity.

4. **Synchronous Condensers.** These are used in receiving substations and give controllable shunt compensation as well as additional short-circuit level. Recently (1980's) they have been replaced by SVS systems.

5, 6, 7. TCR, TCC, SVS. They provide controllable shunt compensation. Thyristors can be controlled rapidly to vary the shunt reactive power compensation. The bus voltage can be dynamically controlled. SVS system give improvement in dynamic stability by rapid variation of reactive power compensation.

52.8. FLEXIBLE AC TRANSMISSION (FACT)

This is a recent development (1986). These systems are likely to be used for AC interconnecting lines and long AC lines.

Fig. 52.2 (*a*) shows a long Flexible AC Transmission system (FACT). It has intermediate substation at an interval of 250 to 350 km. 1, 1... are controllable series capacitors and 1′, 1′ are controllable SVS.

In a typical FACT system, controllable series capacitor installation is achieved by means of bypass Thyristors switch [Fig. 52.2(b)]. By controlling the bypass current I_B through the thyristor controlled switch (TCS) the current I_C through series capacitor (SC) and the amount of series compensation is varied.

$$P = \frac{|V_S| \cdot |V_R|}{X_L - X_{CF}} \sin \delta$$

By controlling X_{CF}, the power flow P is controlled.

where X_L = Series reactance of the long transmission line

X_{CF} = Controllable series reactance of series capacitor of FACT system.

By controlling X_{CF} by means of bypass, thyristors switch, the power transfer P is controlled. The phase control of bypass thyristor switch gives the control over the power transfer P and the power angle δ. The basic limitation of AC transmission line and series compensation had been the lack of controllability. This limitation has been overcome by controllable series capacitors of FACT system. In addition to the controllable series capacitor; the FACT incorporates controllable shunt compensation by means of SVS. Thereby the voltage at the sending-end and receiving-end is controlled by dynamically. This gives voltage stability and improves dynamic stability of the transmission link.

In a typical FACT system, controllable series capacitors and controllable SVS combinations are installed at an interval of approximately 250 km along a long AC line. By controlling series.

Description of a FACT system

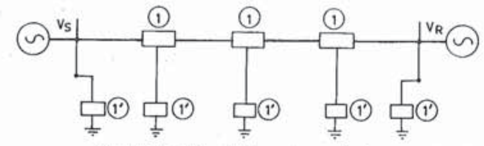
Various configurations are being tried. A likely configuration Fig. 52.2 (*a*) shows a single line diagram of a long AC transmission line incorporating FACT principle.

Controllable series capacitor (1) and controllable shunt compensation (1′) are installed at an interval of 250 to 350 km.

Fig. 52.2 (*b*) shows schematic diagram of the details of controllable series capacitors (1). All the equipments of (1) are installed on *insulating platform* (*IP*). The control unit senses the phase to ground voltage (*V*) at the location of (1) and adjusts phase angle of TCS. Bypass current I_B is controlled.

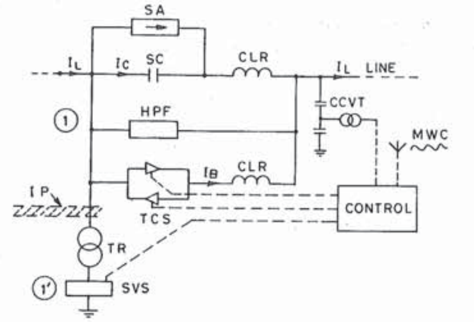
$$I_L = I_C + I_B$$

By varying $\boldsymbol{I_B}$, $\boldsymbol{I_C}$ is varied. This results in variable series compensation which can be controlled from load control centre *via* compensation, the power flow is controlled. By controlling the SVS, the voltages at sending-end, receiving-end and at intermediate substations are controlled.



V_S = Sending-end voltage
V_R = Receiving-end voltage
1 = Controllable series compensation
1′ = Controllable shunt compensation (SVS).

Fig. 52.2 (*a*) Single line schematic diagram of a Flexible AC Transmission System (FACT) (Controllable AC Power Link – CPL)



IP = Insulating platform for (1).
SC = Controllable series capacitor bank with current I_C.
TCF = Thyristor control switch with bypass current I_B.
HPF = High pass harmonic filter to suppress harmonic generated by operation of TCS.
SA = Zinc-oxide Surge Arrester for protection of SC against overvoltages.
CLR = Current Limiting Reactor.
TR = Auxiliary transformer for SVS.
SVS = Static VAr source.
CCVT = Coupling capacitor, voltage transformer.
MWC = Microwave communication channel.

Fig. 52.2 (*b*) Details of controllable series compensation in the FACT installation (only one phase shown).

Series and shunt compensation are controllable and control is fast and over wide range. Hence, FACT gives improvement in the dynamic stability of AC transmission system.

By simultaneous control of 1, 1 ... and 1′, 1′ ... the power flow P, voltages V_S and V_R and power angle δ between V_S and V_R are controlled. The oscillations in P, V, δ are damped by means of control of 1 and 1′.

9. **The Microwave Communication Channel.** By simultaneous control of (1) and (1′), the power flow, power angle and voltages are controlled dynamically.

10. **Fast Circuit-breaker and Protection Systems.** Effect of fast circuit-breakers, Auto-reclosing etc. has been covered in Ch. 41. Circuit-breakers cannot be operated in time less than about 40 milliseconds. Protective relays take approximately 20 milliseconds. Circuit-breakers are not suitable for repeated operations which are necessary for damping control.

These limitations are not present in thyristor controlled devices like SVS, FACT.

Hence circuit-breakers are used for tripping faulty lines, and SVS/FACT systems are used for improving dynamic stability and for damping control.

52.9. DAMPING OF OSCILLATIONS IN AC NETWORKS BY MEANS OF HVDC DAMPING CONTROL

HVDC Transmission links in the form of long distance overhead line/submarine cable/back-to-back coupling station interconnect two (or more) AC Networks.

Asynchronous HVDC interconnection has no parallel AC lines.

Synchronous HVDC interconnection has parallel AC lines(s).

$$Pd = Vd \cdot Id$$

$$= Vd \left[\frac{Vd_1 - Vd_2}{R} \right]$$

Due to small value of R ; Id can be controlled quickly and easily. Therefore, the Power flow (Pd) through an HVDC link can be controlled quickly, precisely in direction and magnitude by means of phase control of thyristor-valves at rectifier and inverter ends (Ref. Ch. 47). This ability is utilized for improving the transient stability and dynamic stability of :

1. Connected AC Networks at terminals.
2. AC transmission lines parallel to HVDC link
3. Adjacent AC transmission systems connected to AC Buses of HVDC system.

During disturbance such as a fault in a transmission line, the power angles of buses experience a swing and oscillations. *By modulating the power flow through HVDC links, the swing is reduced and the oscillations are damped. This is a major advantage of HVDC transmission and with damping control added to HVDC system control the line loading of adjacent/parallel AC Transmission lines can be increased.*

Feedback loop of Δf or $\Delta\delta$ or both is added to the power controller of HVDC pole control. Thereby power flow is modulated to damp the oscillations in AC Networks. Stability of AC Networks/lines is improved.

ASYNCHRONOUS HVDC LINK FOR IMPROVING STABILITY OF AC SYSTEMS

52.10. STABILISATION OF ADJACENT AC LINES

Asynchronous HVDC link has no parallel AC lines. (Ref. Fig. 52.3). The prevailing frequencies of two AC Networks are different and the two AC Networks are not in synchronism.

Consider a transmission system shown in Fig. 52.3 consisting of three AC lines between AC networks 1 and 2 and one bipolar HVDC link from busbar 2 to infinite bus 3. HVDC link has no parallel AC lines. Hence the HVDC link (2-3) is *asynchronous*.

The bipolar HVDC link transfers power (Pd) from busbar 3 to busbar 2. The asynchronous HVDC link connects AC Networks 2 to infinite bus 3. AC Network 3 (infinite bus) is very large and there is no limit on power exchange ($\pm Pd$) between AC Network 2 and Infinite bus 3.

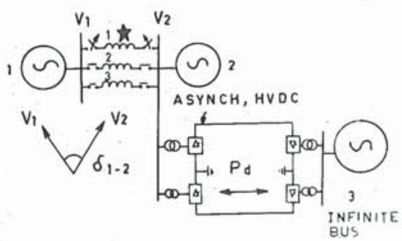


Fig. 52.3. Asynchronous HVDC link 2-3 has no parallel AC lines. Pd is modulated to improve Dynamic Stability of 1, 2.

[Opening an AC line 1 causes oscillations in power angle δ, These are damped

DC power flow $\pm Pd$ can be controlled with modification such that

$$\Delta Pd = \text{function } (\Delta f \text{ or } \Delta\delta)$$

By introducing such a control parameter to the power controller of the HVDC link, the oscillations in power angle δ in AC links between Networks 1 and 2 can be damped. Thus the control of HVDC link can be suitably modified for damping the oscillations in adjacent AC transmission lines (not parallel with the HVDC link). Fig. 52.4 shows oscillations in power angle between 1, for various control modes in DC links 2-3.

Fig. 52.4, Curve 1, shows increasing oscillations leading to dynamic instability. Such curve is obtained if HVDC system 3 is without damping control.

Curve 2 shows damped oscillations obtained by adding damping control feature in HVDC power control.

The stability and swing curves during a disturbance (such as opening and AC line) is influenced by the method of control adopted for HVDC link (3).

Curve : 1. Constant DC power control.
2. Constant power angle δ control.
3. Constant Pd plus control of Δf.
4. Constant δ and control of Δf.

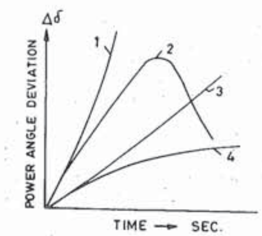


Fig. 52.4. Oscillations in Power Angle δ for phase angle difference $\Delta\delta$ produced by opening on AC line in Fig. 52.3 for various conditions of control.

Fig. 52.4 shows the first swing curve in terms of $\Delta\delta$ versus t, for various types of controls of HVDC link $\Delta\delta$ refers to deviation in power angle δ during the swing.

SYNCHRONOUS HVDC LINK FOR IMPROVING STABILITY OF AC SYSTEMS

52.11. DAMPING OF AC NETWORKS OSCILLATIONS WITH DIFFERENT CONDITIONS OF DC CONTROL FOR SYNCHRONOUS HVDC LINK

Fig. 52.5 shows an HVDC Link 3 which is in parallel with AC lines 1 and 2 and all the lines connect AC Network 1 and 2 synchronously. The terminal AC Networks are at the same frequency and in synchronism. Hence the name *'Synchronous'*. If line AC-1 is opened, the voltage vectors V_1 and V_2 experience a swing and subsequent oscillations.

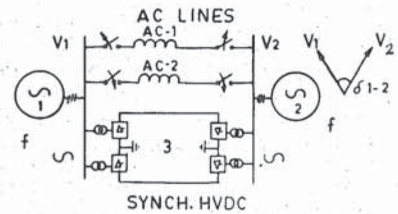


Fig. 52.5. Synchronous HVDC Link.

[Line 1 opened, oscillations in δ_{1-2} being analysed for various controls of HVDC link].

By modifying the HVDC control, the swing in power angle δ can be reduced and the oscillations can be damped. Thereby the transient stability of AC Network 1, 2 and AC transmission lines 1 and can be improved.

The power flow through the HVDC link (3) can have different control criteria, for example constant power Pd or constant power plus damping control. Accordingly, the swing curve and oscillations in δ get modified.

Fig. 52.6 (A) shows the effect of damping control of HVDC link on oscillations in power angle δ_{1-2} of Fig. 52.5.

With only AC lines, stability would have been lost as shown in curve 3 of increasing δ. With HVDC link with modified control (constant Pd plus damping control) the first swing is reduced and the oscillations are damped (curve 1, 2).

Power through HVDC link (Pd) between 1 and 2 can be quickly modulated by damping control. For critical damping high DC power flow is required [curve 1 – Fig. 52.6 (B)]. For under critical damping of oscillations in δ $\sin_{1-2}$ lesser DC power would be required (curve 2).

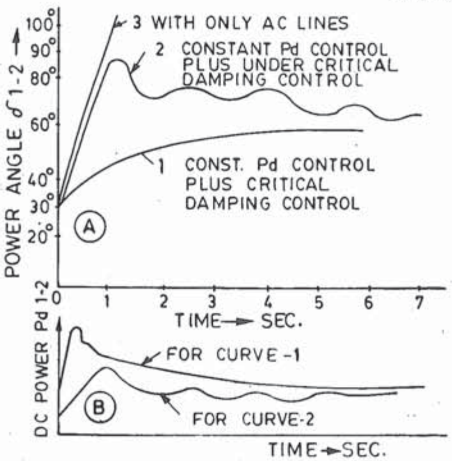


Fig. 52.6 (A). Swing curves for various types of controls applied to HVDC link 3 in Fig. 52.5.
(B) DC Power through synchronous HVDC link 3.

Power through HVDC link can be quickly increased/decreased/modulated in such a way that the power angle swing of δ is not allowed to reach its prospective peak an the oscillations in δ are damped. Thereby the Dynamic Stability of connected AC Networks and parallel/adjacent AC lines is improved.

Methods of HVDC Control for Improved Transient Stability various possibilities of DC control have different effects on the oscillations as illustrated in curve 1 to 4 in Fig. 52.4. The improved transient stability is achieved by reducing the swing angle δ before it reaches unsafe value.

Curve 1 (Fig. 52.4) Constant DC Power Control. In curve 1, the swing curve is steep and angle deviation Δδ overshoots, the safe limits faster indicating severe unstable condition, (worse than curve 2 for three AC lines).

As seen later, constant *Pd* control gives progressive increase in the amplitude of oscillations and this is called *dynamic instability*. Hence constant *Pd* control is not suitable from stability considerations. Power control of HVDC must be modified.

Curve 2 (Fig. 52.4) Constant Power Angle δ Control of HVDC Link (*i.e.* Constant phase angle. In this type of DC control, the control signal for DC power flow is *modulated* such that the power transfer *Pd* is varied to achieve constant power angle δ between two AC Networks vectors V_1 and V_2.

Since measurement of phase angle δ between V_1 and V_2 for long distance is difficult one of the following two parameters are generally used.

$$\frac{d\delta^2}{dt^2} = \text{Angle acceleration}$$

$$= \frac{d}{dt}(\Delta f) = \text{Time derivative of frequency difference between two AC Networks}$$

In this type of control the DC line responds to control like an AC link as shown by curve 2 (Fig. 4). No much improvement is obtained in improving transient stability of AC lines/Networks.

Curve 3 (Fig. 52.4). With Constant Power (Pd) and additional control parameter proportional to the frequency difference (Δ*f*). The frequency deviation Δ*f* is low. Load angle difference Δ*f* increases *more slowly* as shown by curve 3 giving more time to auto-reclosing.

Curve 4 (Fig. 52.4). Constant δ between V_1 and V_2 and additional control parameter proportional to frequency difference Δ*f*.

In this type of control, both Δ*f* and Δδ are limited quickly. Δ*f* is brought down to zero and δ is stabilised to new value critically. *The AC circuit breaker can be reclosed without difficulty.*

Time Delay of control signals. The control signals have inherent time delay of the order of a few tens of m sec. This affects the degree of damping provided by DC control.

Conclusion. With synchronous HVDC link, when a parallel AC line is opened the resulting oscillations of power angle δ in connected AC Network can be damped satisfactorily by choice of suitable control signals added into the HVDC power control. Constant power control with additional control parameter proportional to frequency difference Δ*f* gives minimum swing and brings back the frequency deviation Δ*f* to zero quickly and parallel AC line can be reclosed.

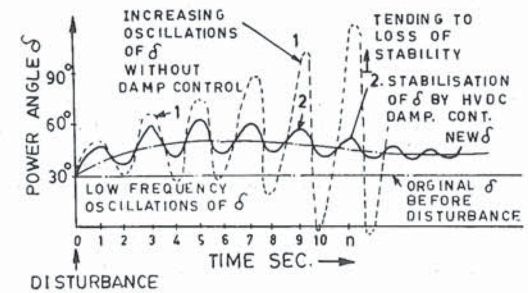


Fig. 52.7. Damping of oscillations in power angle δ_{1-2} of Fig. 52.3 for various types of controls of Asynchronous HVDC link. Curve 2 shows effective damping of oscillations in power angle δ.

Fig. 52.7 shows typical oscillations of power angle δ_{1-2} between vectors V_1 and V_2 of a asynchronous HVDC link shown in Fig. 52.3. Curve 2 shows that Dynamic Oscillations of δ_{1-2} can be damped effectively by modulation of power flow through adjacent HVDC link. Thereby adjacent AC transmission can be made dynamically stable.

SUMMARY

The concepts of stability have undergone gradual changes during last 70 years. Now four important stabilities are defined as

— Steady state stability
— Transient stability
— Voltage stability
— Dynamic stability

Means available for improving transient stability and dynamic stability include : use of SVS, FACT and HVDC transmission, fast AVRs in Excitation System of Synchronous generators with stabilizing features (Ch. 45 D)

Means available for improving voltage stability are : SVS, Tap-changer control, synchronous condensers.

FACT systems incorporate controllable series compensation-plus SVS systems. FACT systems are likely to be used for several long AC lines and interconnecting lines.

HVDC system control can be modified with constant Δδ control or constant Δ*f* control so as to damp the oscillation in δ and limit the maximum swing in δ. Thereby transient and dynamic stability of AC Networks and transmission systems is improved.

HVDC systems can also be used for controlling frequency (f_2) of smaller network interconnected to a large network. The power flow from large network to small network is modified with frequency deviation Δ*f*, where $\Delta f = f_n - f_2$

P_d = Function (Δ*f*)

P_d = Power flow from large network to small network

Δ*f* = Frequency of deviation of small network.

$= f_n - f_2$

f_n = Rated frequency

f_2 = Actual frequency of small network.