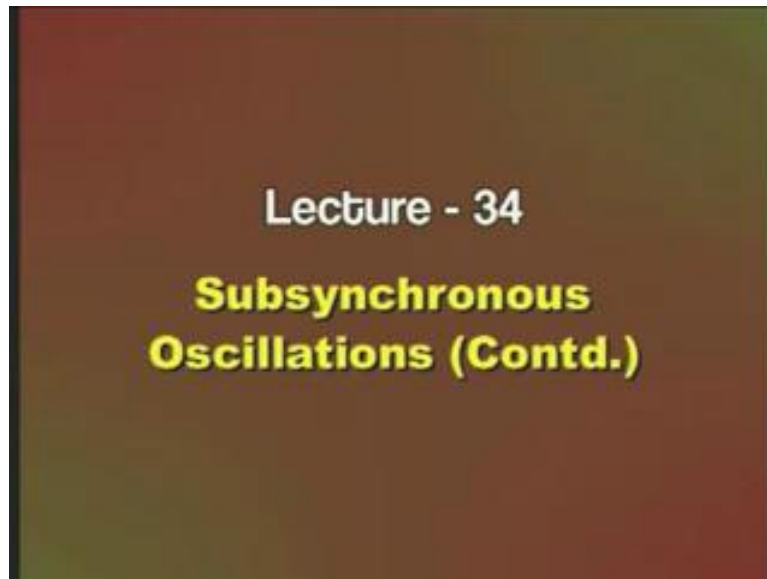


Power System Dynamics
Prof. M. L. Kothari
Department of Electrical Engineering
Indian Institute of Technology, Delhi
Lecture - 34
Sub Synchronous Oscillations (Contd...)

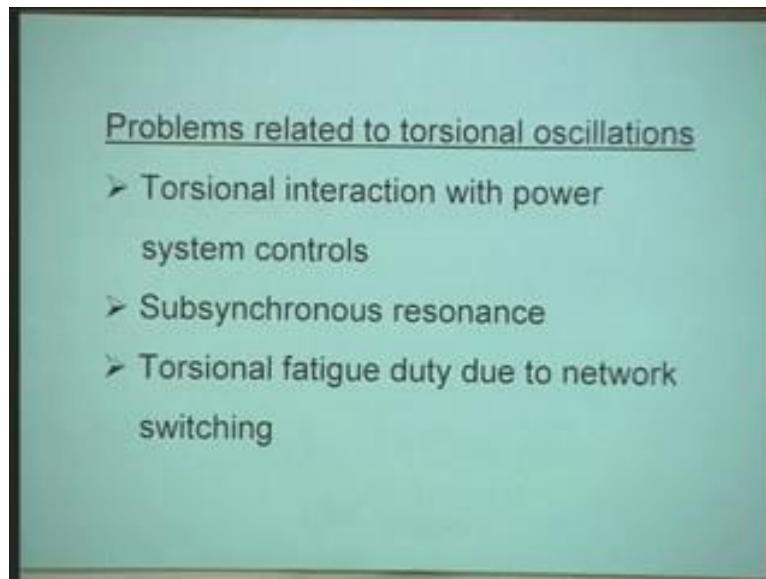
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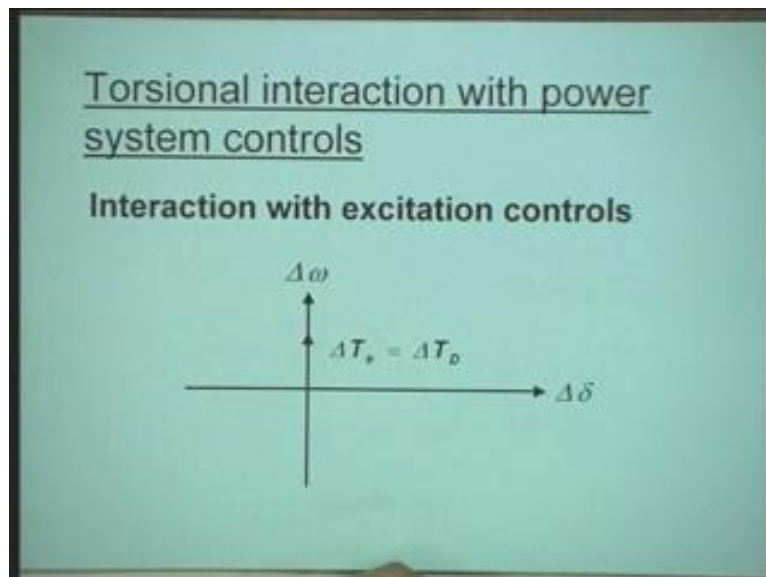
Friends, today we shall continue our study of sub synchronous oscillations. We had developed the non linear and linear dynamic model of turbine generator shaft system, we have also analyzed the different torsional modes of oscillations and the mode shapes using model analysis. The major problems related to the torsional oscillations which we shall discuss today are the torsional interaction with power system controls, sub synchronous resonance and torsional fatigue due to network switching as I pointed out in the beginning that the torsional oscillations may interact in the adverse manner with the power system network and therefore it is necessary to clearly understand the the torsional interaction with power system controls then sub synchronous resonance and torsional fatigue due to network switching.

First we will study about the torsional interaction with power system controls. When we talk about the power system controls I we will address the two important controls one is the excitation control that is interaction of the torsional oscillations with the excitation control and second the interaction of the governor of the steam turbine with the torsional oscillations. Now let us start with the interaction with excitation controls.

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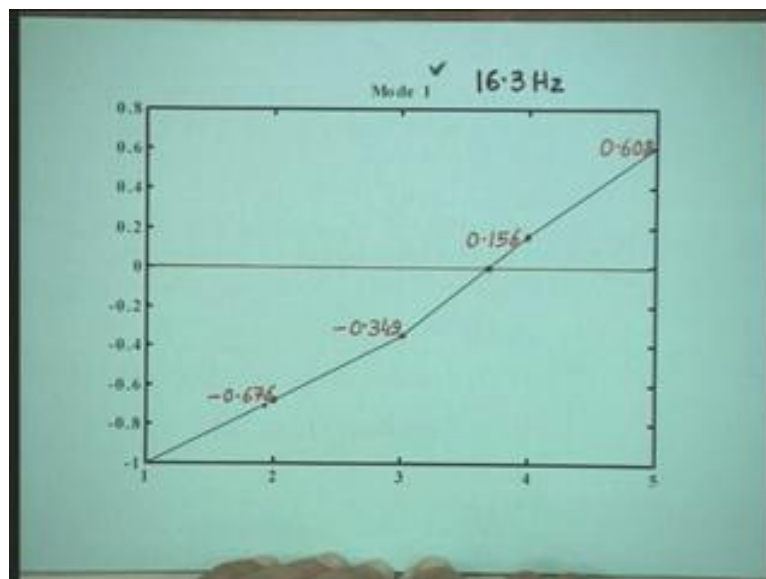


Now we have studied that power system stabilizers are used for damping the system modes of oscillations that is the power system oscillations in the frequency range of .2 to 2 hertz. Now here when we design the power system stabilizer we ensure that a component of electrical torque or component of electrical torque produced is in phase with the speed deviation signal and the parameters of the power systems stabilizers are so chosen so that we get a component of air gap torque in phase with speed deviation and this is pure damping torque.

Now if you look here in the in this diagram I have shown here the on x axis delta delta and on y axis delta omega right. In case we produce a torque which is in phase with speed deviations delta omega that is delta T_e is the torque produced in phase with speed deviation delta omega then this torque is a purely damping torque.

Now in practice what happens is that the that the **the the** speed signal is sensed by using a speed transducer and when we mount a speed transducer say particular location, let us say at the generator end of the turbine generator shaft then at that particular location, location the speed signal has a high component of of the torsional oscillations. If you examine this diagram that is for typical for typical turbine generator system this is the mode shape corresponding to 16.3 hertz and we can easily see here the that the component of speed deviation signal which is sensed at the generator end of the shaft is quite a large one and this component when it is processed through the power system stabilizer will produce produce air gap torque a component of air gap torque which will have a large phase shift between between the speed deviation signal and the air gap torque produced.

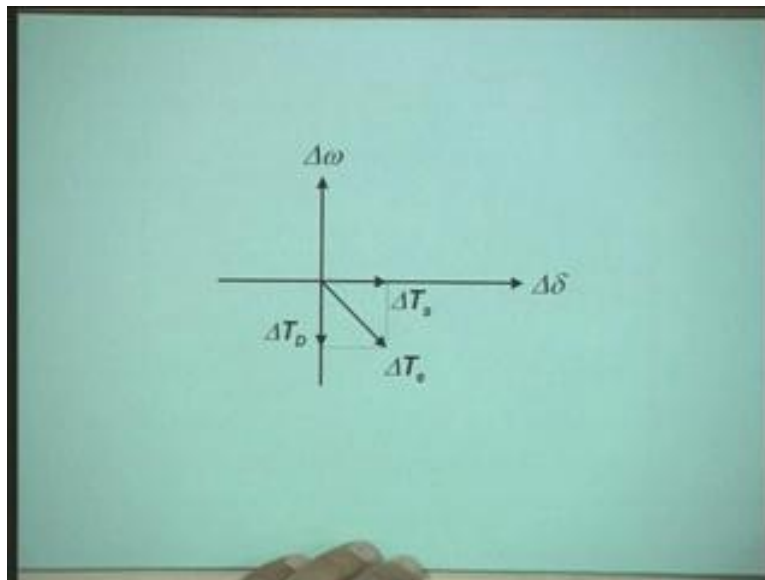
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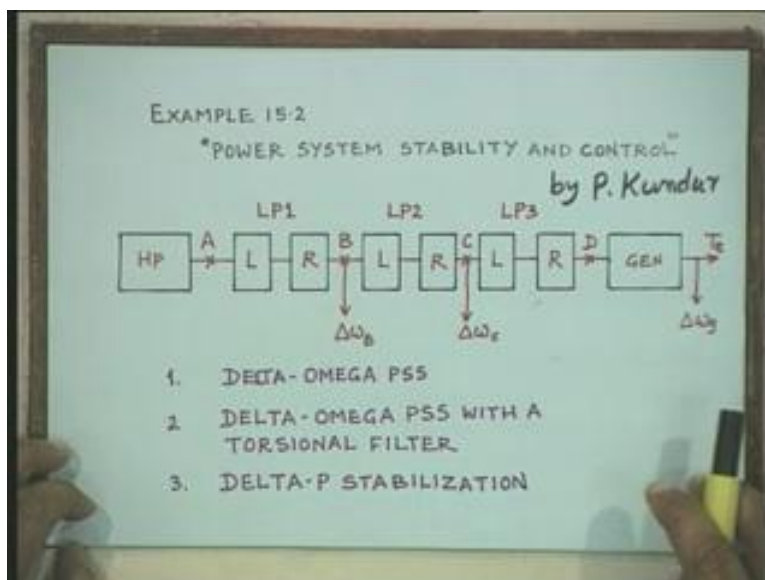
For example, if you see in this diagram in a typical case the air gap torque or the component of air gap torque produced due to due to torsional component which is actually fed back through the power system stabilizer that is the speed signal has a torsional component or high magnitude of torsional component and this signal when it is fed through the power system stabilizer and air gap torque which is produced this air gap torque comes out in the fourth quadrant, a typical case now this air gap torque delta T_e when it is resolve into two components one in phase with angle deviation the delta delta another in quadrature with angle deviation that is in phase with speed deviation signal delta omega. Now the component of the air gap torque in phase with speed deviation comes out to be negative that is the the power system stabilizer will contribute a negative damping torque and this negative damping torque if it is more than the normally

existing system damping then it will cause excitation of the torsional modes because they as we have seen that the damping of the torsional modes is very low right and the moment you have a large negative damping torque produced due to the due to the power system stabilizer then this the net damping will become negative and the torsional oscillations may grow in magnitude and therefore there is a necessity to account for this adverse effect when we design our system.

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Now various measures have been suggested to counteract this problem of excitation of torsional modes due to power system stabilizers, one very interesting example is given in the power system stability and control by Kundur in the text book power system stability and control by P Kundur and example 15.2 addresses the various aspects of the interaction of torsional oscillations with excitation control.

Now to examine this he has considered steam turbine which has high pressure section then they are three sections which are called low pressure sections he names them as LP1, LP2, LP3 and each low pressure section has two sub sections called left and right right and they are all mounted on the same shaft at the end of the generator. Now to overcome the problem of excitation of torsional modes due to adverse interaction between the excitation controlled and torsional oscillations the studies were conducted by putting by putting speed sensing device at the end of the generator that is suppose you put speed sensing device here the speed senses at $\Delta\omega_g$, another location which was identified for sensing the speed is between LP2 and LP3 that is $\Delta\omega_c$ that is at the location c.

Now at c, c forms a coupling between the LP2 and LP3 sections. Similarly, studies are also carried out by sensing speed at the coupling between LP1 and LP2. The reason for trying these difference locations were that at these locations the amplitude of the torsional oscillation or was very small right therefore, if you pick up the speed here then then the chances of accept some torsional modes is practically low. Another step which was taken is that that filter was put in the in the power system stabilizer circuit that is the speed deviation signal is first filtered out by putting a special filter which will which will filter out or eliminate the torsional modes right.

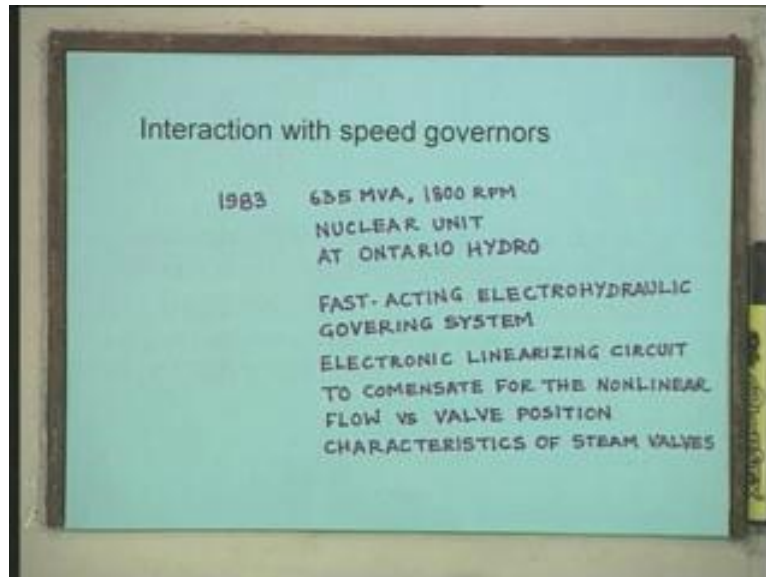
Now in case actually the you have torsional mode one is having the predominant signal then the filter is design designed so that so that the the torsional mode one is completely attenuated while other torsional modes will be highlight attenuated right and the first step which was taken was that study was conducted considering $\Delta\omega$ PSS by locating this PSS as different locations, studies were conducted by putting the speed sensing or speed sensor at location B at location C and then at B and C both right. Then the next stage, the stage were conducted by booting $\Delta\omega$ PSS with the torsional filter right.

Then the last study was carried out by putting a stabilizer where we do not sense the speed deviation as the input signal but we sense the deviation in power as the input signal the ΔP stabilization and the study show that that if you have $\Delta\omega$ PSS only without torsional filter then as you increase the power system stabilizer gain then some of the torsional modes will get excited or they will have negative damping, then further studies were carried out when the torsional filter was put then it is seen actually that with the moment where torsional filter incorporated then the chances of {torse} ((00:12:22 min)) excitation torsional modes is eliminating.

Further, when the ΔP stabilization was put then the then the results obtained were similar to what we got actually in second case where $\Delta\omega$ PSS with a torsional filter was output.

Now all the details are given in the example 15.2, I will suggest the interested readers to go through this example in detail.

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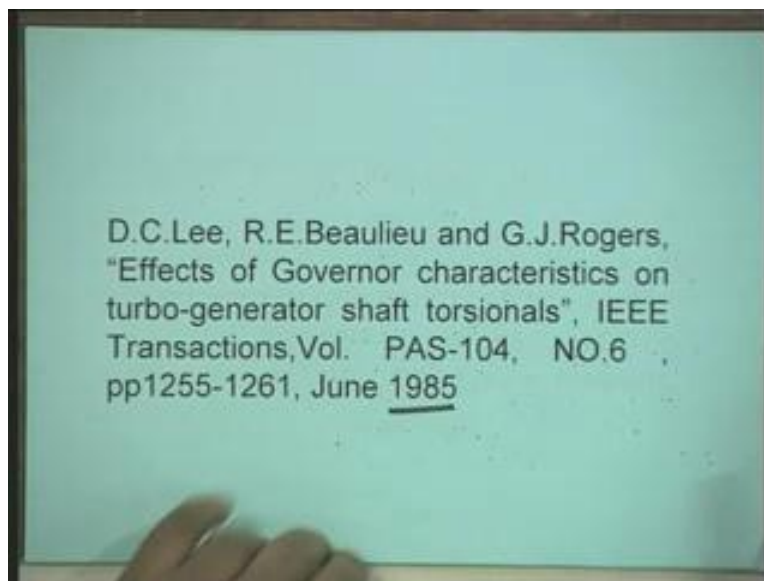
The next aspect we have to address is the interaction with speed governors, how the speed the governors will interact with the torsional oscillations now historically the interaction with speed governors was observed or experienced in 1983 when a 635 MVA, 1800 RPM nuclear unit at Ontario hydro was commission this this unit, this is a nuclear unit basically the the turbine is similar to a steam turbine it is steam turbine only okay and the the difference in this unit was that was equipped with a fast acting electrohydraulic governor system because we may I have the mechanical mechanical controlled system right and we may have fast acting electrohydraulic governor system in this electro hydraulic governor systems which are now provided in most of the modern turbines the the low power functions are performed by using electronic circuits that is the speed sensing and certain processing is done using electronic circuit, one of the important processing which is done in electro hydraulic governor system is they use a linearizing circuit to compensate for the non-linear flow verses valve position characteristic of the steam valves that is if you plot a characteristic which relates the steam valve position with respect to the steam flow.

Then this characteristic is a very linear characters non-linear characteristic and to compensate for the nonlinear characteristic right we provide here electronic linearizing circuit. Then it was observed that when this machine which was under commission when this machine was loaded to 100 megawatt load its capacity is 635 MVA then then the vibrations of the steam valves was observed experienced and then immediately immediately the they looked into the electronic circuits and some retuning of the electronic circuit was done.

With that retuning they could load up to 475 megawatt and at that particular loading condition again it was seen that the steamed valves were vibrating and then by it was examine in detail it was found that this non-linear that is the electronic linearizing circuit right. It was behaving in the different fashion at that particular frequency that is a particular frequency was sensed because here if the governor sense is the speed of the rotor and for sensing the speed of the rotor the speed sensor was mounted on the high pressure end of the stem turbine okay and at that particular end it picks up the various torsional components right and when these torsional components are process through the electronic circuit it was found that the speed droop at 475megawatt loading came out to be something like 12 types more than the normal 4 percent speed droop and then the certain action was taken to overcome this problem or to mitigates this problem.

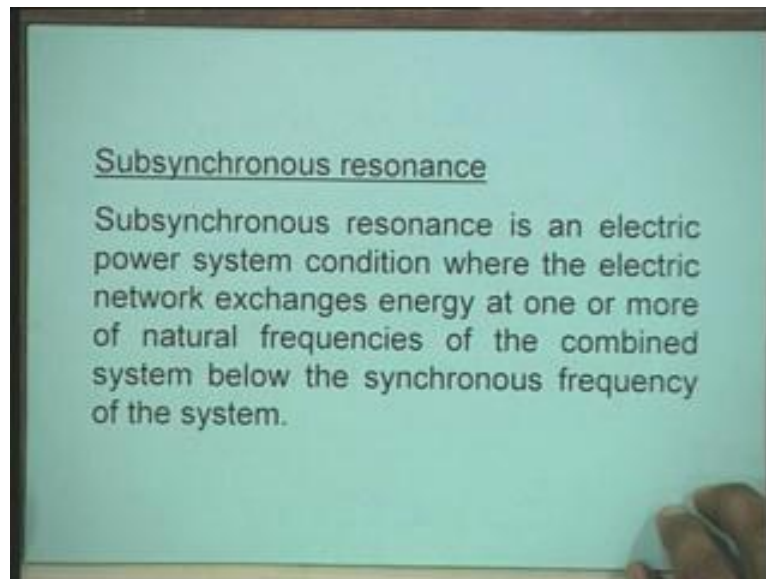
Therefore this is also very series problem when you when you have to address the torsional interaction with governor circuits because modern steam turbines are with electro hydraulic governors and these days, these circuits are so designed, so that all through the loading condition a four percent speed droop is maintained speed droop .You know all the speed droop parameter are which is the governor characteristic where where actually the when you change the load from no load to full load the droop in this speed is 4 percent from the normal value or when the machine is operating under full load condition and if the load is thrown off the increasing in speed will 4 percent of the rated speed.

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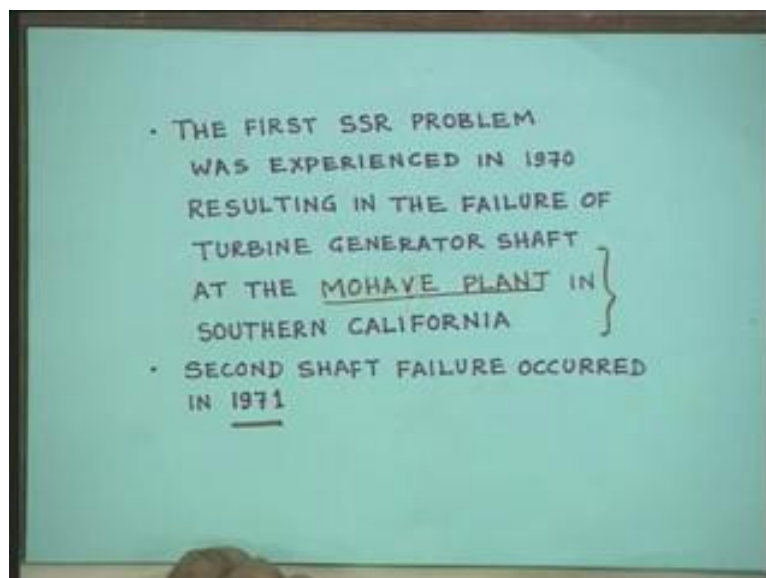
Now this particular problem has been nicely dealt with in the research paper written by D. C. Lee R. E. Beaulieu and Rogers effect of governor characteristics on turbo generator shaft torsionals there is specific is specific problem which was examined this has appeared 1985.

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In fact this torsional oscillations do interact adversely with the near nearby HVDC controls also these they needs to be examined in detail but it is observed that the HVDC controls also interact in adverse matter manner if you do not account for the torsional modes. The next important aspect will we basically study is the sub synchronous resonance. First let us define what you mean by the sub synchronous resonance then we will study this phenomena in detail.

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The sub synchronous resonance is defined as **as** an electric power system condition that is sub synchronous resonance is an electric power system condition where, the electric network exchanges energy at one or more of natural frequencies of the combined system below the synchronous frequency of the system that is here the importance is that the frequencies of interest are the frequencies which are less than the synchronous frequency these are called are the sub synchronous frequency and there is a condition where the electric network that is the power system network exchanges energy energy at one or more of natural frequencies right and therefore to understand this problem very we have to examine the system very carefully and let us understand the SSR phenomena or sub synchronous resonance phenomena, this this SSR phenomena was first experienced in 1970 resulting in the failure of turbine generator shaft at Mohave plant in southern California.

Now till that time till that time people had no idea about the subsynchronous resonance and in the Mohave plant which is located in southern California and USA right in 1970 the shaft of one machine completely damaged then the second shaft failure occurred in 1971 then it was a series problem the studies were conducted the system was modeled and after detailed studies it was found that the shafts were damaged because of SSR phenomena which occurred in the system, this SSR phenomena **phenomena** primarily occurs in series compensator transmission lines okay.

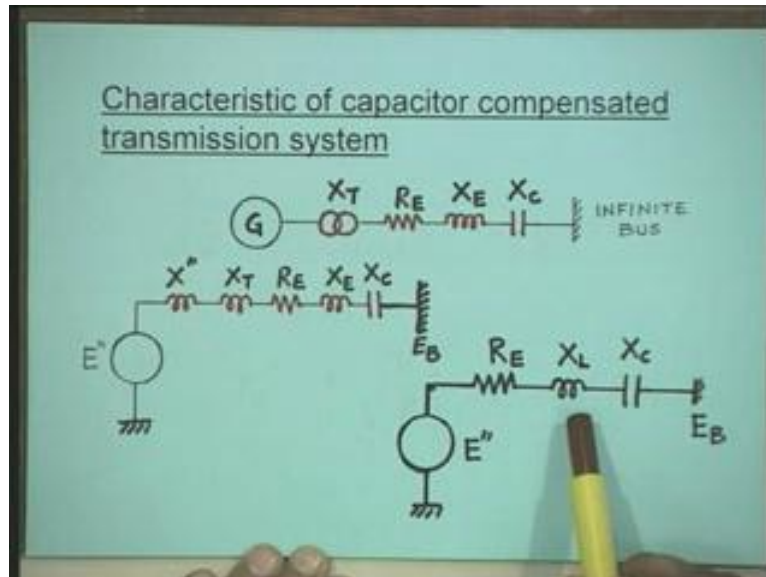
Now there is a necessity for us first to understand the characteristic of the series compensate transmission lines before we understand the SSR and its impact on the system. Now first let me just tell you that suppose you have a uncompensated transmission system and in uncompensated transmission system suppose fault occurs in the transmission line okay, then depending upon the strength in the voltage wave at which the fault occurs there exist a decaying DC component of fault current and this decaying DC component of fault current flows through the distributed stator windings of the system that is when the stator windings which are distributor, 3 phase stator winding right it will carry it will carry the decaying DC component of the fault current and when this decaying DC component of fault current is flowing in the stator winding then then in the air gap torque having frequency equal to 60 hertz will be produced a right.

Now normally under steady state condition the torque which acts on the rotor of the turbine generator system or is always having 0 frequency, it is unidirectional torque when the it is carrying three phase balance currents but the moment actually the stator carries a decaying DC component of current right the torque or air gap torque is produced to its frequencies 60 hertz if it is a 60 hertz system, if it is a 50 hertz system the frequency will be of 50 hertz. Similarly, when you know that whenever there is unbalanced fault which takes place on the uncompensated system then the negative sequence currents will flow in the stator winding of the generator and these negative sequence currents will produce produce the air gap torque whose frequency will be 2 times the system frequency, it is the 50 hertz system the frequency will be 100 hertz, if it is 60 hertz system these 120 hertz and therefore therefore there is necessity that when you design your turbine general shaft none of the torsional modes should be close to 60 hertz or 120 hertz.

Further, if I consider now a series compensator transmission line and the primary purpose of providing series compensation is to reduce the line impedance, so that we can transfer more power on the transmission line. Now let us consider machine infinite bus system where we have

a generator, transformer a step of transformer and the transmission line whose parameter R_E and X_E , the resistance is R_E , reactance is X_E .

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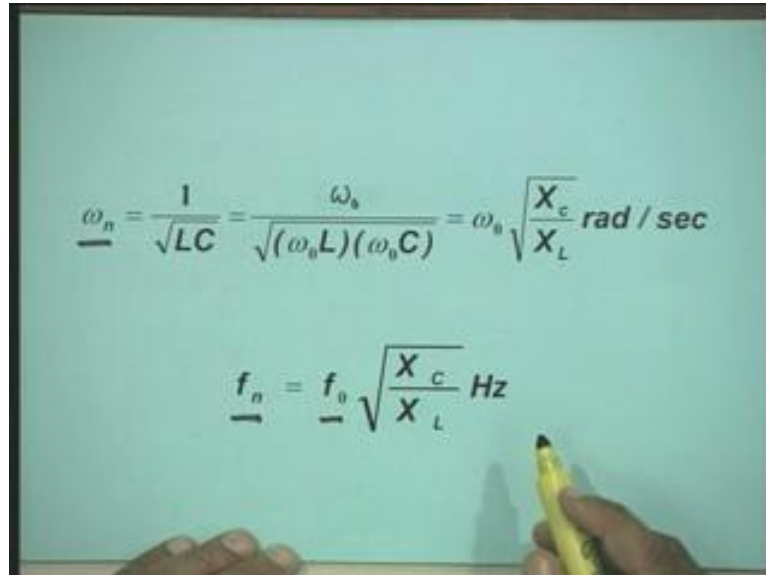


Now we have provided a series capacitor of reactance X_C right. Now this system this system when a fault occurs in this particular series compensated system then the fault currents will also have have components of frequency which will be corresponding to the natural frequency of the inductance and capacitance of the system that is all you know actually that suppose when you rlc circuit, when this rlc circuit is excited right then the then the current which flows will will have frequency of oscillation which depends upon the inductance and capacitance of the circuit. Now since the the capacitance which you put here in the circuit is to partially compensate for the line reactance at power frequency and therefore at frequency less than the power frequency at subsynchronous frequency these two reactance's will become equal right and at that time we say that this is series resonance occurs.

Now we can draw the equivalent circuit of temperature system that is generator can be represent by a voltage in series with the reactance transformer of the reactance X_T line with reactance R_E , X_E and resistance R_E , capacitance X_C the this can be simplified then we can write down a voltage source in series with the resistance the total reactance X_L that is X_C plus X_T plus X double prime, sub transient reactance and a capacitance connected to infinite bus okay. Now for this circuit the natural frequency of a oscillation, it is denoted as by the symbol ω_n is equal to 1 divided by square root of L_C , this is the natural frequency of oscillations, okay. This can be written as ω_n divided by square root of ω_n into L ω_n into C okay this is exactly same as this one there is you have multiplied and divided by ω_n this can be expressed as ω_n multiplied by square root of X_C by X_L okay. Therefore, now we have a relationship between the natural frequency of oscillation f_n with the system frequency f_0 and and

the values of the line reactance and series capacitor, the capacitor, the reactance of the series capacitor.

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$$\omega_n = \frac{1}{\sqrt{LC}} = \frac{\omega_s}{\sqrt{(\omega_s L)(\omega_s C)}} = \omega_s \sqrt{\frac{X_c}{X_L}} \text{ rad/sec}$$

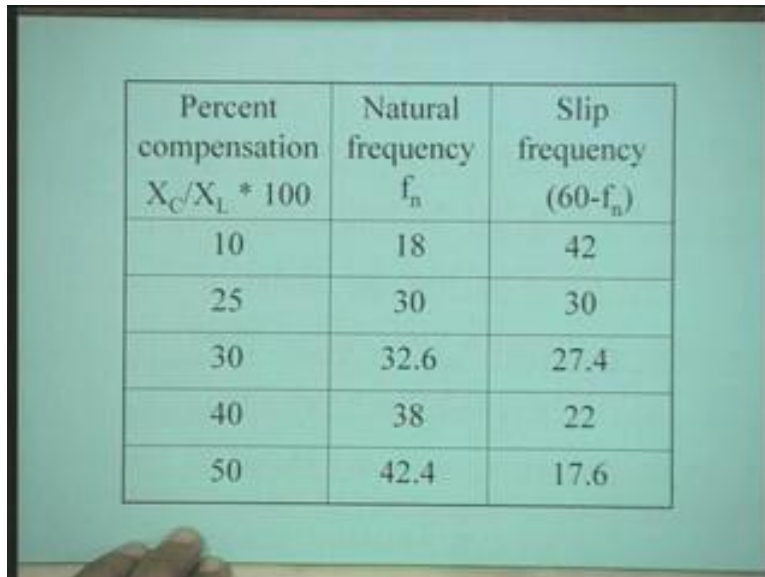
$$f_n = f_s \sqrt{\frac{X_c}{X_L}} \text{ Hz}$$

Now this relationship is a very important one. Now the problem come something like this that that whenever some disturbance takes place right and if the currents of this frequency f_n flows in the stator winding of the synchronous generator then there will be a torque developed in the air gap because air gap torque the frequency of this air gap torque will be equal to f_o minus f_n that is, if f_n is the frequency of the currents which are flowing in the stator winding then in the frequency of the torque developed or frequency of the air gap torque developed due to this current will be f_o minus f_n because we have seen that if f_n is 0 that is if it is carrying DC current decaying DC current the frequency of the torque developed is simply f_o right therefore now if the current flowing has a frequency f_n then the air gap torque will have a frequency which is f_o minus f_n .

Now in case the frequency frequency of the torque developed that is f_o minus f_n , if it coincide with any of the torsional modes then these torsional modes can grow in magnitude or can be sustained that is what is the main philosophy of excitation of torsional modes. This table is an important table which shows which show the percent compensation that is X_C by X_L this ratio multiplied by hundred that shows the degree of compensation for example here when I say ten it is a 10 percent of the line reactance is compensative and so on as shown this 10, 25, 30, 45 and 50 as these frequency the with this with this compensation the natural frequency of oscillation comes out to be 18 hertz, 30 hertz, 32.6 hertz, 38 and 42.4 hertz, while the slip frequency we so add 60 minus f_n right because the when the currents of the natural frequency flows in the stator winding then the torque developed will have a frequency of 60 minus f_n that is the slip frequency slip frequency torque are produced and this slip frequency torque should not should not have

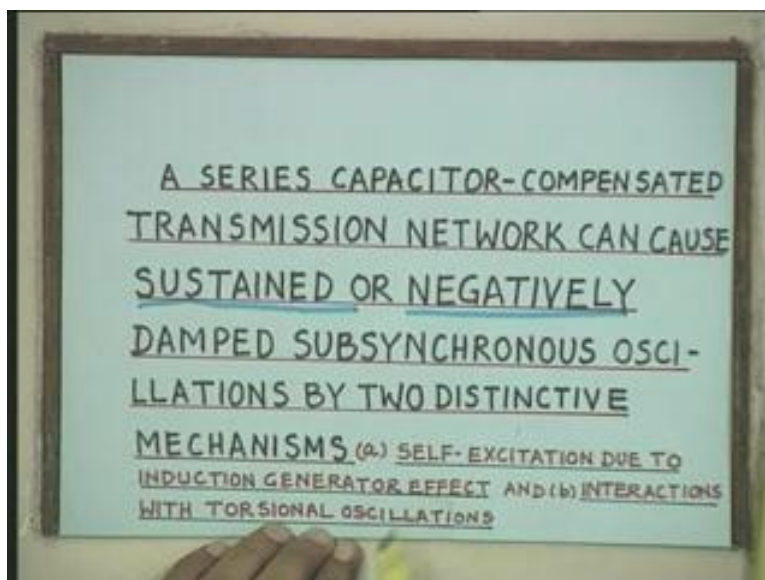
should not coincide with the frequency of any of the torsional modes, this is one of the important requirements.

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Percent compensation $X_C/X_L * 100$	Natural frequency f_n	Slip frequency $(60-f_n)$
10	18	42
25	30	30
30	32.6	27.4
40	38	22
50	42.4	17.6

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A SERIES CAPACITOR-COMPENSATED TRANSMISSION NETWORK CAN CAUSE SUSTAINED OR NEGATIVELY DAMPED SUBSYNCHRONOUS OSCILLATIONS BY TWO DISTINCTIVE MECHANISMS (a) SELF-EXCITATION DUE TO INDUCTION GENERATOR EFFECT AND (b) INTERACTIONS WITH TORSIONAL OSCILLATIONS

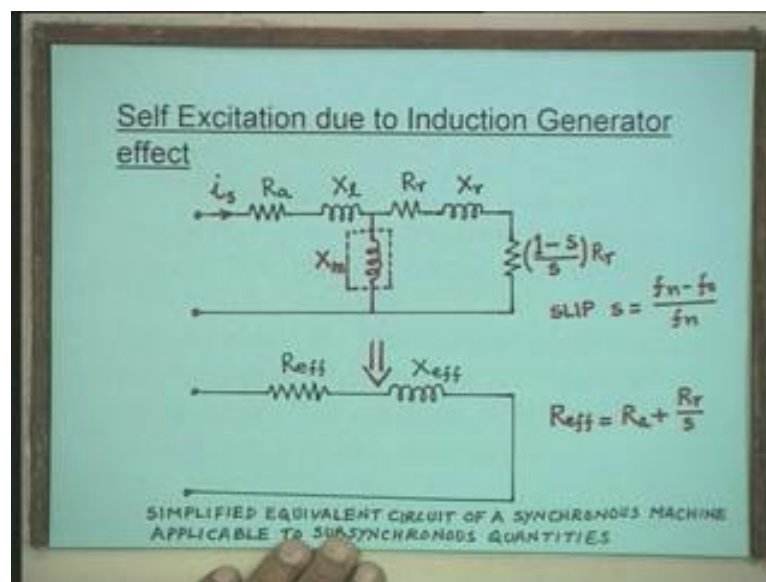
Now you can easily see here actually that at load when the compensation is low the slip frequency is high right and as the compensation increases the slip frequency decrease, suppose you have 50 percent compensation this frequency may come very close to frequency of mode one right and as you decrease this you will find that you will go and match with the higher and

higher as together higher and higher slip frequency and it may match with higher modes. A series capacitor compensator transmission network can cause sustained or negatively damped sub synchronous oscillations by 2 distinctive mechanisms.

Now this is the important aspect which will you address in our study that is a series capacitor compensator transmission network can cause can cause sustained, I am using the word sustained or negatively damped sub synchronous oscillations that two mechanisms, one is the self-excitation due to inductance generator effect and second is interaction with torsional oscillations. Now this these two effects are completely different, now to understand this the self-excitation due to inductance generator effect we can visualized that is a synchronous generator whose rotor is running at synchronous speed.

When the stator of the synchronous generator is carrying sub synchronous frequency currents right then due to the sub synchronous frequency currents a rotating magnetic wheel is produced whose speed will be less than the synchronous speed while rotor is rotating at synchronous speed this is situation similar to inductance generator effect that is if you consider only the situation where the stator is carrying subsynchronous currents right and then the behavior of this synchronous generator can be examined considering the inductance generator effect because in induction generator, the rotor of the generator rotates at a speed higher than the synchronous speed.

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Now when you examine this the self-excitation due to induction generator effect. Let us look at the equivalent circuit of the synchronous generator when it is behaving like a induction generator right we are not considering the synchronous generator aspect here. We are considering only that portion of the system which behaves like induction generator this is the armature resistance this is the leakage reactance this is the resistance of the rotor, this is the leakage reactance of the rotor

and this is the resistance which takes care of the loading that is the load, now here this resistance R_r is 1 minus s by s .

Now this slip is equal to f_n the frequency of the current which is flowing through the stator minus f_o the frequency corresponding to the synchronous speed then f_n minus f_o divided by f_n is the slip because when you define the slip right what we do we, suppose it is inductance motor right the suppose actual speed is m then the synchronous speed is n_s , then the slip is n_s minus m and then this is expression percentage of n_s , okay. Now here corresponding to this n_s I am using this frequency f_n because the current which is flowing is natural frequency current f_n that is f_n minus f_o by now since f_n is less than f_o the slip is negative, when the slip is negative then this quantity this part of the resistance will become negative because because s is negative the denominator right with 1 plus this was positive but this is a negative term here this system become negative.

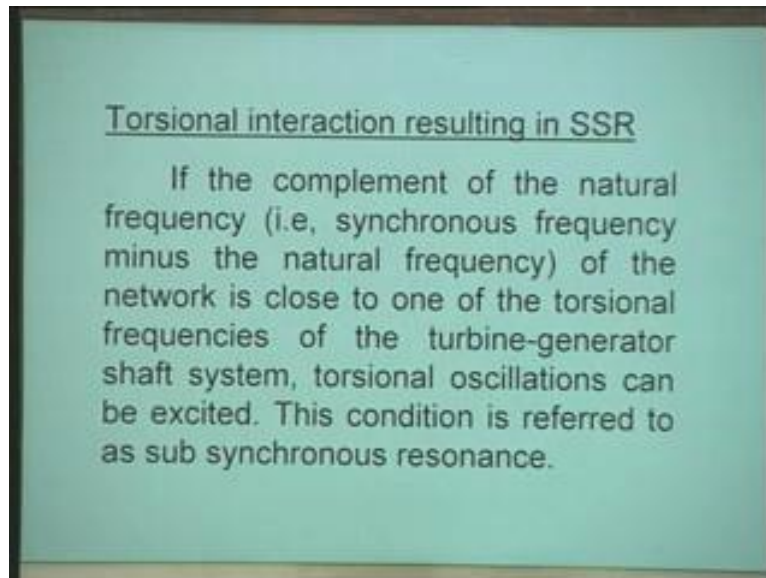
Now when if you neglect this magnetizing reactance then equivalent circuit can be shown as R effective plus X effective this is the equivalent circuit looking into the stator terminals of the synchronous generator that is when you look into the stator terminals then this circuit or stator circuit will behave as if it has effective resistance and effective reactance therefore the net effective resistance is equal to R_a R_a plus R_r by s and now s is negative right and therefore in case R_r by s will exceed R_a when R effective becomes negative. Now the point here is that they we have when **when** we look at the stator with side only the stator is connected to the transmission network through transformer and it is a series compensated line. Now in case the currents of a natural frequency f_n flow in the stator winding right and if the circuit has circuit has net resistance which is less than 0 or negative resistance then these oscillations can grow that is the in rlc circuit if r is positive then the oscillation will damp out okay.

They will decay but if r becomes 0 the oscillations will sustain but when r is negative oscillations will grow right and this is the phenomena where we say actually that due to due to the series compensated transmission line right and due to induction generator effect, the effective resistance of the circuit as a whole will become negative or very or 0 then the oscillation can either grow or again sustained right and when the oscillations are sustained right their magnitudes are increasing then the torque developed on the generator of corresponding to the slip frequency and as I told you that this torque should not have a frequency which should match with any of the torsional modes you want to avoid the damage to the system. The another aspect which I have to emphasize here is the torsional interaction resulting in SSR.

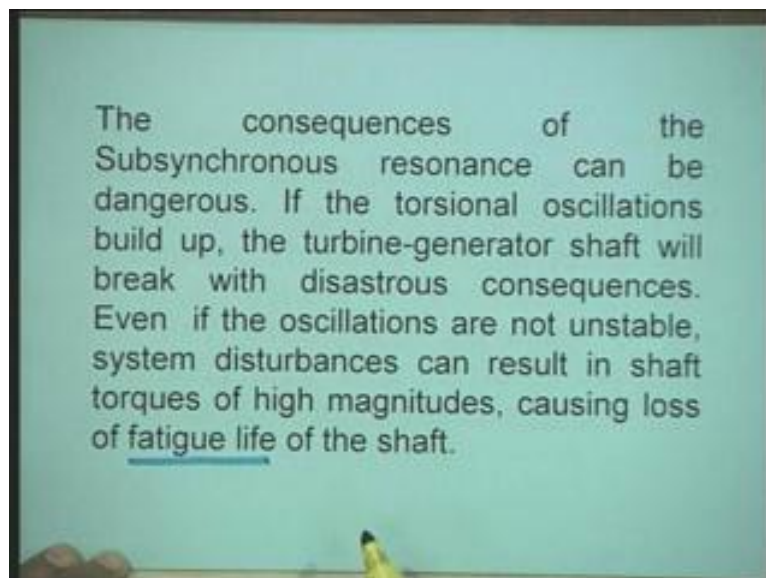
Now as I have told you that so far the induction generator effect is concerned concern there is no interaction with the torsional modes right and this phenomena is basically a circuit phenomenon, when you talk about the torsional interaction resulting in SSR. Now if the complement of the natural frequency when complement that is the synchronous frequency minus the natural frequency of the network is close to one of the torsional frequencies of the turbine generator shaft system the torsional oscillations can be excited this is what we have already seen. This condition is referred to as sub synchronous resonance that is in case in case the complementary frequency, complementary frequency you always call the word complementary frequency because **because** the slip frequency plus the natural frequency the sum is equal to the system

frequency you called the complementary frequency. In case the complement of natural frequency is closer to any of the torsional modes right then the oscillation can be excited and this phenomena is called SSR nominal.

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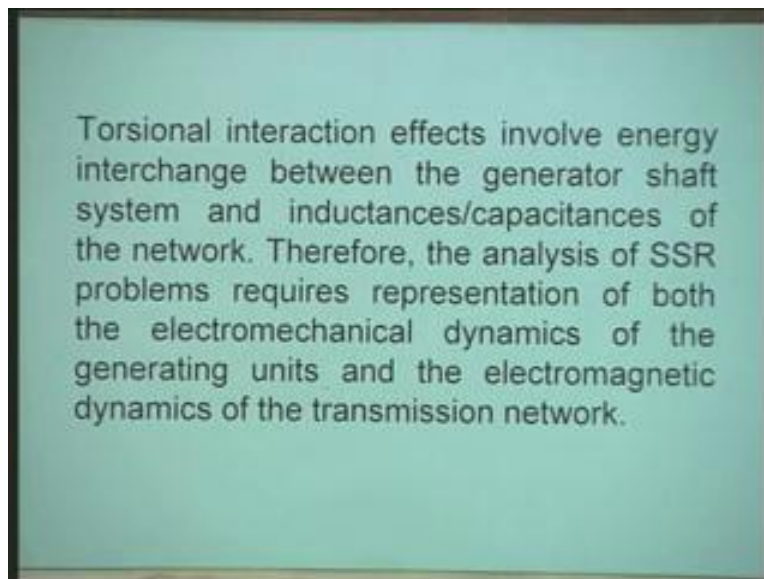
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The consequences of the subsynchronous resonance can be dangerous, if the torsional oscillations build up the turbine generator shaft will break with disastrous consequences as you have seen actually that at Mohave the shaft damage took place and it was ultimately identified

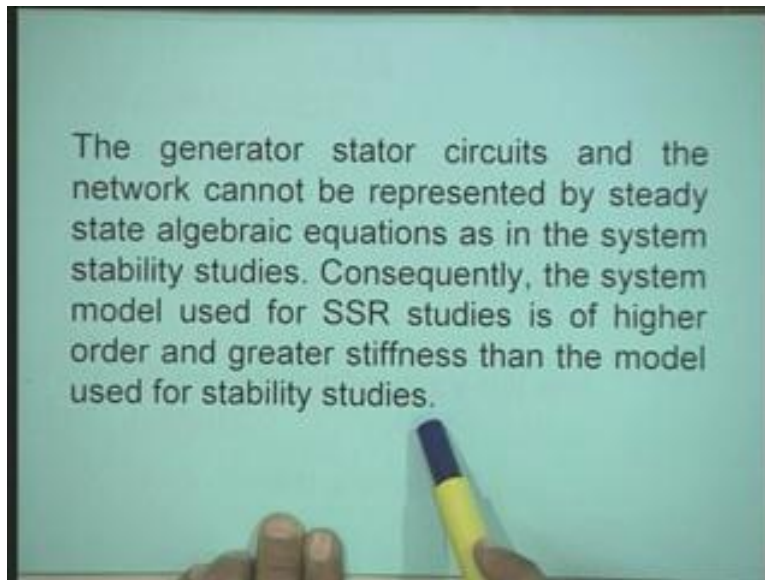
due to the occurrence of SSR phenomena even if the oscillations are not unstable I am using the word. Now oscillations may be stable or unstable system disturbances can the system disturbances can result in shaft torques of high magnitudes causing loss of fatigue life of the shaft the idea here is that when the oscillations are produced in the shaft okay even if suppose the oscillations do not grow right the shaft is subjected to increasing and decreasing stresses right and due to this there is certain fatigue cause to the shaft and there is the terminology which is used is called it the fatigue life that is each shaft has some fatigue life right and and when this shaft is subjected to this oscillatory torques the fatigue life is lost or it decreased.

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Now another important aspect is very important the torsional interactions effects or torsional interactions effects involve energy interchange between the generator shaft system and inductance of the capacitances of the network that is basically there are basically there is a exchange of energy between the generator shaft system and the network inductance and capacitance because they are the energy storing devices. Therefore, the analysis of SSR problem requires representation of the both the electromechanical dynamics of the generating units and the electromagnetic dynamics of the transmission network this is point I want to highlight because when we studied the power system dynamics okay and when we develop the synchronous generator model we neglected the stator transients right the stator circuit is represented by algebraic equations okay and similarly the transmission line equations are also obtained by steady state analysis or transmission line performance is also obtained through algebraic equations it means we have not represented the dynamics of the transmission line network or transmission network or the stator network but here when you want to analyze the the torsional interaction then we have to develop detailed dynamic model of the electromechanical system as well as the electromagnetic dynamics of the transmission network and that is why whenever you develop the model the dimensional of the model will become higher right and a lot of research work has been done on modeling the the system for analyzing the SSR phenomena.

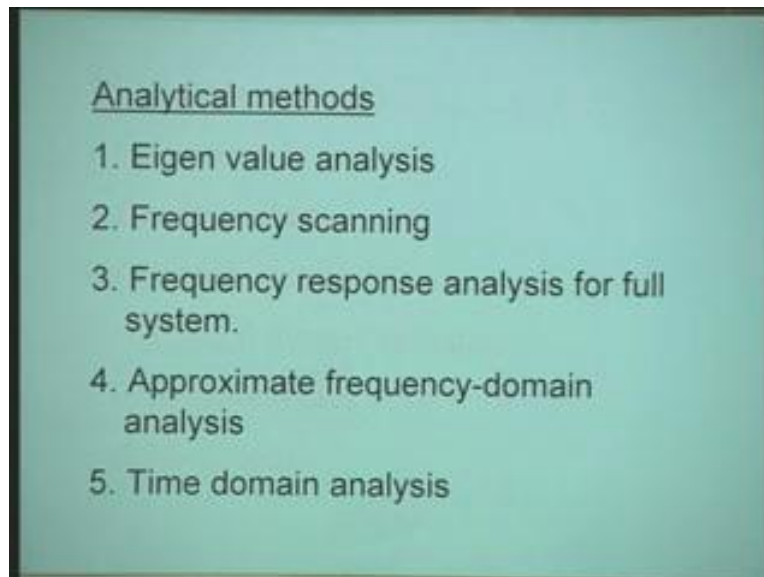
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The generator stator circuits and the network cannot be represented by steady state algebraic equations as in the system stability studies which is just now I have highlighted the consequently the system model used for SSR studies is of higher order and greater stiffness than the model used for stability studies is it clear that is when I say that the when you develop the model of the system system for SSR study the dimension of the model is high, it is a high order dynamic model of the system and since the we know about the stiffness what do you mean by the stiffness that is the smallest Eigen value to the largest Eigen value that this ratio gives us the stiffness therefore, since actually there will be different type of time constant involved the stiffness also is different greater stiffness is there and therefore when you solve these equations you may have to take small integration step.

Now several techniques have been used to analyze the SSR phenomena I will just briefly discuss these techniques them out of all the technique the simplest technique is Eigen value analysis where you develop the linear dynamic model of the system and obtain the Eigen values of the system and you performed the studies whether **whether** the system is stable or not stable and which are the modes which may get excited depending upon the damping's associated with or damping ratios of various modes of oscillations that is when you consider the realistic system right then the Eigen values will be compressed conjugate or real right and we can find out the damping the associated with each of the modes and we can find out what is the damping associated with this in case damping is poor or if it gets excited, if damping is negative then minus you take some measure.

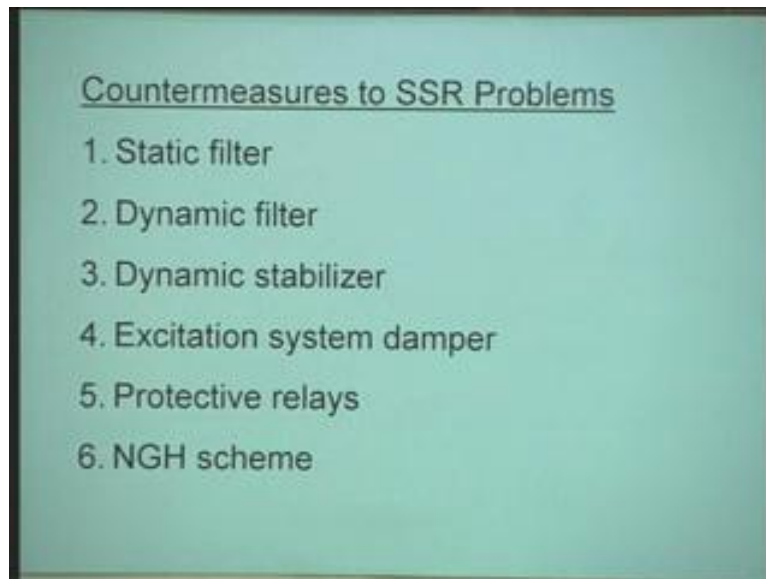
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The second method is called frequency scanning method. This method is used actually to do some preliminary studies. What is done is that looking from the internal bus of the synchronous generator, you try to see what are the frequencies of the various components that is you can just find out the impedance of the network to different frequencies. Right, and that helps us actually in finding out which help us in finding out preliminary, the occurrence of SSR phenomena because we can easily find out actually what is the impedance to this particular frequency, what is the impedance to the next frequency called frequencies scanning. Right, wherever the impedance is very low to particular frequency that that is the corresponding concern.

Another is the frequency response analysis for full system that is we have we can find out the stability of the subsynchronous modes by applying the multidimensional Nyquist criteria for this particular system. This is a completely a frequency domain analysis for analyzing the stability of the sub synchronous modes. Then we also have one simple technique or frequency domain analysis but this technique is approximate as compared to the frequency response analysis however the most most efficient technique is time domain analysis that is we can perform the and obtained a time domain solution or response of the system using EMTP program. In this you can model the three phase system you can model the non-linearities of the system and the complete transient behavior can be studied applying the EMTP program or today we are using the EMTDC or PSK program. Right. These programs are very useful in analyzing the SSR phenomena and IEEE has given 2 standard models for studying the SSR phenomena, one is called the first benchmark model and second is the second benchmark model.

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Then we have come to a very important aspect that okay, if suppose SSR problem takes places then we have to take some counter measures to eliminate the SSR problems. The various techniques have been reported to mitigate this SSR problem is some of the methods for or counter measures are static filter, dynamic filter, dynamic stabilizer, excitation system damper, protective relays and NGH scheme in state the basic, in the static filter the basic approaches that we put in series with the stator winding a circuit which is having parallel resonance to a particular **particular** torsional mode.

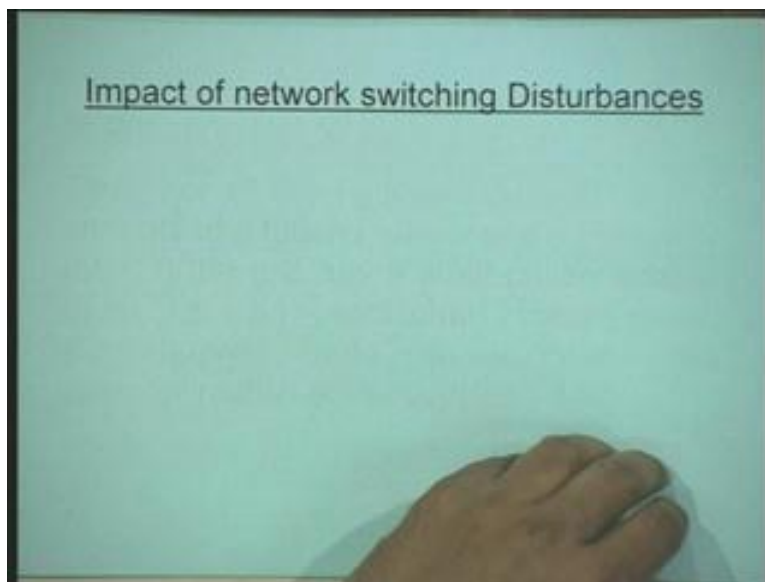
So that the stator circuit will not carry frequency or in current of sub synchronous frequency that is if this parallel network is tuned for some subsynchronous frequency right then no currents can circulate in the stator circuit of that particular subsynchronous frequency and therefore we can mitigate this problem. Another is the dynamic filter in this dynamic filter again we put we inject a voltage in series with the stator circuit which will be equal and opposite to the sub synchronous voltage which is generated in the stator winding.

So that we nullify the voltage which is developed in the stator winding of sub synchronous frequency. So that no currents of sub synchronous frequency will flow. This dynamic stabilizer is basically shunt connector device right and it is a thyristor control by appropriately controlling this reactors by switching on and off the thyristors the this SSR problem can also be overcome. Again excitation system damper, now we have the power system stabilizer similarly, you can design a stabilizer right to damp the SSR problem because power system stabilizer is designed to take care of low frequency response to 2 hertz and therefore if you want to use this PSS or excitation system damper then it is designed for those torsional modes of oscillation right.

The protective relays are designed so that agent when this SSR problem is sensed the relays will disconnect the system from the supply that is the machine before it gets damage it is disconnected, this is what is the meaning of the protective relays they will sense the subsynchronous phenomena and then disconnect the machine. The last scheme is NGH scheme this NGH scheme , N stands for Narayan G. Hingorani , this is the first person this is the person who is the father of fec technology and he has suggested scheme for mitigating the SSR problem. Here, again the approach is very simple across the series capacitor capacitor a thyristor control resistor is connected that is across that is there is a shunt resistance which is controlled by by switching on and off the thyristors right and as we know actually that whenever the sub synchronous frequency currents flow the voltage across the capacitor will become non sinusoidal and the period of this voltage wave will be less than 180 degrees or more than 180 degrees.

Therefore this NGH scheme senses the period of the voltage way which is developed across this capacitor and it will short circuit the capacitor in case period is more than this. So that energy corresponding to the sub synchronous frequencies will dissipated and that that way it will be ensure that the voltage across the capacitor remains more or less sinusoidal, if the voltage across the capacitor is sinusoidal then no current will be half sub synchronous frequency this is what is the philosophy and students have done projects using NGH scheme. The last aspect which we should address is the impact of network switching disturbances.

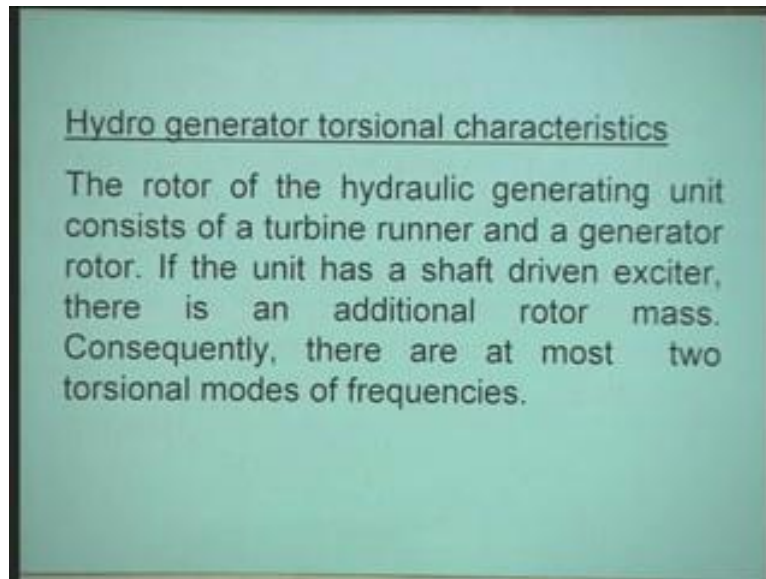
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Now this is a very important aspect I will just tell you that in any power system this we have number of switching phenomena, switching phenomena are planned or unplanned, planned phenomena means suppose I want to switch off transmission line this is a planned okay but unplanned means the faults occurrence of the faults clearance of the fault re-closure of the lines right. Now all these all these switching phenomena will cause a sudden change in the electrical power output of the generator. Suppose there is a transmission line which is supplying some sort

power and if this line is switched off the electrical power will become suddenly 0 and because of the sudden change in the electrical power output the shaft of the synchronous generator is subjected to stresses and that causes the loss of fatigue life and therefore this subject is a detail subject of importance and that is why number of frequency studies have been conducted **conducted**. So that the fatigue loss of fatigue life due to switching phenomena is reduced.

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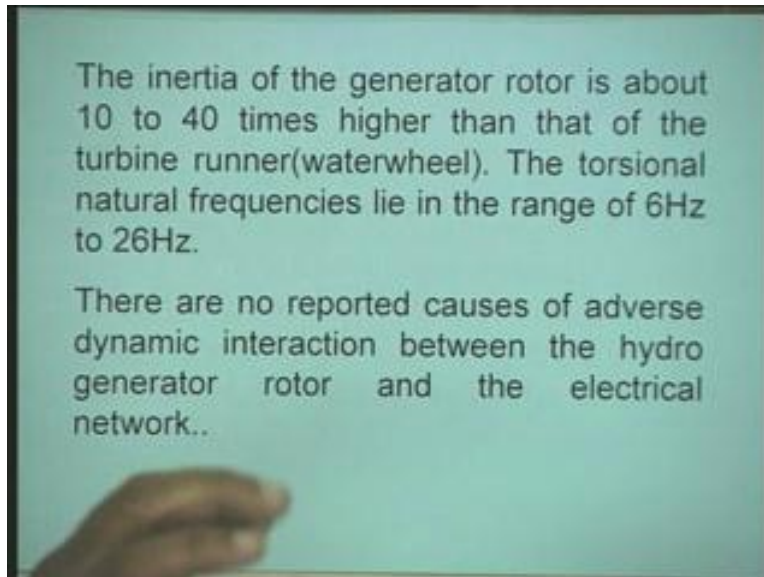


Now next point is the hydro generator torsional characteristic, till now whatsoever I have talked is the torsional characteristics of steam turbine generator. The rotor of the hydraulic generating unit consists of turbine runner and a generator rotor, if the unit has a sub-driven exciter there is an additional rotor mass consequently there are at most 2 torsional modes of frequencies that is generator, runner that is the hydro turbine and exciter therefore, there cannot be more than two modes of torsional oscillations. The inertia of the generator rotor is about 10 to 40 times higher than than that of the turbine runner or water wheel the torsional natural frequencies lie in the range of 6 to 26 hertz that is because of vast difference in the inertia constants the torsional frequencies are in this range 6 to 26 hertz for typical, this is a typical range there are no reported causes of adverse dynamic interaction between the hydro generator rotor and the electrical network.

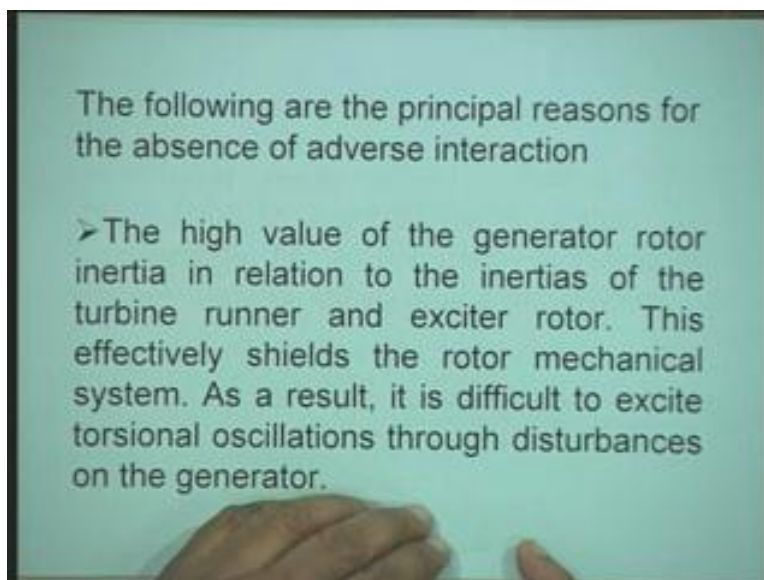
Now there are two principal reasons of no adverse interaction one is the high value of generator rotor inertia in relation to the inertias of the turbine runner and exciter rotor. This effectively shields the rotor mechanical system as a result it is difficult to excite torsional oscillations through disturbances on the generator that is whenever some disturbance takes place in the generator these oscillations are not excited. The last one is that the runner is moving in a water and therefore there exist a good damping is viscous water wheel damping this makes the

inherent damping of the torsional oscillations for 2 hydro units significantly higher than the steam turbine generators right.

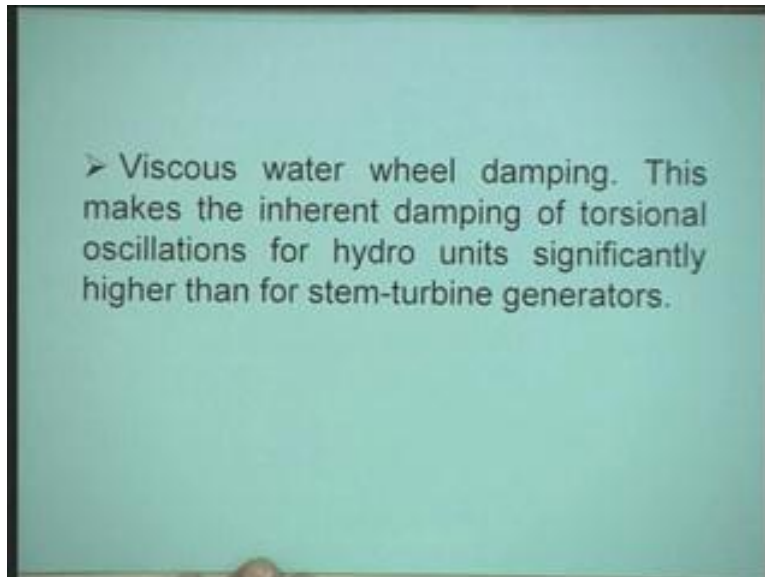
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Do you understand this point that in the steam turbine the turbine blades are moving in the steam. Here it is moving in water therefore there is lot of viscous friction right and therefore the damping is very high. Now let me conclude here that today we have studied the interaction or a torsional interaction between the system control as excitation system control, governor control. We also study the SSR phenomena we also study the techniques for analysis of SSR phenomena and countermeasures for overcoming the SSR problem, we have also studied that this SSR problem does not exist in hydro turbines. Thank you!