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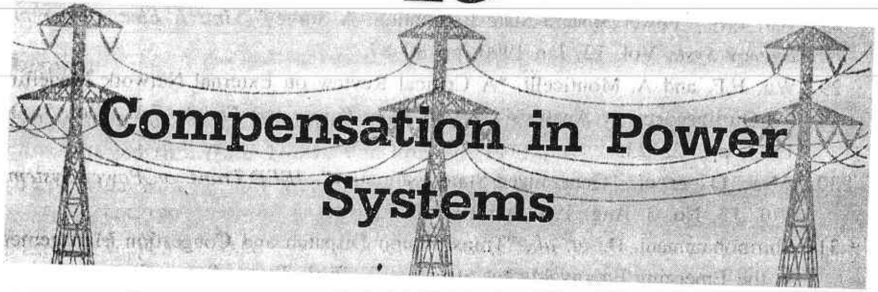

Compensation in Power Systems

15.1 INTRODUCTION

For reduction of cost and improved reliability, most of the world's electric power systems continue to be interconnected. Interconnections take advantage of diversity of loads, availability of sources and fuel price for supplying power to loads at minimum cost and pollution with a required reliability. In a deregulated electric service environment, an effective electric grid is essential to the competitive environment of reliable electric service.

Now-a-days, greater demands have been placed on the transmission network, and these demands will continue to rise because of the increasing number of nonutility generators and greater competition among utilities themselves. It is not easy to acquire new rights of way. Increased demands on transmission, absence of long-term planning, and the need to provide open access to generating companies and customers have resulted in less security and reduced quality of supply.

Compensation in power systems is, therefore, essential to alleviate some of these problems. Series/shunt compensation has been in use for past many years to achieve this objective.

In a power system, given the insignificant electrical storage, the power generation and load must balance at all times. To some extent, the electrical system is self-regulating. If generation is less than load, voltage and frequency drop, and thereby reducing the load. However, there is only a few percent margin for such self-regulation. If voltage is propped up with reactive power support, then load increase with consequent drop in frequency may result in system collapse. Alternatively, if there is inadequate reactive power, the system may have voltage collapse.

This chapter is devoted to the study of various methods of compensating power systems and various types of compensating devices, called compensators, to alleviate the problems of power system outlined above. These compensators

can be connected in the system in two ways, in series and in shunt at the line ends (or even in the midpoint).

Apart from the well-known technologies of compensation, the latest technology of Flexible AC Transmission System (FACTS) will be introduced towards the end of the chapter.

15.2 LOADING CAPABILITY

There are three kinds of limitations for loading capability of transmission system:

(i) Thermal (ii) Dielectric (iii) Stability

Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, conditions of the conductor, and ground clearance.

There is a possibility of converting a single-circuit to a double-circuit line to increase the loading capability.

Dieletric Limitations From insulation point of view, many lines are designed very conservatively. For a given nominal voltage rating it is often possible to increase normal operating voltages by 10% (i.e. 400 kV – 440 kV). One should, however, ensure that dynamic and transient overvoltages are within limits. [See Chapter 13 of Ref. 7].

Stability Issues. There are certain stability issues that limit the tiansmission capability. These include steady-state stability, transient stability, dynamic stability, frequency collapse, voltage collapse and subsynchronous resonance.

Several good books [1, 2, 6, 7, 8] are available on these topics. The FACTS technology can certainly be used to overcome any of the stability limits, in which case the final limits would be thermal and dielectric.

15.3 LOAD COMPENSATION

Load compensation is the management of reactive power to improve power quality i.e. V profile and pf. Here the reactive power flow is controlled by installing shunt compensating devices (capacitors/reactors) at the load end bringing about proper balance between generated and consumed reactive power. This is most effective in improving the power transfer capability of the system and its voltage stability. It is desirable both economically and technically to operate the system near unity power factor. This is why some utilities impose a penalty on low pf loads. Yet another way of improving the system performance is to operate it under near balanced conditions so as to reduce the flow of negative sequence currents thereby increasing the system's load capability and reducing power loss.

A transmission line has three critical loadings (i) natural loading (ii) steady-state stability limit and (iii) thermal limit loading. For a compensated line the natural loading is the lowest and before the thermal loading limit is reached, steady-state stability limit is arrived.

High Voltage DC Transmission
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Module No: # 01
Lecture No: # 01
Evolution of HVDC Transmission

Welcome to this HVDC transmission video course in NPTEL program, phase 2. The first lecture I will be discussing about this evolution of HVDC transmission system. First, I will discuss what are the various contents in the various modules and then, I will discuss about the first module and contents, one that is the evolution of HVDC system.

So, this HVDC transmission system course is divided in 7 modules and the first module basically, it is including the evolution of HVDC transmission system and then, in this evolution of HVDC system.

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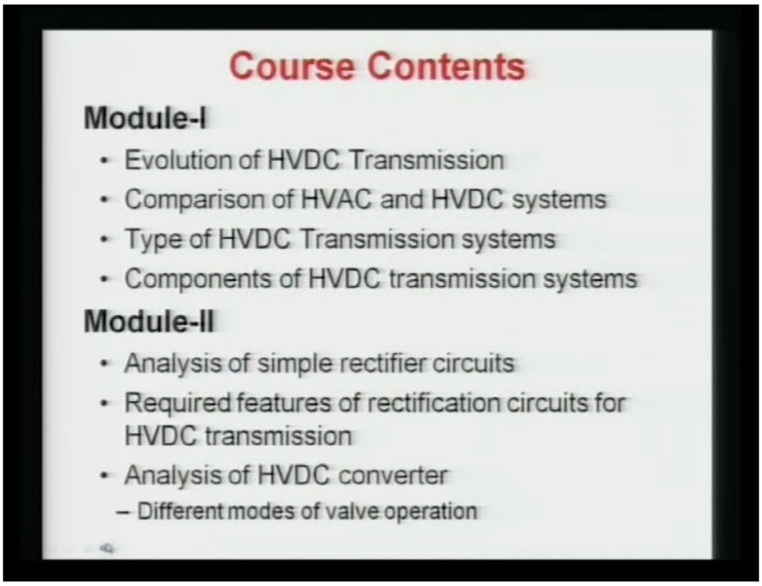

Before that I will discuss about the evolution of power system then we will see how this HVDC came into the picture along with the AC transmission system. Then, I will compare the HVAC and HVDC systems together and we will see the various problems in HVAC system and then HVDC systems, and already and also, their advantages and the disadvantages in the system. Then, I will discuss about the various types of HVDC transmission systems; that is, the various links and then in that module, the last lecture is lecture number 4, will be dedicated to the components of HVDC transmission system including your converter DC lines; your trans converter transformers and other filters and snooping vector, etcetera. In module 2, it will be devoted to the analysis of the converter circuit and you know the converter is a very very important in HVDC transmission system; that is, we are having rectifier site as well as the inverter operations as a inverter end. So, these converters are very very important in HVDC transmission.

So, module 2 is completely dedicated for the analysis of the converter circuit and this HVDC converter circuit will be represented by the equivalent electrical circuit at the end to start with first I will discuss in this module that is a analysis of the simple rectifier circuit it may be the single phase rectifier circuit and also along with will see the 3 phase circuits then we will go for the various configurations and we will see what are the advantage and the disadvantages and the we will see the various terminologies those will be used like the DC output voltage, peak inverse voltages and commutation group as well then with this terminology I will jump to the required feature for the rectification operation or rectifier circuit operation in HVDC link. So, we will see the various requirement that we require the high output DC voltage for a given input AC voltage we require the better transformer utilization we will also see the less peak inverse voltage also we will be requiring that the harmonics should be minimum. So, these are the basically desired features and based on that we will arrive the what should be the optimal configurations for this HVDC converters

After deciding the converter circuits that is the 6 pulse converter circuit will be analyzed for the different modes of the operation different modes I mean yeah basically the overlap angle I will be discussing overlap angle means the one valve or one thyristor is taking current and then it is another is going to be turn on then how the current is going to shifted it is instantaneous that is ideal case then we will say the value of u that is a overlap the current shifting from one valve to another valve the values u angle if it is a less the 60 then it is mode one if it is a 60 then it is mode 2.

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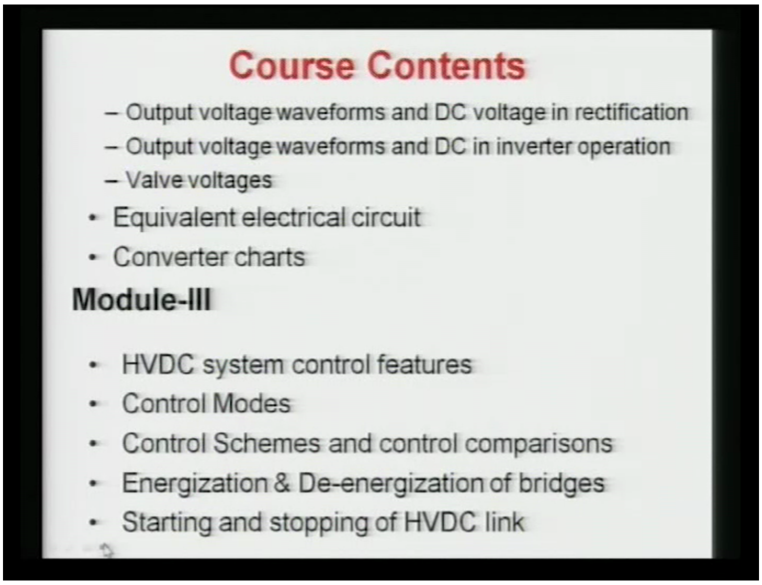

If it is more than 60 then mode 3 and 4 operations we will say. So based on that the output voltage as well as the waveform will change and then we will analyze detail about the circuit. So, in both output waveforms of various modes we will analyze both waveforms like it the valve voltage, DC output voltage, currents in the phases of the transformer and also we will see this what will be the DC average value of the rectification operation and the similarly we will see for the inverter operation as well now we will also as here already have. Thus, we have also going to discuss the valve voltages this is the very important because if the voltages of the valve should be known then we can see what are the various mal-operation of the valve and based on that we will design some circuit to avoid the mal-operations of the valve.

After this once you are having the complete analysis we can form means we can substitute this HVDC link by simple equivalent circuit electrical circuit having a variable voltage source and with the some commutation resistances and the line resistances and then we can calculate the current in the DC link. Another part of this module 2 is basically, analysis is based on the converter charts; we will see the converter charts. Basically, the DC variables we are having alpha delta and gamma and the beta are the DC variables. So, we are going to draw and the 2 planes; one is the DC voltage and the DC current. Then, we will see the DC variables impact and the current converter chart will be drawn and another one we will see the AC variables like P and Q will be your axises and then we will see your power factor apparent power AC current, etcetera, will be and recti-power as well and in another chart. So, this 2 variety of charts will be discussed and then we will see based on that how that we can analyze for any particular current we can get the voltage u and another angles as well.

So, third module basically, now is a dedicated for the converter control in the first lecture I will be discussing about this; what are the desired features of HVDC control and then we will go for the various control modes. We will derive the control characteristic that should be the suitable for the HVDC transmission operation and then we will discuss the various types of control schemes for the firing of the valves because, in HVDC this is a main. We are, what we are doing? We are generating the gate pulses to turn on the your valves or thyristors and then we will see the various comparisons of various schemes suggested by various inventors and we will see which are the bad and which are the miss say, we are going for a demerits and the merits of the various control schemes. Another lecture will be dedicated for the energization and the de-energization of bridges. If your HVDC link is having the many more than 2 bridges in converter side or inverter side and if you want to take one bridge out of operation for the maintenance in other purposes then, how you are going to de-energize? How you are going to bypass that bridge? Again, once it is a repaired then, how you are going to put into the HVDC link again? So, energization and de-energization are discussed in detail in this module 3 as well. Another aspect here, even though if suppose your HVDC link is down for some maintenance or some problems in the fault in the DC line then we have to start the HVDC line then how to start it. So, the starting concept will be discussed and also if you want take whole HVDC link down for any maintenance another repair or any other purposes then what should be the stopping way procedures is basically discussed in your starting and stopping of HVDC link.

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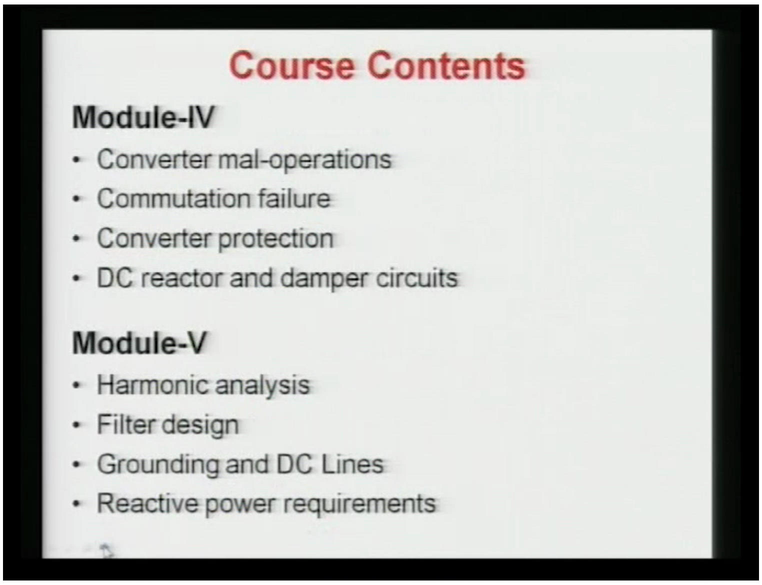

In module 4 basically, it is dedicated for the protection as well as the mal-operation of the converter circuit. So, the malconverter circuit maloperations the various mal-operations in the converter circuits are discussed including your arc-back, arc-through, misfire, commutation failure, quenching all will be discussed in detail along with the web snips of your output voltage as well as the valve voltages and but, the commutation failure which is only occurring in your inverter side. It is a very frequent phenomena; it is discussed again in detail for the single commutation failure or it is a double commutation failure. Single commutation failure means in one cycle it is only one commutation failure if it is happening more than one, it is called multiple commutation failure. So, in this module the first and second commutation failures are discussed and we will see what will be the output voltages; what will be the impact of the valve voltages, etcetera will be analyzed. Then, we will see how to protect overall converter circuit; that is we want to protect the converter circuit; we want to protect our HVDC lines. So, we are going for the over voltage protection; we are going for the over current protections similar to your AC current. Now also we are going to have the differential protections for the checking the link differential current. So, the complete inverter as well as your rectifier side system protection is discussed.

Another discussion here is this smoothing reactor. Basically, the DC reactor I am discussing and this DC reactor is if it is used to limit the rate of rise of voltage or current. So, what will be the inductance values? So this is basically it is discussed and the one problem is also solved. Then, in this module as well the damper circuit because, we are having the various type of dampers like the voltage oscillations if they are there then we are going to have the inner dampers if you are going to have the current oscillation ,you are going to have a line oscillation. So, we are having the various RC and RL seeder dampers are used and they are discussed in detail in this module.

Module 5 is basically dedicated to design the various aspects because, we have to design the filter circuit we have to design the grounding and the DC lines. So, to design the filter we have to analyze the whole converter operation and its. So, we want to know what are the various types of harmonics. So, various harmonics that is a characteristic and uncharacteristic harmonics are discussed and analyzed for the 6 pulse operation as well as the 12 pulse operation of the HVDC link and based on that we are going to design the filter circuit. So, we will see the various options for the that is a tune seal filter circuit or it is a your bypass band pass filter circuits design. So, the design of the filter will be done in this lecture. Another aspect of this module that it will be also analyze the reactive power requirements and we will analyze even the filter circuit if it is designed for particular harmonics to provide the minimum impedance for that harmonics. But, this filter circuit provides the reactive power support to the converters for the fundamental components and that will be analyze and we will see the requirements of your reactive power.

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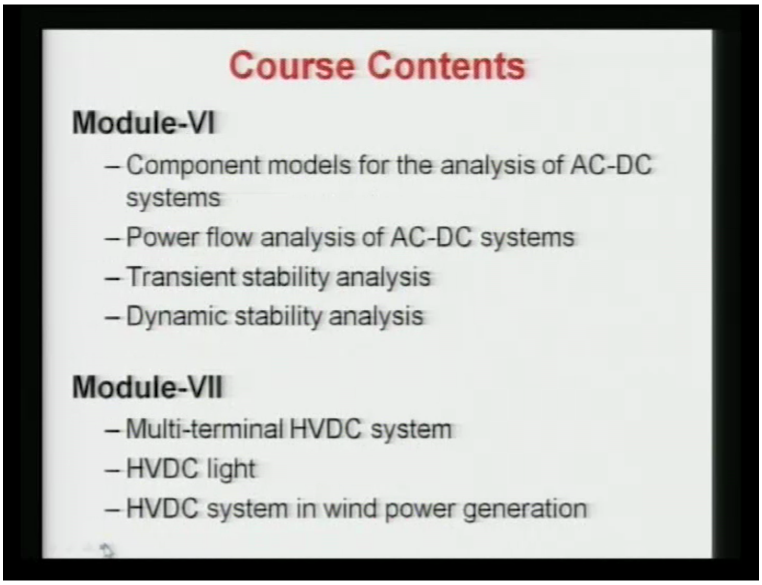

So in your module 6 is completely dedicated for the power system analysis aspect. So, here first I will model the various components of ac-dc systems including your DC the base powers etcetera, for AC and DC completely we have to match the AC base powers and the voltage and also the DC base power as well the voltage and then we will model them in detail and later then we will go for the AC DC load flow. Various techniques are already suggested that is a sequential based AC DC power flow analysis or it is a elimination based or unified schemes they are discussed much in detail in this module 6

After the modeling, this module is also will be discussing here. The various the stability analyses like the transient stability analysis as well as we will also discuss about the dynamic stability analysis in this module. The last module that is module 7 is basically dedicated for the diverse aspect like new concept is arising this HVDC light is basically using the transistor technology. It is very fast as well as the communication requirement is reduced it has a various advantages. So, that will be discussed; also, we will discuss about the multi-terminal HVDC link because till now up to the module your module fifth I discuss about only the 2 terminal HVDC. So, in this 7 will discuss the aspects problems and what are the advantage of multi-terminal HVDC links then the last lecture will be dedicated for this HVDC system that is used for the wind power generations. In the wind power generations you know the wind farm may be located very far from the actual load centers is it may be even though in offshores so, it may be in sea, we have to see how this HVDC system is useful and a beneficial for the wind power and the green power generation in whole power system. So, these are the brief course contents of this HVDC transmission system video course that is NPTEL phase 2.

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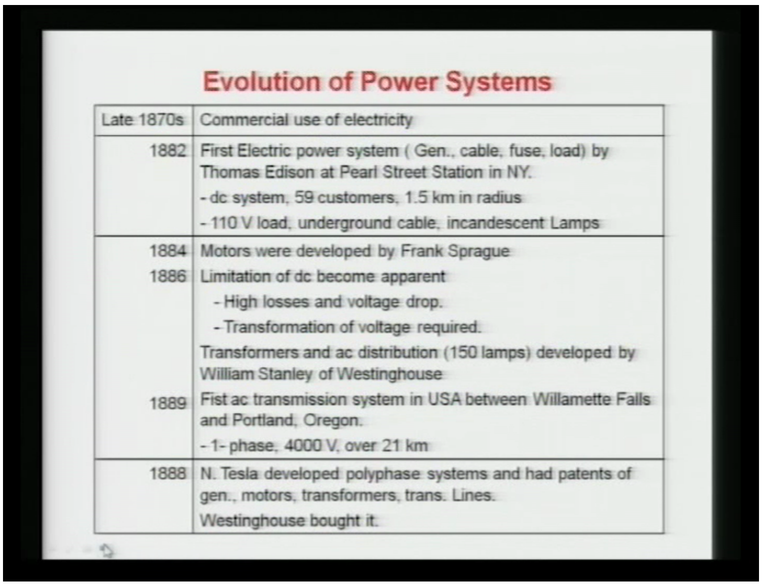

Now, as in the first part of this lecture I will be discussing the evolution of the power system then we will move that and we will see how the HVDC system came. So, to start with you can see the slide here the commercial use of electricity; basically, started in late 1870s, but the first power system was developed by your Thomas Alva Edison. It was at a pearl street of New York station and it was commissioned and operated in1882.

This was the DC system it is surprising, but it was the low voltage DC system, but however this course is devoted for the high voltages. So, that time the high voltage DC system was not possible because the several problems like your generations because it was the DC generators it was used and also to transmit the power the insulation and other problems were there. So, this power station, the first electric power station which was the DC it was consisting of a DC generators then it was using cables, fuses were used for the over current protection and it was providing the load and this load was nothing, but it was simple incandescent lamps were there the simple bulb loads were there and it was feeding to only 59 customers in the radius of 1.5 kilometers. So, it was a small system, but it was a complete in the sense and it is said the power system because a power system should comprise of generation, transmission as well as the distribution. So, it was consisting all. So, that is why it is called it is a first electric power system.

It was the DC system because, the DC generators were used at that time AC power was not even though invented so, the DC system was there. In 1884 the motors were developed by the Frank Sprague and with the addition of this motors in the DC system make the electricity more and more useable and people were more preferring this electricity because, now for using the electricity only for the lighting propose is not very much appreciated. But, the using the load you know the motors load and these motors loads the mechanical load you can just connect it that means you can achieve various applications in normal human life you can say.

So, the motors were added in the system but in 1886 the limitation of DC system becomes apparent with the 2 aspect that one is the voltage drop and high power loss. To minimize this we require some transformation of the voltage which was not possible by the DC system. So, people were starting thinking for the new one. At the same time, the transformers and the AC distribution system of 150 lamps developed by the William M Stanley for the Westinghouse was developed at the same in 1886 nearby. So, the limitations of the DC was arising and the now AC and DC system, they started arguing to each other because the DC system was advocated by the Thomas Alva Edison and AC system was advocated by the Westinghouse because, this Westinghouse purchase all the patents of the AC we will see that later on. So, this is the first AC transmission system was basically commissioned and operated between the Willamette fall and the Portland. This was the single phase it even at that time the 3 phase AC was not invented and it was having the 4 kilo volt and it was feeding the power over 21 kilometer.

So it was bigger because, AC system DC system was not feasible; because this much distance if you are going then you are incurring more loss and high voltage drop. So, in 1889 the first AC transmission system was operated in 18 before that even though Tesla this Nicolas Teals developed so many poly phase AC systems basically, he had the patents of generators, AC generators, motors, transformers, transmission lines, etcetera and all these patents were basically purchased by the Westinghouse. So, the Westinghouse now started developing the AC system - AC power system. I can say and Thomas Alva Edison always advocated for the DC system. So, parallely the AC and DC systems were existing for the different pockets of the all over the word and the fight started that whether we should go for the AC system or the DC system and due to the limitation of the DC system, AC won the race and DC system slowly and slowly phased out, that is here already.

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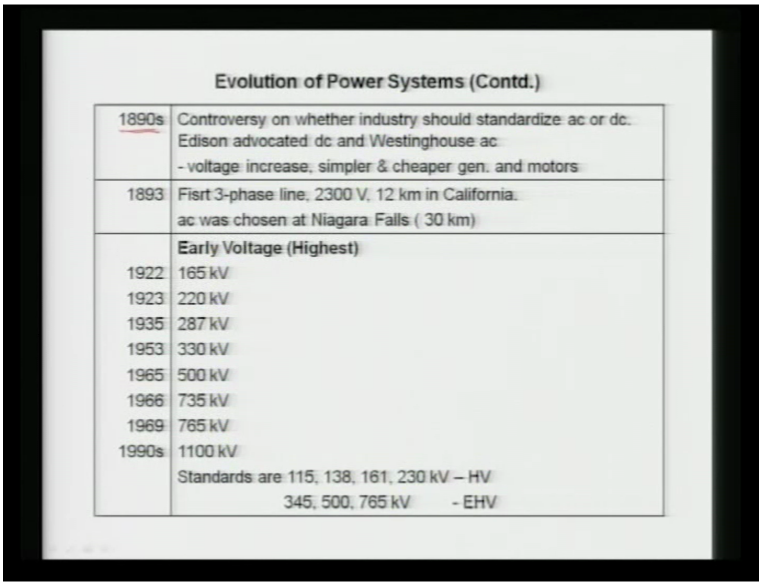

In 1890 it is said the controversy whether the industry should rest and rise AC or DC Edison who advocated DC was favoring the DC. However, the Westinghouse who had the lot of patents of AC system advocated for the AC systems. So, AC basically becomes more and more feasible because the it was possible to increase the voltage by the transformer actions and also it is a simpler in terms of generation and the motors and it is a rugged and very versatile and then it was the DC system was slowly and slowly the dismantled and the AC systems becomes very popular.

First 3 phase power system that was operated here in 1893 and the voltage was 2.3 kilo volt, it was in California. It was basically chosen for the Niagara fall which is 30 kilometers away from this Niagara falls. AC system becomes very popular but, the voltage at the beginning was very less due to the various problems in the design and availability of the insulating materials due to the various advancement in the insulating materials the voltages you can see now is a various voltages keep on increasing it was 1992 it was 165 kV in 1923 it went to 220 kV in 1935 it was 287 kV and in 1953 is 330 and so on. In 1990 it went up to 1100 kilo volts the transmission level.

Similarly, there were also improvements or you can say new developments in the generation side. So, we also increase our generating voltage up to 33 kV. So, it was and also in terms of megawatt more and more power generation for the single units. So, the standards basically adopted EHV system when it is more than 300. Then, it went through EHV system high voltage and it is less than 300 then it becomes the high voltage that is the various voltage levels.

Now, these voltage levels are the different for the different countries and the each country are having the different sets of the various voltages because they have to use transformers. So, it is not that we can have the n number of the transformations and the volt transformers. So, all the countries they standardize the various voltage levels to have the interconnections because the interconnections also had a lot of advantages when we keep on growing the AC system DC system AC system sorry and then we keep on interconnecting them to make better and better reliability and also to decrease the cast and. So, many other advantages as you know the interconnections advantages.

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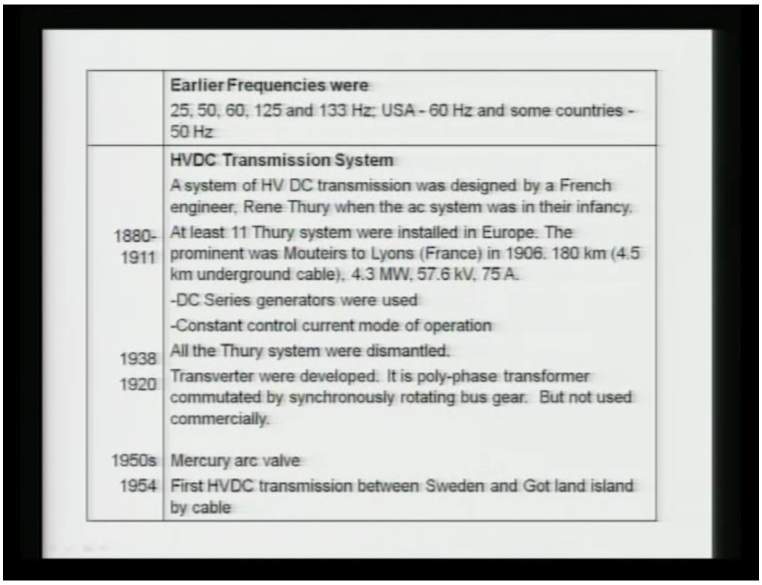

	Earlier Frequencies were 25, 50, 60, 125 and 133 Hz; USA - 60 Hz and some countries - 50 Hz
1880-1911 1938 1920 1950s 1954	**HVDC Transmission System** A system of HV DC transmission was designed by a French engineer, Rene Thury when the ac system was in their infancy. At least 11 Thury system were installed in Europe. The prominent was Mouteirs to Lyons (France) in 1906. 180 km (4.5 km underground cable), 4.3 MW, 57.6 kV, 75 A. -DC Series generators were used -Constant control current mode of operation All the Thury system were dismantled. Transverter were developed. It is poly-phase transformer commutated by synchronously rotating bus gear. But not used commercially. Mercury arc valve First HVDC transmission between Sweden and Got land island by cable

To have the interconnections, we know require the single frequency of the system. In the beginning it was witnessed that various frequencies were existing all over the world and now due to the interconnection problem it was realized that there should be the single frequencies and then the 2 frequencies after that were standardized like the 60 hertz came to the US and the Canadian countries and the 50 hertz came to the Europe and the Asian countries. So, we are operating our system at the 60 hertz and they are operating system at the 60 hertz.

Now, here if you will see the HVDC transmission system because I just explain how the HVAC system how it is grown to 1100 kV no doubt the beginning the DC was there then there was a limitations of the DC was experienced then AC people started thinking out the AC power system, but at the same time this people will also started thinking if any how we can increase the voltage. So, that we can have the minimum loss and also the minimum drop. So, people were started thinking and developing the various systems. So, the HVDC transmission system first designed by the French engineer that is a Rene Thury here when the AC system was in their infancy because AC system was also developing slowly and slowly. So, between 1880 and 1911 at least 11 Thury system because the Thury system was given based on his name Rene Thury was installed in Europe and the prominent was the Moutiers to Lyon in France in the 1906 it was 180 kilometers and I mean having 4.5 underground cables it was only carrying 4.3 megawatt power, but the voltage level was 57.6 kilo volt and the current was 625 A the main features of theory system was that it was having the DC generator and this is a series DC generators and it was operating at the constant current control mode because the current control here the current in this DC system here the current was fix; however, we will see in the AC system the voltage is fix and the current is changing depending by the load, but in this DC system he preferred current should be constant and the voltage can be changed to control the power and feed the power, but in here 1938 all the Thury systems were dismantled because there was several problems in this system because the safety problems was one concern.

And also, there was another problems here that we are adding the more and more series generators there was maintenance the cost other problems were experienced and at the same time the ac development was there and it was felt that AC system is the better than the DC system even though it was also witnessed that the our in 1920 the transverter it is a similar type of mechanical converters were developed and it was using the poly-phase transformer commutated by the synchronously rotating bus gear, but it was not used commercially it was only used the for the experimental another purpose.

So, once the theory died basically then whole the theory system was vanished and the people started talking about only the AC system. So, till 1950 when the mercury arc valves were developed and the designed then before that we were having only the AC DC AC systems with the development of the mercury arc valves it was possible to convert the AC to DC. So, in 1954 the first HVDC it is not DC it is high voltage DC transmission between the Sweden and the Gotland island of the Sweden itself was connected by the cable it was the 70 km approximately 70 kilometers away and the AC cables were not so feasible. So, it was decided to go for the HVDC transmission in terms of cable in the sea and mercury arc valves were used. So, this was the beginning of again starting to think of HVDC system now the question again arise why people started to think for the HVDC system because there was so many limitations of HVAC systems. So, we will see in the next slides.

So, in AC systems here before this end this I will discuss this what is the problem in HVDC and AC systems in detail basically in this AC system the major problem in the AC system is that we don’t have the power control.

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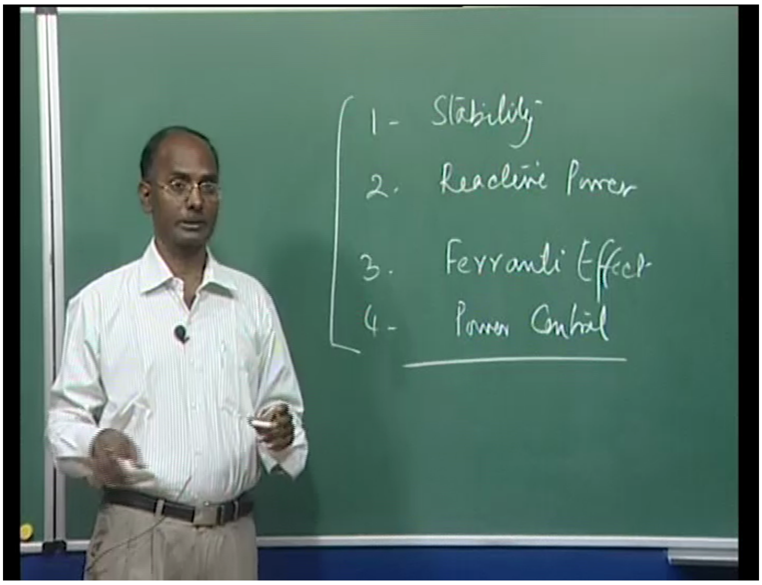

I can say the stability problem stability is the one concern if you are going more and more power transfer. So, this stability issue another is your reactive power requirement then third is your the Ferranti effect Ferranti effect also it will be discussed the Ferranti effect is nothing, but your receiving end voltage sometimes become higher than your sending voltage. Specially due to the charging or the capacitance between the line to ground and the line to line and 4 that we do not have the power control facility power control. So, the power control is not possible here. So, this is the one of the big problem in the AC systems in whole your AC system if this is your control is not possible because, nowadays we are also thinking to be provide the AC control if the AC control is possible then we can operate our power system in a much better and in the efficient manner.

So, these 4 are the major reasons for people are start to thinking to go for the DC transmission system these are basically problem which I am discussing in terms of the HVAC transmission system. So, to avoid these the DC transmissions were there because the reactive power you can see the first HVDC transmission system which came in the Sweden and the Gotland island it was basically due to the charging because the 70 kilometers cable it was at that time it was not feasible 70 kilometer. So, then it was realized that we can go for the DC cables and these DC cables were feasible. So, then what they did here? The this system you are the Sweden and this was your island and they connected by your the DC system here and they operated and this was your cable. So, this first HVDC basically, therefore was developed to reduce the charging effect of the system.

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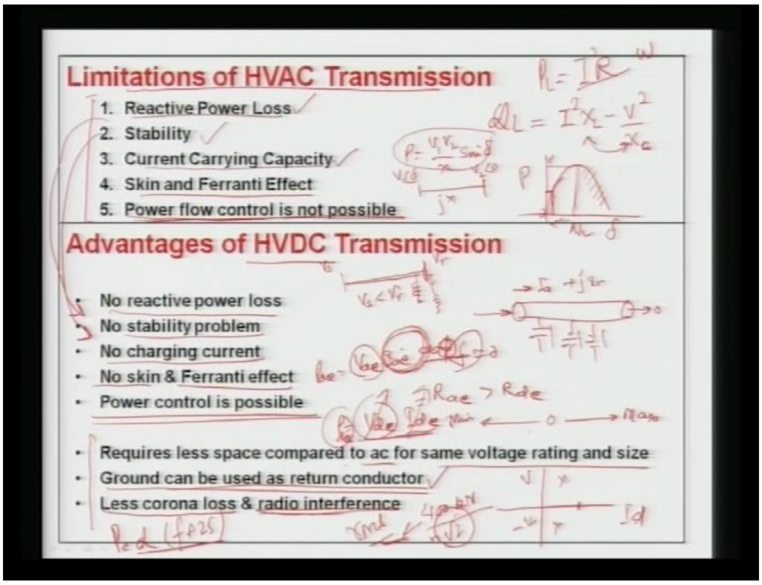

So here, in this you can also see that is I have summarized the 5 major problems limitations are HVAC transmission system that is a reactive power loss the stability concern the current carrying capacity that is the charging, skin and the Ferranti effect and the power flow control which is not possible in the AC system.

Reactive power loss we know it very well because the reactive power loss can be defined that is a Q loss you know real power loss it is very well that is $I^2 R$ here whatever the resistance and that is flowing in this your line it is having resistance it means not only line in the transformer as well. So, in all operators if are having the resistance R and the current is this. So, $I^2 R$ loss that is it is basically in watt it is your real power loss. Reactive power loss basically some people talk about here $I^2 X$, X is the reactance of that element, but it is not only this loss because we are having another component that is a it is I can say X_l it is a reactive component that is a inductive part and we are also having some charging part. So, that is basically I can say $\frac{V^2}{X_c}$ here that is the capacitive part. So, the reactive power loss is basically total of the that is the reactive power consumed in the element and some of the elements they generate the reactive power. So, the total sum of this is treated as the reactive power loss.

And this concept is only happening in HVAC because this X components that is here is only is occurring in AC and in the DC only the resistance is there. So, this reactive power loss has no impact because this is not existing at all in the HVDC transmission system. So, this is does not this Q loss does not arise and thereby why what happens if your line which is carrying the current of both active and reactive components. So, here you can see if we can there is no reactive component though line can carry both active power and then we can improve the performance of the systems.

Stability is the one of the concern to explain the simple way of the stability here you know this p angle this curve here this is a δ this a power that is a flowing between the 2 nodes of the element. So, here this is the maximum power that at the δ $\frac{\pi}{2}$ the maximum power that can be transported through that element we never go for this always we go for the lesser one due to the various reasons if there is some disturbance then we go into the unstable reason this is unstable area and this is your stable. So, we have to operate our system in such a way that the power flow in that line should be less than here this is a P max and here this is 0 in between. So, normally we operate our element that angle difference between the 2 adjacent node not should exceed more than 20 to 30 degree. So, that whenever there is any disturbance we can go here and our system cannot lose a synchronous.

So, the stability concern here basically this expression is the P is derived your $\frac{V_1 V_2}{X}\sin\delta$ here and this is basically the 2 elements this is your δ if this is angle 0. Here, I can say V_2 here V_1 and this is your X of the line. So, the power flow can be simplified if you are assuming this line is loss less we can just get this power flow and we will see here we can go for the minimum delta. So, this stability concern again does not arise in the DC system because the δ has does not derived because we only talk about the voltage and the resistance. So, no X nothing. So, this concept does not in that your DC system another is a current carrying capability here because the current carrying capability is basically the if any wire or cable here which is there the current is I is flowing inside this here this is called the current carrying capability now this current is if it is AC system it is having 2 component one is it is a active and another is your reactive components are there.

Now, it is the total current which is flowing, but if your here element is having more charging. So, what happens it is a more let us suppose capacity here elements are there like cable. So, even though you are not taking here any active power here this there is a possibility the current which is drawn here it will be the rated of this cable because due to this current which is flowing here in the charging. So, the current carrying capability of the AC elements or transmission line or your cables are very less compare to your DC because there is a no reactive component of current flowing over the cable or the transmission line. So, that is why here as mention. So, this if you are going for the cable longer than 50 kilometer is very costly and it earlier it was not possible now it is possible and it is not very much feasible, but it is better to go for the DC system.

Another here that is your skin effect skin effect is nothing, but if it is a AC system here the current this is your complete conductor area current will try to go from outer side due to the again the frequency of the system is some more frequency current will go more outer side. So, here the current is non-uniform because the inn in at center current will be less outside it will be more. So, what happen the density of the current in this over this area of the conductor is the different and that is why the resistance effective resistance will be more and there by the loss will be more. So, this skin effect only arise in your AC cable AC lines because AC has a some frequency f and that is why it is having if f is 0 it is a DC and finally, it will be the current will be the uniform and therefore, that is why always we say R_{AC} is always greater than your R_{DC} means thus resistance if you'd measure the AC resistance will be more than your the DC resistance due to your skin and the proximity effect if another conductor is there again there is flux linkage. The Ferranti effect which is basically if this 2 system here the big transmission line is there and this is called V sending end voltage and this is your receiving end voltage at the lightly loaded or no load condition you are the V_s magnitude here I am talking it is less then sometimes it is your V_r and this is called Ferranti effect and this is due to the charging basically charging of the on the capacitance formed due to this conductor with respect to ground.

So, what we do we go for the various mechanisms to limit this voltage especially if you are charging the line there is no load and then the high voltage will be there at the end and there will be again tripping of the system? So, we put the various here the reactors we put the line reactors if the line is very long and then if still you require more reactive powers then you can put the bus reactors and sometimes also we use the tertiary reactors as well.

The another major concern here the power flow control is not possible power flow control I mean that we want the power flow control in the smooth manner sometimes we also want the power should be reverse from one direction to another direction which is not feasible not possible in the AC system unless until you are putting another device nowadays again the flexible AC transmission systems are invented they are in the place in the system now with help of them we can control the power in the AC system as well, but at that time it was earlier it was not possible before 90 it was not possible and HVDC control was only possible. So, that why the various types of links were developed and based on those links we were controlling the power flow as well in the lines as well as every neighboring areas.

So, to avoid these 5 limitations it was found the HVDC is better in terms of several problems of the HVAC transmission. First you will see regarding the reactive power loss here you can say there is a no reactive power loss at all as I explain it is true the stability concern you can say there is no stability concern in HVDC system no doubt we are it is not mean that we can flow up as much as power in any transmission line HVDC transmission line it has some limit, but that limit now is your thermal limit; however, in the AC system we are having thermal limit and stability limits and the voltage regulation limits as well, but it depending upon the length of line which limit is coming first is basically decided by the length of line if length of line is very long your stability limit is the governing criteria than the thermal limit because thermal limit value is very high if line is less then stability concern is not there very less. So, the thermal limit will be governing criteria, but here in HVDC only the thermal limit is the governing condition you can load your transmission line up to it is a thermal limits where it is designed, but the stability problem is not a concern of HVDC transmission no charging current because the if there is no change smooth here the perfect DC voltage and perfect current flowing. So, there is no charging here and this no capacity and the charging current is not there because once it is the capacitance will be formed once you are having the 2 potential difference medium is the dielectric medium, air is a also a dielectric medium. So, capacitances are formed, but it is the constant and there is no charging.

Here no skin effect no Ferranti effect because the charging is not their skin effect is not there because again the frequency is 0 here in the DC system and the power flow control is possible that we can control our converters in a such a way that we can control the power because the DC power here it is a P_{DC} is your V_{DC} into your I_{DC} means the DC current multiplied by the simple DC current, but and this is called your P_{DC}; however, your P_{AC} is your the voltage AC voltage and your AC current into the cosine theta then theta are here I am writing theta is the power factor angle between the voltage and current and the cosine of this is a power factor. Here the P_{DC} can be controlled by the voltage control can be controlled by current control or can be controlled by both, but we prefer the current should be the constant and the voltage can be varied and thereby we can vary here the DC power.

So, here basically what this your DC power is very effectively controlled even though it is not only controlling from 0 to it is maximum value it is also possible that we can control it is the minimum value in the negative direction means because the voltage can be vary from -V to 0 to +V. So, that we can have the power reversal also with the help of this HVDC link and that is it means you can have a full 2 quadrant operation because the 2 quadrant which I mean here this is your I_d we had as I said it is a constant and your voltage here the positive voltage here negative voltage you can operate this and this co-ordinate very effectively and then you can basically control the power from one end to another end and as well as you can return it back.

So, the controllability here is very better and very effective, but some other advantages minor advantages are also there with the your HVDC transmission system that it is said that it requires less space compared to the AC system for the same voltage rating and the size because the same voltage here you know if you are having let us suppose 400 kV system 400 kV system means you have to design this 400 kV is your r m s value. So, you have to design your system for it is peak value and peak value here is nothing, but multiplied by under root 2.

So, you are going to multiply this your design is basically, but in the power here calculation is a 400. So, what happens? You require the less space in terms of suppose you are having the insulators and crossarms and also in the substations clearance here and there we require the less space in the DC due to this factor as well because we always see the peak inverse peak voltages for the AC system.

Another advantage here that the ground can be used as the return path in as I will discuss in the next and other lectures, that the various type of links are feasible. It is called mono polar, bipolar and homo-polar. In the mono-polar, only one pole, only one wire is there and the ground is used as a return path. So, we can use the ground as a return path means we can minimize we can reduce the cost of the conductor. But, it is not very practical because the if you are using ground current then there are so, many other problems like the communication interference there will be some erosion there may be some if there is some potential is developed and from there is shock and safety majors as well. So, ground is used as a return path especially in the emergency conditions when there is one problem in the one poles so then, we can use the ground as path providing the power for the limited period of time especially in the bipolar if one pole has gone then we can use another pole as the mono-polar operation and we can operate we can give the 50 percent power transfer from one area to another area. So, this is another advantage that we it is possible for AC system phase you have to completely shut down and then, you have to maintain it.

Another advantage is the less corona loss because, the corona loss you know it is the always this proportional to f + 25. Here, that is I can say P_c corona loss is a proportional to this. You know the in DC f is 0 and your AC here f is 50 or 60 hertz. So, it is the more loss in AC system compared to your DC system. So, what happens here, the corona loss in HVDC system is less compared to your DC system. Another is radio interference here the RI if frequency is 0 so, radio interference is 0 but, due to the some harmonics and other thing there will may be some radio interference, but this value is very less.

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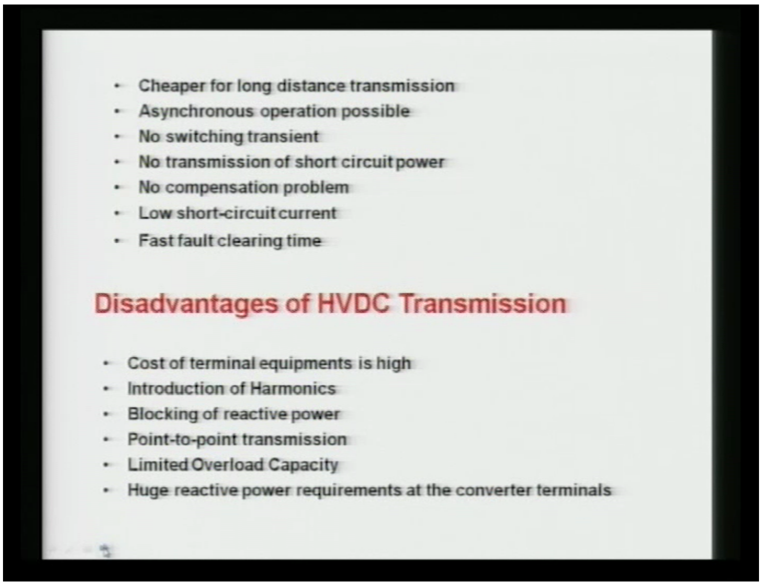

So overall, we can see here that the advantage of HVDC is basically taking place and it is trying to minimize the limitations of HVAC transmission system but, it is not HVDC is not having limitations. It is also having the various limitations in terms of its cost, in terms of generating harmonics, in terms of tapping of the power and in terms of some other limitations like here you can say the overload capability we can the blocking of the reactive power and some are all other things there. So, advantages here some other various minor advantages are listed here you can say the fault clearing time, the compensation problem, no compensation is required for the capacitance low short circuit. No, transmission of short circuit power it has a less and no switching transient or synchronous operation is possible and it is a cheaper for the long distance problem.

So, all these again I will discuss the next lecture, but in this lectures my main intention is to give you a concept. Why this HVDC transmission system is taking place all over the world especially for the long distances transmission in the those countries, which is very small in the geographical area HVDC is not very feasible for the long distance transmission.

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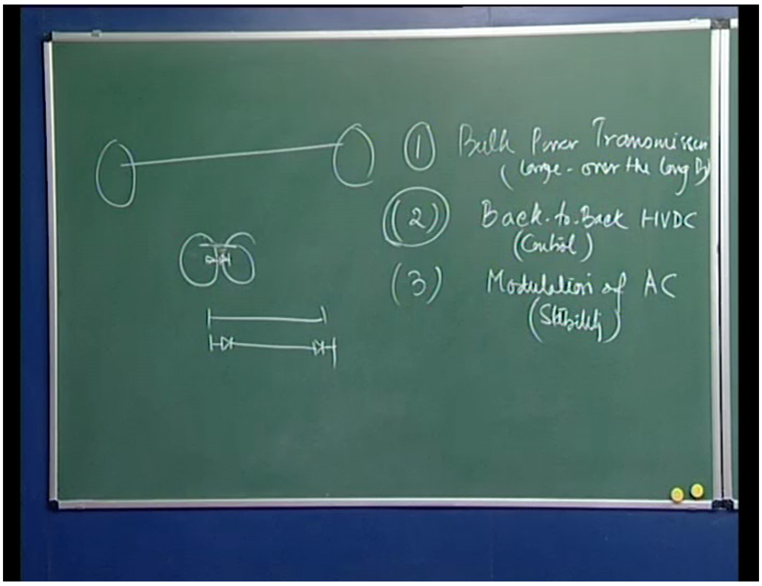


So we are having basically the 2 types - 3 types of HVDC links for this control of AC DC power system. One is called if you want to have a bulk power transmission and second is you want it is called back to back concept. Back to back modulation of AC network basically, here in the bulk power transmission. What I want to say if you want to transmit the power from one region over a long region without tapping power in between, it is called bulk power transmission.

Here the concept that the generation if suppose in this area is very high, load demand in this area is very high we want to transmit power without tapping in between the DC is the best and the cheap option. But, that is I mentioning if area is small then it is possible that you can go for the AC system and then you can transmit the power but, those country is a very long and you want to transfer for the long distance. There is no other option; you have to go for the

DC system at all. So, we have to use the HVDC bulk power transmission especially in India, it is very important if you are trying to trap power from north east and taking it to the central part of the India. We require huge HVDC links to transmit the power but, this concept is now common not only here at the basics of here to control the power, here the concept was to transmit the power here this control aspect even though if you are having the 2 regions very nearby.

Here, you can have your the DC here back to back even those converter and inverter stations are put together very near to each other may be less than one kilometers away even the one substation and the purpose here that we can monitor how much power is flowing from one region to another region. So, that is it is called back to back because inverter and converter are same back to back here only. We do not want to transfer bulk amount of power here. We want to control the power because it is based on the contract; it is based on some negotiations and also in terms some sort of the emergency you know, if there is some problem this region this link is there. Then, we can open this and the disturbance cannot be propagated in another region. But, if you are having a AC line here certainly the disturbance here that can go there. If it is not protected well then both system will be the collapse. So, it has various advantages here we want to control, we want to provide the emergency support and also we can just meet our the contractual requirement. So, the back to back connections are there.

Here, the modulation of AC DC system basically is mini; that if you are having some here AC line and this line is very weak. Sometimes, there is some problem here due to the power oscillations or you can say power swings are there. We can have another here HVDC link small HVDC link that can support this one means whenever there is a problem we can just control in a such a way that we can modulate the power over this AC line means it is used to improve the stability of the system. So, you can see these 3 objectives are for the HVDC transmission system. Here, it is basically to feed the power over the long distance means, large power over the long distance. This is also control we do it control no doubt but, the basic is huge power which is fed from one area to another area. Here, as I said this one is the control of power; is the primary objective. That is, we can control the power. How much it is going if it is AC system is there? So, if this area is drawing more power it will be flowing here without any control you cannot control here, but the DC here connection is there you can fix the power it cannot take more power from this area unless until this controller or tune for this one is basically used for your stability of the system.

So basically, it is used in this AC system to stabilize the AC DC system as well. So, that is why here the transmission part is now going. If your objectives are these then, you have to go for your DC systems and it is we are talking about the high voltage DC system. So, nowadays that is why we are having the AC generation; we are having the AC distribution system and of course, the utilization now we are again shifting from the AC to the DC because, we are having lot of power electronics based devices those are giving and also communication mobiles and another DC power are required in the houses, but the transmission distribution is AC and after that again people are using some converter conversion technology to get the DC power for the charging of the batteries here and there generation is still your conventional generators; they are AC. We are also generating some part of the DC power based on your photovoltaic but, if you want to connect in the system then you should require some converter and then you convert to the AC system and then you can connected it to the grid but, the transmission if this transmission is the combination of your AC and DC system, specially based on the various objective, so it is believed that your transmission part will be the mixture of your AC as well as the DC system and here, the DC system we are talking high voltage DC we don't have the DC low voltage DC because, again the problem of high loss and the voltage drop will be there.

So, high voltage DC transmission along with the your AC transmission it includes both your high voltage EHV and the low voltage AC transmission as well. So this is the scenario which is emerging all over the world. So to conclude in this whole lecture number one basically I discussed the course contents which will be the giving the basics that what we are going to discuss in the various modules various lectures and it was decided in based on that. So, the total this whole course will be basically schedule for 35 to 40 lectures based on the various contents and also some numerical problems will be solved and will be showed so that the students can get benefited. Even the teachers also they can be benefited from this and here, in the first lecture I had just summarized the evolution of the power system along with the special emphasis was your DC system from your small high voltage DC systems. Then, we went for the large DC system and then we discussed some of the limitations of HVAC system and then, along with it we discussed that how this DC system will be the advantageous to remove the limitations of HVAC system.

So, the various disadvantages are also there that will be discussed in the next lecture and also we will discuss the various types of links in this module and also the various of components the basic background will be given in this module so that, we can move to the various modules. Then, it will be analysis control the protection; then, analysis and then, we will see the total performance of HVDC, AC, DC and the AC system as well. So, with this I should stop this; thank you.

Keywords: Evolution of HVDC transmission, first electric power system, DC generators, HVAC system, Ferranti effect, skin effect.

15.4 LINE COMPENSATION

Ideal voltage profile for a transmission line is flat, which can only be achieved by loading the line with its surge impedance loading while this may not be achievable, the characteristics of the line can be modified by line compensators so that

(i) Ferranti effect is minimized.

(ii) Underexcited operation of synchronous generators is not required.

(iii) The power transfer capability of the line is enhanced. Modifying the characteristics of a line(s) is known as *line compensation.*

Various compensating devices are:

- Capacitors
- Capacitors and inductors
- Active voltage source (synchronous generator)

When a number of capacitors are connected in parallel to get the desired capacitance, it is known as a bank of capacitors, similarly a bank of inductors. A bank of capacitors and/or inductors can be adjusted in steps by switching (mechanical).

Capacitors and inductors as such are passive line compensators, while synchronous generator is an active compensator. When solid-state devices are used for switching off capacitors and inductors, this is regarded as active compensation.

Before proceeding to give a detailed account of line compensator, we shall briefly discuss both shunt and series compensation.

Shunt compensation is more or less like load compensation with all the advantages associated with it and discussed in Section 15.3. It needs to be pointed out here that shunt capacitors/inductors can not be distributed uniformally along the line. These are normally connected at the end of the line and/or at midpoint of the line.

Shunt capacitors raise the load pf which greatly increases the power transmitted over the line as it is not required to carry the reactive power. There is a limit to which transmitted power can be increased by shunt compensation as it would require very large size capacitor bank, which would be impractical. For increasing power transmitted over the line other and better means can be adopted. For example, series compensation, higher transmission voltage, HVDC etc.

When switched capacitors are employed for compensation, these should be disconnected immediately under light load conditions to avoid excessive voltage rise and ferroresonance in presence of transformers.

The purpose of series compensation is to cancel part of the series inductive reactance of the line using series capacitors. This helps in (i) increase of maximum power transfer (ii) reduction in power angle for a given amount of power transfer (iii) increased loading. From practical point of view, it is desirable not to exceed series compensation beyond 80%. If the line is 100% compensated, it will behave as a purely resistive element and would cause series resonance even at fundamental frequency. The location of series capacitors is decided by economical factors and severity of fault currents. Series capacitor reduces line reactance thereby level of fault currents.

A detailed discussion on various issues involved in series and shunt compensators now follows.

15.5 SERIES COMPENSATION

A capacitor in series with a line gives control over the effective reactance between line ends. This effective reactance is given by

$$X_l' = X - X_c$$

where

X_l = line reactance

X_C = capacitor reactance

It is easy to see that capacitor reduces the effective line reactance*. This results in improvement in performance of the system as below.

(i) Voltage drop in the line reduces (gets compensated) i.e. minimization of end-voltage variations.

(ii) Prevents voltage collapse.

(iii) Steady-state power transfer increases; it is inversely proportional to X_l'.

(iv) As a result of (ii) transient stability limit increases.

The benefits of the series capacitor compensator are associated with a problem. The capacitive reactance X_C forms a series resonant circuit with the total series reactance

$$X = X_l + X_{\text{gen}} + X_{\text{trans}}$$

The natural frequency of oscillation of this circuit is given by.

$$f_C = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{\frac{X}{2\pi f}\,\frac{2\pi f C}{2\pi f}}} = f\sqrt{\frac{X_C}{X}}$$

where f = system frequency

*Reactive voltage drops of a series reactance added in a line is I^2X
It is positive if X is inductive and negative if X is capacitive. So a series capacitive reactance reduces the reactance voltage drop of the line, which is an alternative way of saying that

$$X_l' = X_l - X_c.$$

$$\frac{X_C}{X} = \text{degree of compensation}$$

$$= 25 \text{ to } 75\% \text{ (recommended)}$$

For this degree of compensation

$$f_C < f$$

which is subharmonic oscillation.

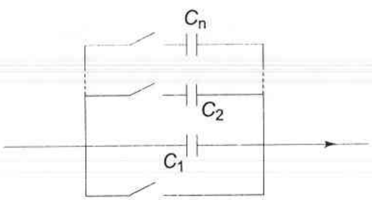
Even though series compensation has often been found to be cost-effective compared to shunt compensation, but sustained oscillations below the fundamental system frequency can cause the phenomenon, referred to as subsynchronous resonance (SSR) first observed in 1937, but got world-wide attention only in the 1970s, after two turbine-generator shaft failures occurred at the Majave Generating station in Southern Nevada. Theoretical studies pointed out that interaction between a series capacitor-compensated line, oscillating at subharmonic frequency, and torsional mechanical oscillation of turbine-generator set can result in negative damping with consequent mutual reinforcement of the two oscillations. Subsynchronous resonance is often not a major problem, and low cost countermeasures and protective measures can be applied. Some of the corrective measures are:

(i) Detecting the low levels of subharmonic currents on the line by use of sensitive relays, which at a certain level of currents triggers the action to bypass the series capacitors.

(ii) Modulation of generator field current to provide increased positive damping at subharmonic frequency.

Series inductors are needed for line compensation under light load conditions to counter the excessive voltage rise (Ferranti effect).

As the line load and, in particular the reactive power flow over the line varies, there is need to vary the compensation for an acceptable voltage profile. The mechanical switching arrangement for adjusting the capacitance of the capacitor bank in series with the line is shown in Fig. 15.1. Capacitance is varied by opening the switches of individual capacitances with the capacitance C_1, being started by a bypass switch. This is a step-wise arrangement. The whole bank can also be bypassed by the starting switch under any emergent conditions on the line. As the switches in series with capacitor are current carrying suitable circuit breaking arrangement are necessary. However, breaker switched capacitors in series are generally avoided these days the capacitor is either fixed or thyristor switched.



With fast advancement in thyristor devices and associated switching control technology, the capacitance of the series capacitance bank can be controlled much more effectively; both stepwise and smooth control. This is demonstrated by the schematic diagram of Fig. 15.2 wherein the capacitor is shunted by two thyristors in antiparallel. Upon firing the thyristors alternately one carries current in positive half cycle and the other in negative half cycle.

In each half cycle when the thyristor is fired (at an adjustable angle), it conducts current for the rest of the half cycle till natural current zero. During the off-time of the thyristor current is conducted by the capacitor and capacitor voltage is v_c. During on-time of the thyristor capacitor is short circuited i.e. $v_c = 0$ and current is conducted by the thyristor. The same process is repeated in the other half cycle. This means that v_c can be controlled for any given i, which is equivalent of reducing the capacitance as $C = v_c/i$. By this scheme capacitance can be controlled smoothly by adjusting the firing angle.

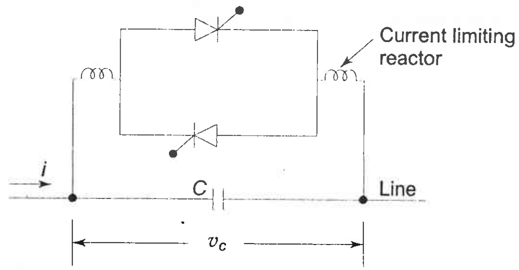


Fig. 15.2

Thyristors are now available to carry large current and to withstand (during off-time) large voltage encountered in power systems. The latest device called a Gate Turn Off (GTO) thyristor has the capability that by suitable firing circuit, angle (time) at which it goes on and off can both be controlled.

This means wider range and finer control over capacitance. Similarly control is possible over series reactor in the line.

All controlled and uncontrolled (fixed) series compensators require a protective arrangement. Protection can be provided externally either by voltage arrester or other voltage limiting device or an approximate bypass switch arrangement. In no case the VI rating of the thyristors should be exceeded.

Depending on (i) kind of solid-state device to be used (ii) capacitor and/or reactor compensation and (iii) switched (step-wise) or smooth (stepless) control, several compensation schemes have been devised and are in use. Some of the more common compensation schemes are as under.

(i) Thyristor Controlled Series Capacitor (TCSC)

(ii) Thryristor Switched Series Capacitor (TSSC)

(iii) Thyristor Controlled Reactor with Fixed Capacitor (TCR + FC)

(iv) GTO thyristor Controlled Series Capacitor (GCSC)

(v) Thyristor Controlled reactor (TCR)

Capacitor and/or reactor series compensator act to modify line impedance. An alternative approach is to introduce a controllable voltage source in series with the line. This scheme is known as static synchronous series compensator (SSSC). SSSC has the capability to induce both capacitive and inductive voltage in series with line, thereby widening the operating region of the scheme. It can be used for power flow control both increasing or decreasing reactive flow on the line. Further this scheme gives better stability and is more effective in damping out electromechanical oscillations.

Though various types of compensators can provide highly effective power flow control, their operating characteristics and compensating features are different. These differences are related to their inherent attributes of their control circuits; also they exhibit different loss characteristics.

From the point of view of almost maintenance free operation impedance modifying (capacitors and/or reactors) schemes are superior. The specific kind of compensator to be employed is very much dependent on a particular application.

15.6 SHUNT COMPENSATORS

As already explained in Sec. 15.4 and in Ch. 5 (Sec. 5.10) shunt compensators are connected in shunt at various system nodes (major substations) and sometimes at mid-point of lines. These serve the purposes of voltage control and load stabilization. As a result of installation of shunt compensators in the system, the nearby generators operate at near unity pf and voltage emergencies mostly do not arise. The two kinds of compensators in use are:

(i) *Static var compensators (SVC):* These are banks of capacitors (sometimes inductors also for use under light load conditions)

(ii) STATCOM: static synchronous compensator

(iii) *Synchronous condenser*: It is a synchronous motor running at no-load and having excitation adjustable over a wide range. It feeds positive VARs into the line under overexcited conditions and negative VARS when underexcited. (For details see Sec. 5.10.)

It is to be pointed out here that SVC and STATCOM are static var generators which are thyristor controlled. In this section SVC will be detailed while STATCOM forms a part of FACTS whose operation is explained in Sec. 15.10.

Static VAR Compensator (SVC)

These comprise capacitor bank fixed or switched (controlled) or fixed capacito bank and switched reactor bank in parallel. These compensators draw reactiv (leading or lagging) power* from the line thereby regulating voltage, improv

*A reactance connected in shunt to line at voltage V draws reactive power V^2/X It is negative (leading) if reactance is capacitive and positive (lagging) if reactance is inductive.

stability (steady-state and dynamic), control overvoltage and reduce voltage flicker. These also reduce voltage and current unbalances. In HVDC application these compensators provide the required reactive power and damp out subharmonic oscillations.

Since static var compensators use switching for var control. These are also called static var switches or systems. It means that terminology wise

SVC = SVS

and we will use these interchangeably.

Basic SVC Configurations (or Designs)

Thyristors in antiparallel can be used to switch on a capacitor/reactor unit in stepwise control. When the circuitary is designed to adjust the firing angle, capacitor/reactor unit acts as continuously variable in the power circuit.

Capacitor or capacitor and inductor bank can be varied stepwise or continuously by thyristor control. Several important SVS configurations have been devised and are applied in shunt line compensation. Some of the static compensators schemes are discussed in what follows.

(i) *Saturated reactor*

This is a multi-core reactor with the phase windings so arranged as to cancel the principal harmonics. It is considered as a constant voltage reactive source. It is almost maintenance free but not very flexible with respect to operating characteristics.

(ii) *Thyristor-controlled reactor (TCR)*

A thyristor-controlled-reactor (Fig. 15.3) compensator consists of a combination of six pulse or twelve pluse thyristor-controlled reactors with a fixed shunt capacitor bank. The reactive power is changed by adjusting the thyristor firing angle. TCRs are characterised by continuous control, no transients and generation of harmonics*. The control system consists of voltage (and current)

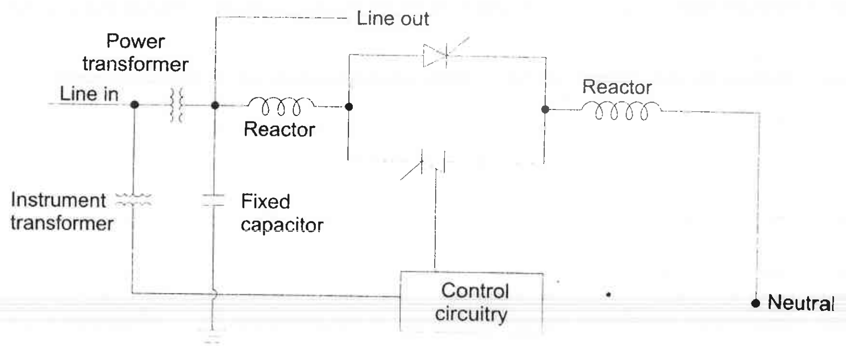


Fig. 15.3 Thyristor controlled reactor (TCR) with fixed capacitor

*Though λ –connected TCR's are used here, it is better to use Δ-connected TCR's since it is better configuration.

measuring devices, a controller for error-signal conditioning, a linearizing circuit and one or more synchronising circuits.

(iii) *Thyristor switched capacitor (TSC)*

It consists of only a thyristor-switched capacitor bank which is split into a number of units of equal ratings to achieve a stepwise control (Fig. 15.4).

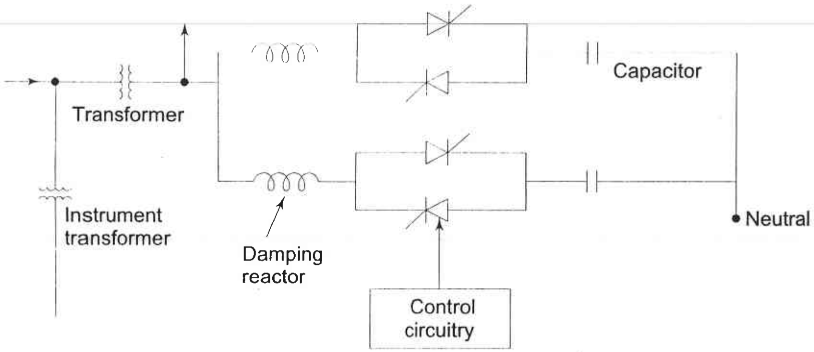


Fig. 15.4 Thyristor switched capacitor (TSC)

As such they are applied as a discretly variable reactive power source, where this type of voltage support is deemed adequate. All switching takes place when the voltage across the thyristor valve is zero, thus providing almost transient free switching. Disconnection is effected by suppressing the firing plus to the thyristors, which will block when the current reaches zero. TSCs are characterised by step wise control, no transients, very low hormonics, low losses, redundancy and flexibility.

(iv) *Combined TCR and TSC Compensator*

A combined TSC and TCR (Fig. 15.5) is the optimum solution in majority of cases. With this, continuous variable reactive power is obtained throughout the complete control range. Furthermore full control of both inductive and capacitive parts of the compensator is obtained. This is a very advantageous

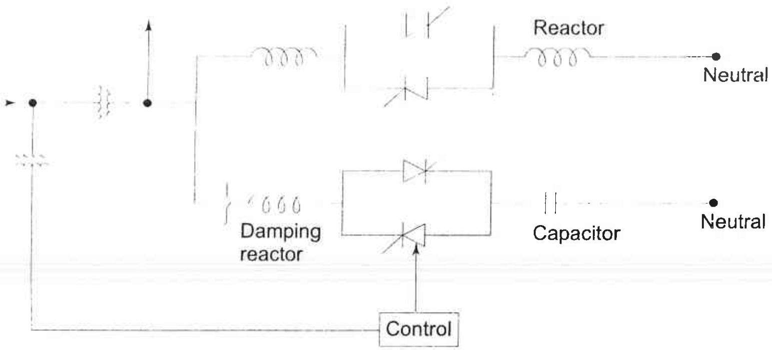


Fig. 15.5 A combined TCR/TSC compensator

feature permitting optimum performance during large disturbances in the power system (e.g. line faults, load rejection etc) TSC/TCR combinations are characterised by continuous control, no transients, low generations of harmonics, low losses, redundancy, flexible control and operation.

The basic characteristics of the main static var generator schemes are given in Table 15.1.

Table 15.1 Comparison of Static Var Generators

Type of Var Generator	*TCR-FC* (1)	*TSC-(TSR)* (2)	*TCR-TSC* (3)
VI and VQ characteristics	Max comp. current is proportional to system voltage. Max cap. var output decreases with the square of the voltage decrease.	Max. Comp. current is proportional to system voltage. Max. cap. var output decreases with the square of the voltage decrease.	Same as in (1) or (2)
Loss Vs var output.	High losses at zero output. Losses decrease smoothly with cap. output, increase with inductive output	Low losses at zero ouput. Losses increase step-like with cap. output	Low losses at zero output. Losses increase step-like with cap. output, smoothly with ind. output
Harmonic generation	Internally high (large pu TCR) Requires significant filtering	Internally very low Resonance may necessitate tuning reactors	Internally low (small pu TCR) Filtering required
Max. theoret. delay	1/2 cycle	1 cycle	1 cycle
Transient behaviour under system voltage disturbances	Poor (FC causes transient over-voltages in response to step disturbances)	Can be neutral. (Capacitors can be switched out to minimise transient over-voltages)	Same as in (2)

15.7 COMPARISON BETWEEN STATCOM AND SVC

It may be noted that in the normal linear operating range of the V-I characteristic and functional compensation capability of the STATCOM and the SVC are similar [2]. However, the basic operating principles of the STATCOM, which, with a converter based var generator, functions as a shunt-connected synchronous voltage source, are basically different from those of the SVC, since SVC functions as a shunt-connected, controlled reactive admittance. This basic operational difference renders the STATCOM to have overall superior functional characteristics, better performance, and greater application flexibility as compared to SVC. The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient (first swing) stability.

Comparison between series and shunt compensation:

Advantages of series compensation:

(i) Series capacitors are inherently self regulating and a control system is not required.
(ii) For the same performance, series capacitors are often less costly than SVCs and losses are very low.
(iii) For voltage stability, series capacitors lower the critical or collapse voltage.
(iv) Series capacitors possess adequate time-overload capability.
(v) Series capacitors and switched series capacitors can be used to control loading of paralled lines to minimise active and reactive losses.

Disadvantages of series compensation:

(i) Series capacitors are line connected and compensation is removed for outages and capacitors in parallel lines may be overloaded.
(ii) During heavy loading, the voltage on one side of the series capacitor may be out-of range.
(iii) Shunt reactors may be needed for light load compensation.
(iv) Subsynchronous resonance may call for expensive countermeasures.

Advantages of SVC

(i) SVCs control voltage directly.
(ii) SVCs control temporary overvoltages rapidly.

Disadvantages of SVC

(i) SVCs have limited overload capability.
(ii) SVCs are expensive.

The best design perhaps is a combination of series and shunt compensation. Because of higher initial and operating costs, synchronous condensers are normally not competitive with SVCs. Technically, synchronous condensers are better than SVCs in voltage-weak networks. Following a drop in network voltage, the increase in condenser reactive power output is instantaneous. Most synchronous condenser applications are now associated with HVDC installations.

15.8 FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)

The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for better utilization of

existing systems. Since 1990, a number of control devices under the term FACTS technology have been proposed and implemented. FACTS devices can be effectively used for power flow control, load sharing among parallel corridors, voltage regulation, enhancement of transient stability and mitigation of system oscillations. By giving additional flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. Mechanical switching has to be supplemented by rapid response power electronics. It may be noted that FACTS is an enabling technology, and not a one-on-one substitute for mechanical switches.

FACTS employ high speed thyristors for switching in or out transmission line components such as capacitors, reactors or phase shifting transformer for some desirable performance of the systems. The FACTS technology is not a single high-power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more of the system parameters.

Before proceeding to give an account of some of the important FACTS controllers the principle of operation of a switching converter will be explained, which forms the heart of these controllers.

15.9 PRINCIPLE AND OPERATION OF CONVERTERS

Controllable reactive power can be generated by dc to ac switching converters which are switched in synchronism with the line voltage with which the reactive power is exchanged. A switching power converter consists of an array of solid-state switches which connect the input terminals to the output terminals. It has no internal storage and so the instantaneous input and output power are equal. Further the input and output terminations are complementary, that is, if the input is terminated by a voltage source (charged capacitor or battery), output is a current source (which means a voltage source having an inductive impedance) and vice versa. Thus, the converter can be voltage sourced (shunted by a capacitor or battery) or current sourced (shunted by an inductor).

Single line diagram of the basic voltage sourced converter scheme for reactive power generation is drawn in Fig. 15.6. For reactive power flow bus voltage V and converter terminal voltage V_0 are in phase.

Then on per phase basis

$$I = \frac{V - V_0}{X}$$

The reactive power exchange is

$$Q = VI = \frac{V(V - V_0)}{X}$$

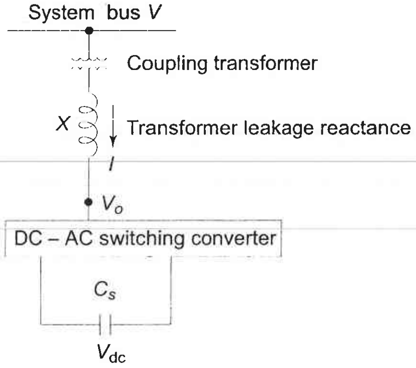


Fig. 15.6 Static reactive power generator

The switching circuit is capable of adjusting V_0, the output voltage of the converter. For $V_0 < V$, I lags V and Q drawn from the bus is inductive, while for $V_0 > V$, I leads V and Q drawn from the bus is leading. Reactive power drawn can be easily and smoothly varied by adjusting V_0 by changing the on-time of the solid-state switches. It is to be noted that transformer leakage reactance is quite small (0.1–0.15 pu), which means that a amall difference of voltage $(V - V_0)$ causes the required I and Q flow. Thus the converter acts like a static synchronous condenser (or var generator).

A typical converter circuit is shown in Fig. 15.7. It is a 3-phase two-level, six-pulse H-bridge with a diode in antiparallel to each of the six thyristors (Normally, GTO's are used). Timings of the triggering pulses are in synchronism with the bus voltage waves.

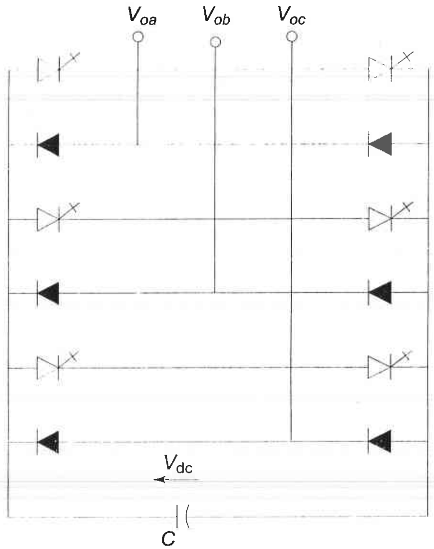


Fig. 15.7 Three-phase, two-level six-pulse bridge

As the converter draws only reactive power, the real power drawn from the capacitor is zero. Also at dc (zero frequency) the capacitor does not supply any reactive power. Therefore, the capacitor voltage does not change and the capacitor establishes only a voltage level for the converter. The switching causes the converter to interconnect the 3-phase lines so that reactive current can flow between them.

The converter draws a small amount of real power to provide for the internal loss (in switching). If it is required to feed reai power to the bus, the capacitor is replaced by a storage battery. For this the circuit switching has to be modified to create a phase difference δ between V_0 and V with V_0 leading V.

The above explained converter is connected in shunt with the line. On similar lines a converter can be constructed with its terminals in series with the line. It has to carry the line current and provide a suitable magnitude (may also be phase) voltage in series with the line. In such a connection it would act as an impedance modifier of the line.

15.10 FACTS CONTROLLERS

The development of FACTS controllers has followed two different approaches. The first approach employs reactive impedances or a tap changing transformer with thyristor switches as controlled elements, the second approach employs self-commutated static converters as controlled voltage sources.

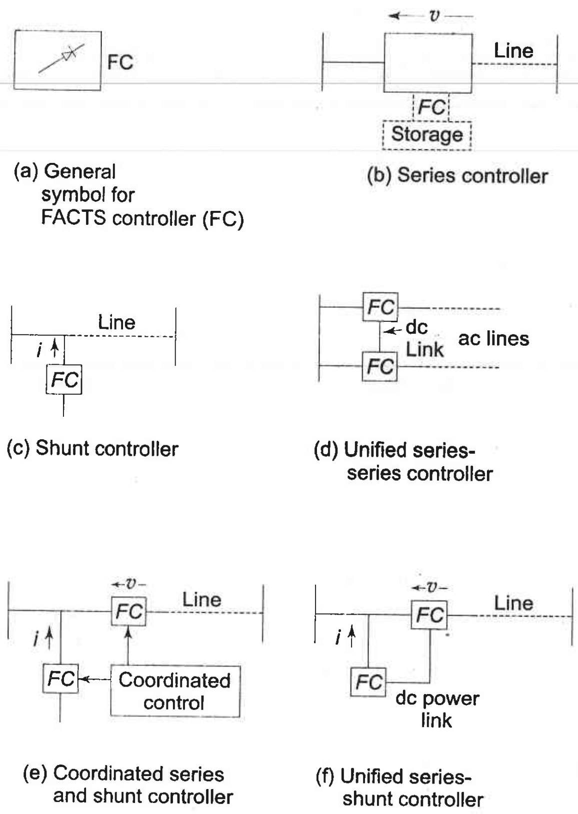
In general, FACTS controllers can be divided into four categories.
(i) series (ii) shunt (iii) combined series-series (iv) combined series-shunt controllers.

The general symbol for a FACTS controller is given in Fig. 15.8(a). which shows a thyristor arrow inside a box. The *series controller* of Fig. 15.8b could be a variable impedance, such as capacitor, reactor, etc. or a power electronics based variable source. All series controllers inject voltage in series with the line. If the voltage is in phase quadrature with the line, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve real power also.

The *shunt controllers* of Fig. 15.8c may be variable impedance, variable source or a combination of these. All shunt controllers inject current into the system at the point of connection. Combined series-series controllers of Fig. 15.8d could be a combination of separate series controllers which are controlled in a coordinated manner or it could be a unified controller.

Combined series-shunt controllers are either controlled in a coordinated manner as in Fig. 15.8e or a unified Power Flow Controller with series and shunt elements as in Fig. 15.8f. For unified controller, there can be a real power exchange between the series and shunt controllers via the dc power link.

Storage source such as a capacitor, battery, superconducting magnet, or any other source of energy can be added in parallel through an electronic interface to replenish the converter's dc storage as shown dotted in Fig. 15.8 (b). A controller with storage is much more effective for controlling the system dynamics than the corresponding controller without storage.



(a) General symbol for FACTS controller (FC)
(b) Series controller
(c) Shunt controller
(d) Unified series-series controller
(e) Coordinated series and shunt controller
(f) Unified series-shunt controller

Fig. 15.8 Different FACTS controllers

The group of FACTS controllers employing switching converter-based synchronous voltage sources include the STATic synchronous COMpensator (STATCOM), the static synchronous series compensator (SSCC), the unified power flow controller (UPFC) and the latest, the Interline Power Flow Controller (IPFC).

STATCOM

STATCOM is a static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. The STATCOM, like its conventional counterpart, the SVC, controls transmission voltage by reactive shunt compensation. It can be based on a voltage-sourced or current-sourced converter. Figure 15.9 shows a one-line diagram of STATCOM based on a voltage-sourced converter and a current sourced converter. Normally a voltage-source converter is preferred for most converter-based FACTS controllers. STATCOM can be designed to be an active filter to absorb system harmonics.

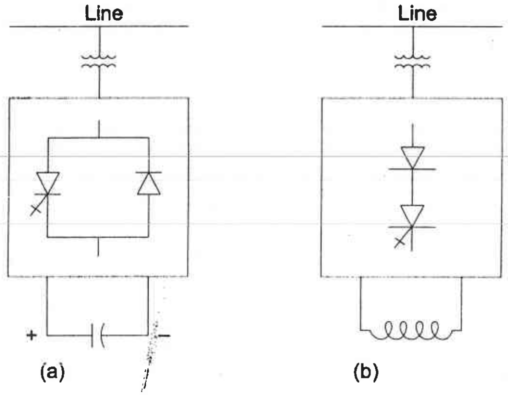


Fig. 15.9 (a) STATCOM based on voltage-sourced and (b) current-sourced converters.

A combination of STATCOM and any energy source to supply or absorb power is called static synchronous generator (SSG). Energy source may be a battery, flywheel, superconducting magnet, large dc storage capacitor, another rectifier/inverter etc.

Static Synchronous Series Compensator (SSCC)

It is a series connected controller. Though it is like STATCOM, but its output voltage is in series with the line. It thus controls the voltage across the line and hence its impedance.

Interline Power Flow Controller (IPFC)

This is a recently introduced controller [2, 3]. It is a combination of two or more static synchronous series compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive series compensation for the control of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. Thus it manages a comprehensive overall real and reactive power management for a multi-line transmission system.

Unified Power Flow Controller (UPFC)

This controller is connected as shown in Fig. 15.10. It is a combination of STATCOM and SSSC which are coupled via a common dc link to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. These are controlled to provide concurrent real and reactive series line compensation without an external energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently/simultaneously or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive line flows. The UPFC may also provide independently controllable shunt reactive compensation.

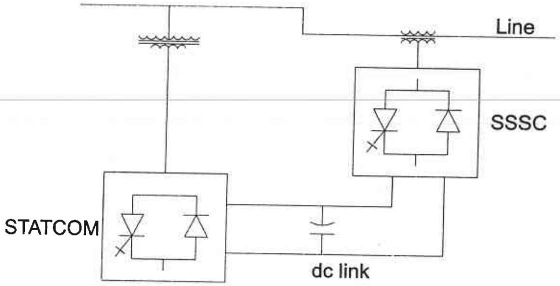


Fig. 15.10 Unified Power Flow Controller UPFC

Thyristor-Controlled Phase-Shifting Transformer (TCPST)

This controller is also called Thyristor-controlled Phase Angle Regulator (TCPAR). A phase shifting transformer controlled by thyristor switches to give a rapidly variable phase angle.

Thyristor-Controlled Voltage Regulator (TCVR)

A thyristor controlled transformer which can provide variable in-phase voltage with continuous control.

Interphase Power Controller (IPC)

A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set inpedendently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches.

Thyristor Controlled Braking Resistor (TCBR)

It is a shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimise power acceleration of a generating unit during a disturbance.

Thyristor-controlled Voltage Limiter (TCVL)

A thyristor-switched metal-oxide varistor (MOV) used to limit the voltage across its terminals during transient conditions.

HVDC

It may be noted that normally HVDC and FACTS are complementary technologies. The role of HVDC, for economic reasons, is to interconnect ac systems where a reliable ac interconnection would be too expensive. HVDC

transmission as well as back-to-back HVDC system can improve transient stability and control line flows. Voltage source converter based (self-commutated) HVDC system may have the same features as those of STATCOM or UPFC. This system also regulates voltage and provides system damping.

A comparative performance of major FACTS controllers in ac system is given in Table 15.2 [14].

Table 15.2 A comparative performance of major FACTS controller

Type of FACTS Controller	*Load flow control*	*V control*	*Transient stability*	*Oscillation Damping*
SVC/STATCOM	×	×××	×××	××
TCSC	××	×	×××	××
SSSC	×××	×	×××	××
TCPAR	×××	××	×	××
UPFC	×××	×××	×××	×××

* ×××—strong influence; ××—average influence; ×—small influence

SUMMARY

Since the 1970s, energy cost, environmental restrictions, right-of-way difficulties, along with other legislative social and cost problems have postponed the construction of both new generation and transmission systems in India as well as most of other countries. Recently, because of adoption of power reforms or restructuring or deregulation, competitive electric energy markets are being developed by mandating open access transmission services.

In the late 1980s, the vision of FACTS was formulated. In this various power electronics based controllers (compensators) regulate power flow and transmission voltage and through fast control action, mitigate dynamic disturbances. Due to FACTS, transmission line capacity was enhanced. Two types of FACTS controllers were developed. One employed conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers such as SVC and TCSC. The second category was of self-commutated switching converters as synchronous voltage sources, e.g. STATCOM, SSSC, UPFC and IPFC. The two groups of FACTS controllers have quite different operating and performance characteristics. The second group uses self-commutated dc to ac converter. The converter, supported by a dc power supply or energy storage device can also exchange real power with the ac system besides controlling reactive power independently.

The increasing use of FACTS controllers in future is guaranteed. What benefits are required for a given system would be a principal justification for the choice of a FACTS controller. Its final form and operation will, ofcourse, depend not only on the successful development of the necessary control and