Power System Dynamics
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Lecture - 15
Excitation Systems (Contd….)

Okay gentleman, we start with the study of excitation systems. Today we shall cover the control and protective functions.

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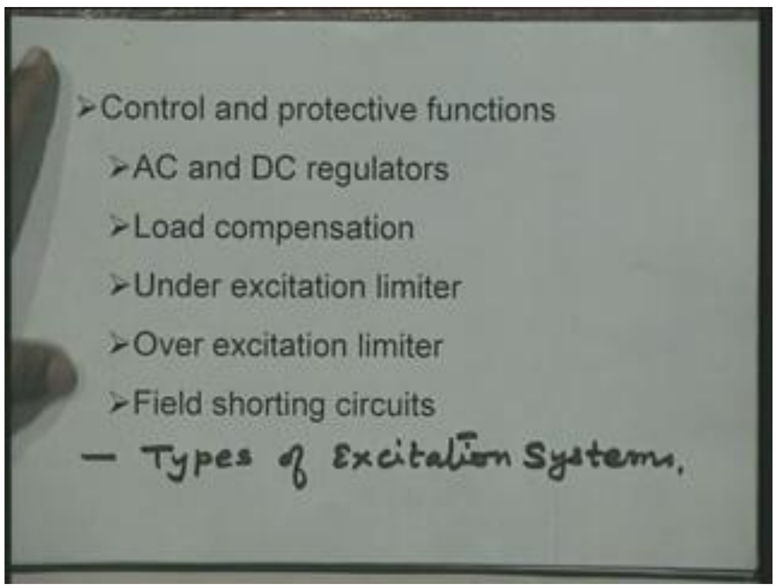

The control and protective functions provided in excitation systems are AC and DC regulators load compensation, under excitation limiter, over excitation limiter and field shorting circuits. We shall also study today the types of excitation systems, types of excitation systems briefly.

As you all know the control and protective functions are required to achieve the desired performance of the generator and power system we have excitation control, excitation limiting and excitation protection that is there are 3 different functions are control, protection and limiting. Here this is the most general block diagram of the excitation system which shows, which shows the different control protection and limiting functions. Now let us just look at here in this diagram this is our exciter just as usual the the exciter is a field shorting circuit, we will discuss the need for the field shorting circuit and the output of the exciter is given to the field winding of the generator right and it is connected to the system.

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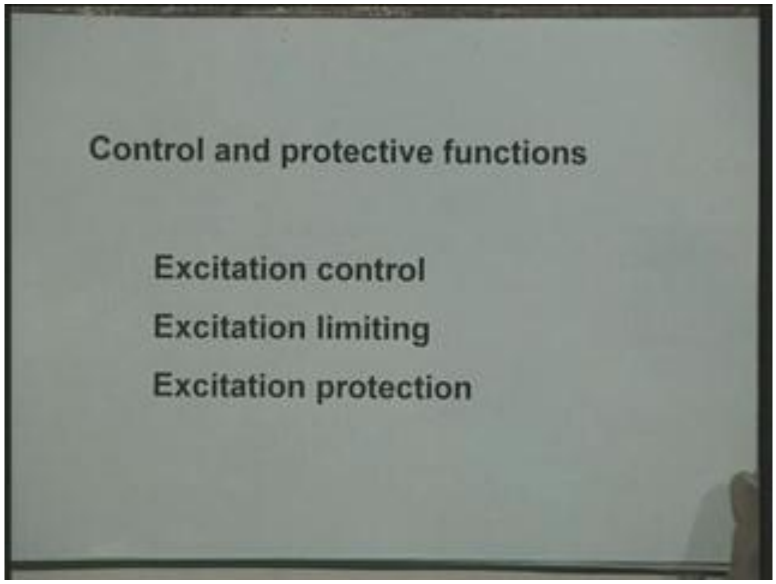

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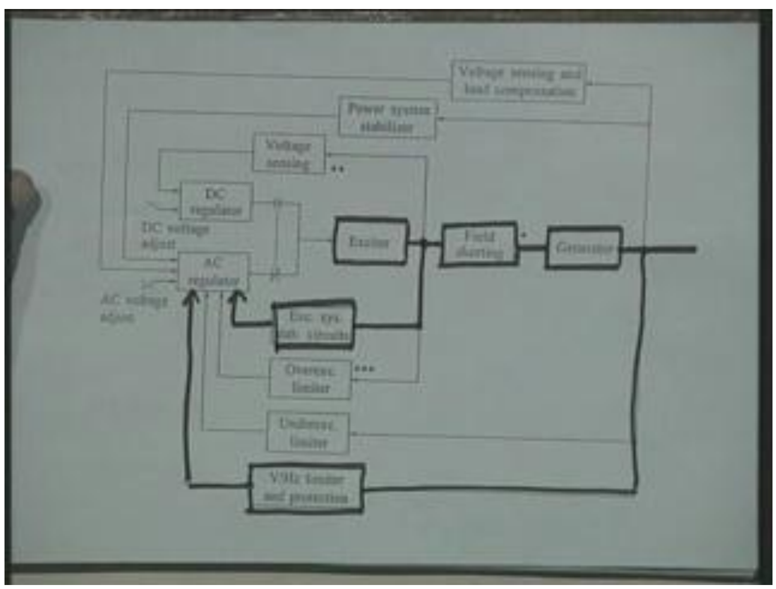

Now the different controls of protection functions are here, one is the excitation system stabilizer circuits and just see it here. This is excitation systems stabilizer circuit here what we do is that we take the signal from the terminal of the exciter and this is fed to AC regulator then there are a 3 limiting circuits, one is the over excitation over excitation limiter, under excitation limiter and volts per hertz limiter and protection.

Now this say over excitation limiter takes it input signal from the output of the exciter and again feeds this to the AC regulator, under excitation limiter gets its signal from the terminal of the generator and again operates through the AC regulator, voltage per hertz limiter as well as the protection right this also gets its signal from the generator terminals okay and it feeds to the AC regulator. Okay earlier we have seen that the control functions start like the voltage sensing and load compensation that also acts through the regulator, AC regulator. We have power system stabilizer that also acts through the AC regulator right and in addition to the AC regulator because in the previous block diagram, I had sawn only one regulator.

Now here we have shown two regulator one is called DC regulator another is called AC regulator. The the DC regulator has a very limited role most of the time only the AC regulator which functions okay but when the AC regulator is taken out because of some or the other reasons in that case the DC regulator comes in or is put into service, DC regulator instead of controlling the terminal voltage in generator it basically regulates the output of the exciter. The output of the exciter is a DC voltage and in a DC voltage which is regulated by the DC regulator while the AC regulator is concerned it has all these multiple functions control protection limiter all these functions are through AC regulator.

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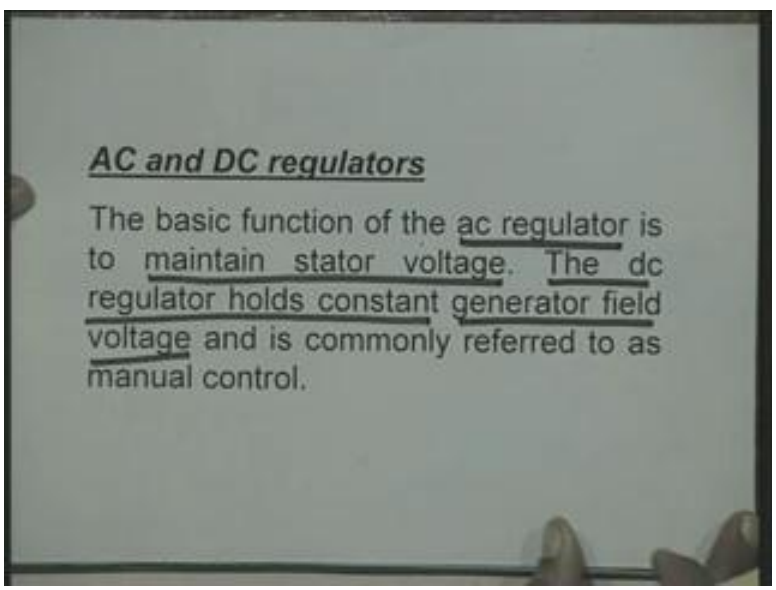

Now we will briefly discuss these components before I talk about the component separately, let me mention here that in any excitation system you may have all these functions or some of these functions it is not necessary that any given excitation system will have all these functions associated with it depending upon the requirements some functions may be present some functions may not be incorporated. Now, let us just discuss briefly AC and DC regulators the basic function of the ac regulator is to maintain stator voltage right that is the output of the synchronous generator. The dc regulator holds the holds constant the generator field voltage and is also referred to as manual control okay.

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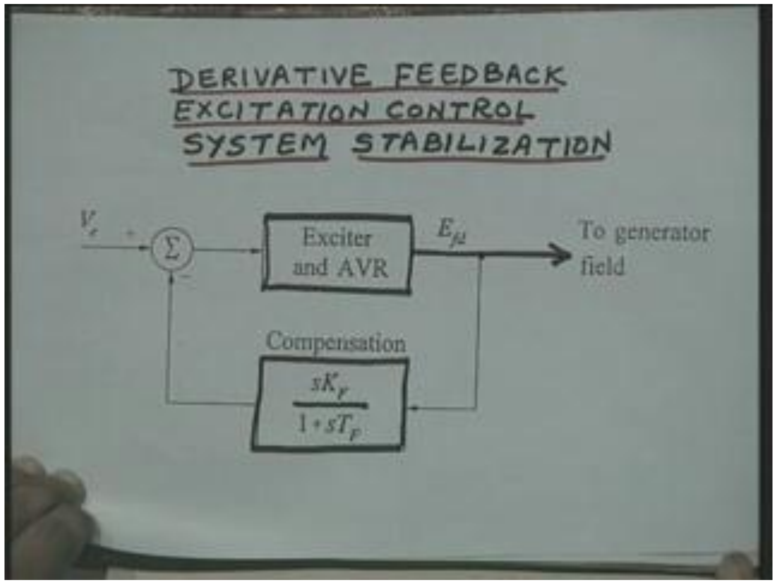

Now in any excitation system, any excitation system we require the excitation system stabilization right and the the simple block diagram of the excitation system stabilizer is shown here. This this block represents the exciter and AVR okay and the output of this exciter is the DC voltage which is represented by the Efd the voltage which is applied to the field winding of the synchronous generator then in order to have stable performance of this exciter and AVR, the simplest stabilizer circuit which is used is derivative feedback, derivative feedback and this derivative feedback is achieved through this transfer function.

We will discuss the details about this derivative feedback when I did talk about the the models of components of the excitation system because after we discuss the basic functions, we will go to the modeling and while talking about the modeling we will first talk about the models of various components and then the excitation system model as a whole right. Now this feedback block you can see here has the transfer function of this form sKF divided by one plus s times TF right.

Now this denominator represents the time delay which is provided and in the numerator, we have actually this function sKF, the s stands for d by DT and therefore it provides a derivative feedback signal and by properly adjusting the values of these parameters KF and TF, we can achieve the desired dynamic performance of the exciter okay.

The next component is load compensation. This load compensation here, we derive a voltage V_c which is obtained by adding a voltage drop R_c plus j times X_c into I_t 2 terminal voltage that is to the terminal voltage of the synchronous generator, you add a voltage drop which is represented by this term that is a complex number R_c plus j times X_c is a complex number multiply this by the terminal current right and you perform this phasor addition and then obtained at quantity which is proportional to the magnitude of this quantity that is V_t E_t plus j E_t plus R_c plus j times X_c into I_t this is a phasor is a complex number find the magnitude of this and therefore, V_c is the a scalar quantity right and this quantity this V_c represent the terminal voltage plus voltage drop in the complex impedance or in the impedance R_c plus j times X_c.

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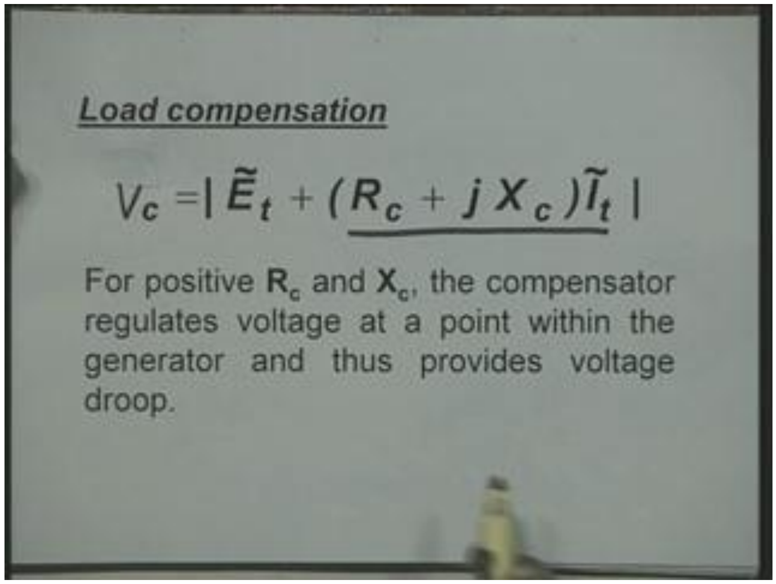

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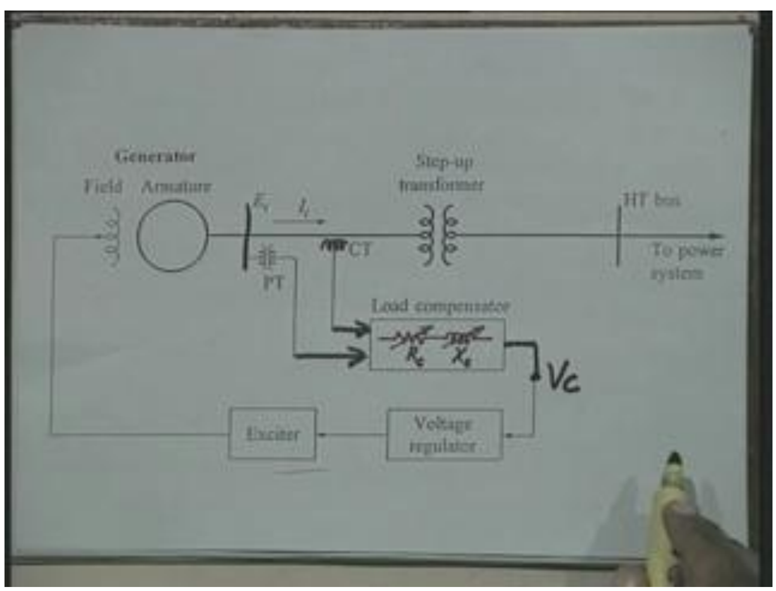

Now in a practical system practical system the the voltage V_c is derived by this basic schematic diagram using this schematic diagram from the terminal voltage you put a potential transformer and get a voltage signal which is proportional to the terminal voltage in the output of the synchronous generator right, we put current transformer and extract a current proportional proportional to the load current right.

Now these two quantities that is this is a quantity proportional to the terminal voltage here is the quantity which is proportional to the terminal current. Okay these are fed to a block diagram which is called load compensator right it has a real term R_c and a imaginary term which is represented by X_c that is this can be visualized as if you have a impedence of the value of the Rc plus j times X_c right, practically it will not be an impedence it is only actually a a complex number which can be used actually to derive a voltage signal V_c.

Now this voltage signal is fed to the regulator right and ultimately the field current of the synchronous generator is regulated like this. In case in case we do not want any load compensation then the R_c and X_c will be set to 0, okay so that what you regulate will be the terminal voltage of the synchronous generator okay.

Now suppose if I take the R_c and X_c positive, positive then the voltage which we regulate is not the terminal voltage but what we regulate is the voltage which is which is somewhere inside the synchronous generator because here this that is from the what is all some voltage is generator inside the synchronous generator right that voltage drops and we get a terminal voltage here.

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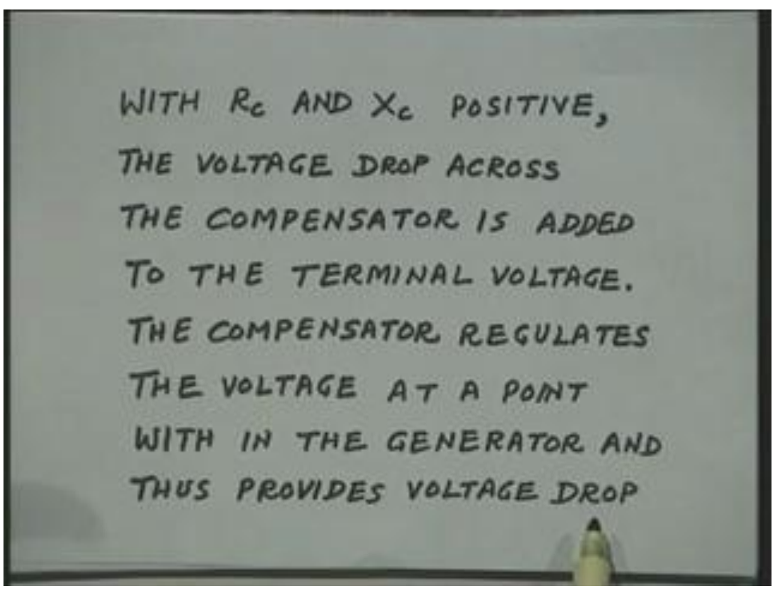

Therefore, what we get by a setting R_c and X_c positive the voltage drop across the compensator is added to the terminal voltage. Okay the compensator regulates the voltage at a point within the generator and thus provide the voltage drop. Now this is particularly required when you have 2 generators right which are connected in parallel and we want to do the reactive load sharing right. Now the reactive load sharing by the two generators will depend upon the internal voltage which is generated and therefore, here we are trying to regulate the internal voltage.

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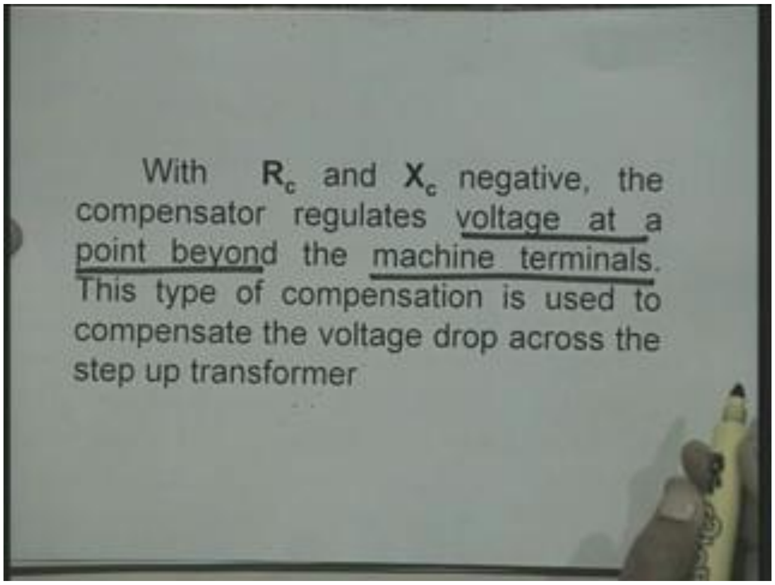

In case you put R_c and X_c negative right because as I told you that you can make the real term negative reactive term also can be made negative the compensator regulates voltage at a point beyond the machine terminals that is terminal voltage is e_t right from this e_t we had subtracting some voltage drop and therefore basically you are trying to regulate a voltage somewhere beyond the terminal voltage of the machine right.

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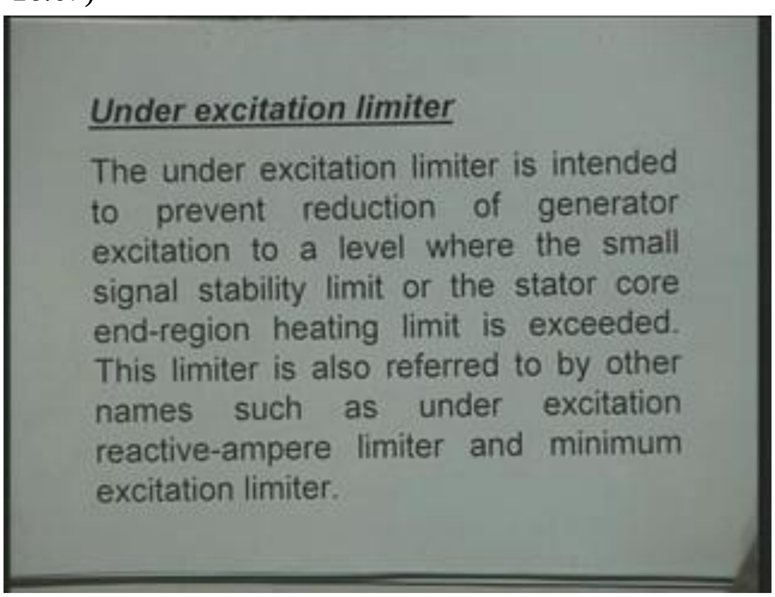

Now this type of ah compensator is required where you parallel the two generators having individual transformers there is a terminal voltage, a generator it is on generator transformer, a generator it is on generator transformer and then they are parallel on the high voltage side. Next component is the under excitation limiter. Now the under excitation limiter means actually that in case the excitation current in the field winding of the synchronous generator goes below a certain value then this type of operation is not permissible that is we should not reduce the field winding current below a certain set value. The basic reason is here, the under excitation limiter is intended to prevent reduction of generator excitation, reduction of generator excitation to a level where the small signal stability limit or the stator core end-region heating limit is exceeded.

Now these details actually one has to look into the capability chart of the synchronous generator where if the excitation becomes very low right then the small signal stability limit is evaluated okay and there are different names which are given to this under excitation limiter.

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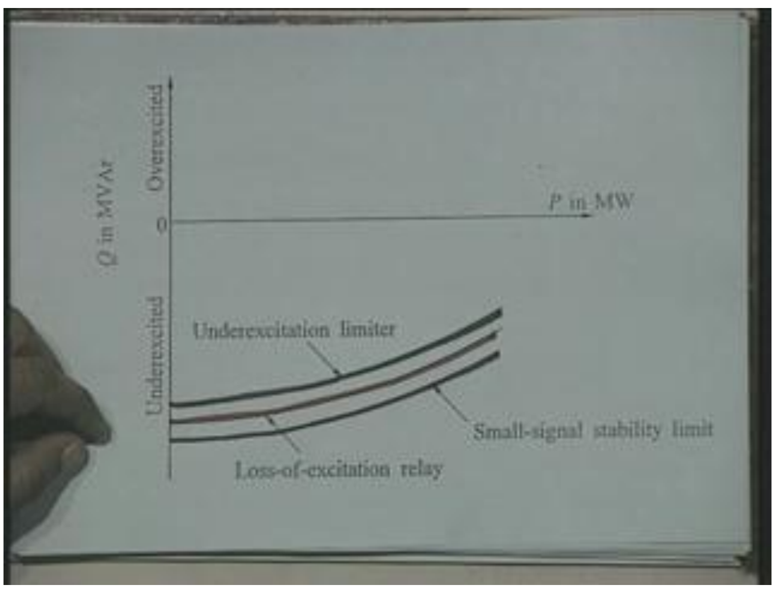

When we look the operation of the synchronous generator in the PQ plane right. Now this is the P axis that is the real power output this is the reactive power output when the then it is over excited it supplies positive Q and where the under excited it supplies negative Q and the operating limits this is the under excitation limiter which is shown here the under excitation limiter setting is done. So as that it is coordinated with respect to the small signal stability limit that is this curve so the small scale of the small signal stability limit that is in case you operate in this portion of the PQ plane the system is stable for small perturbations. If you operate somewhere in this region that is on this side of this characteristic system becomes unstable right, the small signal stability we will be studying separately okay.

Now keeping some margin the under excitation limit is set like this there is also one characteristic which is also provided it is called the loss of excitation relay that is whenever the synchronous machine looses its excitation then there is a relay which is used to protect the synchronous generator right. The characteristic of the loss of excitation relay is also shown here in this diagram, this is the characteristic of the loss of excitation relay right. Therefore, these three characteristics actually that when you set the under excitation limiter settings. Okay these have to be coordinated with respect to the small signal stability limit and loss of excitation relay characteristic, okay and we have to see at the same time that both these characteristics are outside the setting of the under excitation limiter. This margin whatsoever we provide that is a safety margin, the next limiter is the over excitation limiter.

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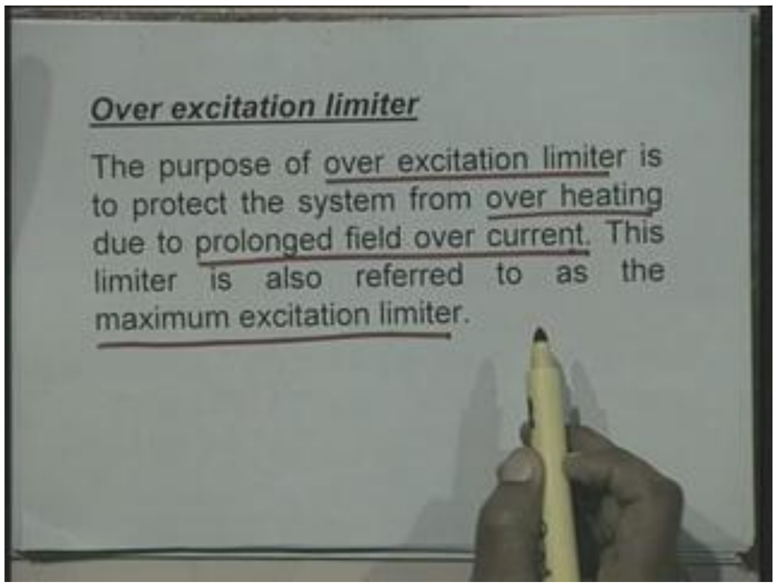

The purpose of over excitation limiter is to protect the system from overheating due to prolonged field over current. In case, in case the field current is more than the permissible or the the the rating of the synchronous generator right and if that current is more than the rated value for a prolonged time then naturally because of overheating of the field winding the field winding may get damaged right. Therefore the purpose of the over excitation limiter is to protect the system from overheating due to prolonged field over current. This limiter is also referred to as the maximum excitation limiter whether you call it over excitation limiter or maximum excitation limiter they are the two different names which are used in the literature.

The over excitation limiting function typically detects the high field current condition there is a, it has to detect the high field current condition and after a certain time delay acts through the ac regulator to ramp down the excitation to the present value. In case, in case the current in the field circuit is more it is detected then since actually the over excitation is permitted for some small amount of time, okay then this limiter what it will do is it will ramp down it will bring down the field current and bring it to the rated value.

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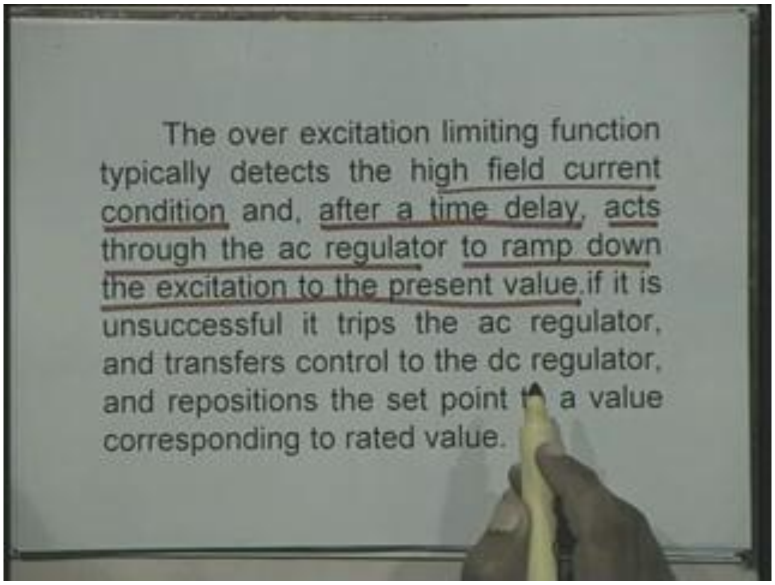

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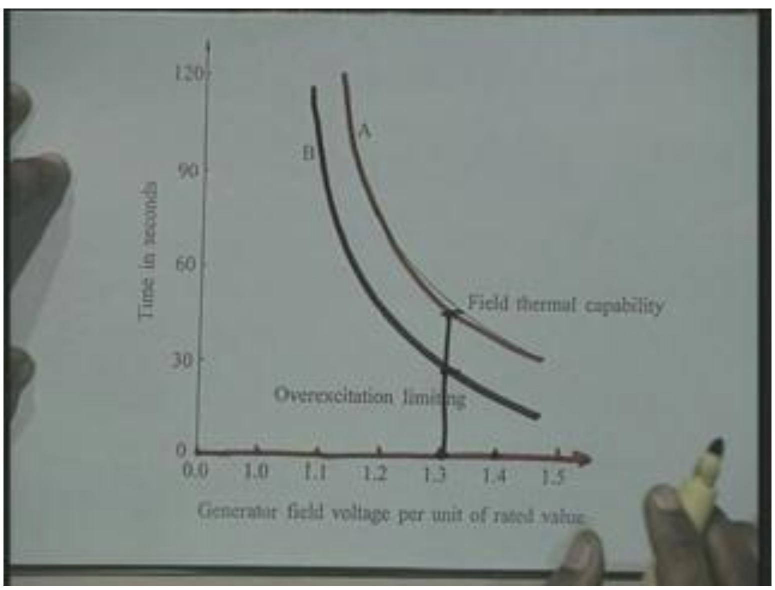

Now this graph shows the characteristic of the over excitation limiting that is on this axis, we have marked axis what is marked is generator field voltage per unit of rated value that is you start from a rated value is 1, 1.1, 1.2, 1.3, 1.4, 1.5 like this and on this y axis we are putting the time in seconds right, the times are 30 second, 60 second, 90 second and 120y second. This gives you the, you know range over which actually the excitation system, over loading is permitted or over excitation is permitted.

Now this characteristic A which you can see it here right this characteristic shows the field thermal capability. You can easily understand actually that suppose I the generator field voltage per unit of the rated value, now here the whatsoever voltage you apply right the corresponding current will flow because under steady state, steady state conditions the field current is equal to the field voltage divided by the field resistance right and therefore, this generator field voltage per unit of rated value also represents the corresponding field current and you can easily see that as this value increases the time for which it can be permitted is decreasing. This is practically this type of characteristic inverse characteristic and the characteristic of the over excitation limiter is to be coordinated with respect to the field thermal capability.

You have to always keep some margin and therefore, the characteristic of the over excitation limiting is given by giving some margin, in the sense that suppose I take this example here for example if you let us say field field voltage is 1.3 per unit okay then it can withstand this over voltage for this much time right but keeping some margin, our limiter will operate in a time which is less than the upper limit right. Therefore, this this is the margin which is provided a safety margin you can call it.

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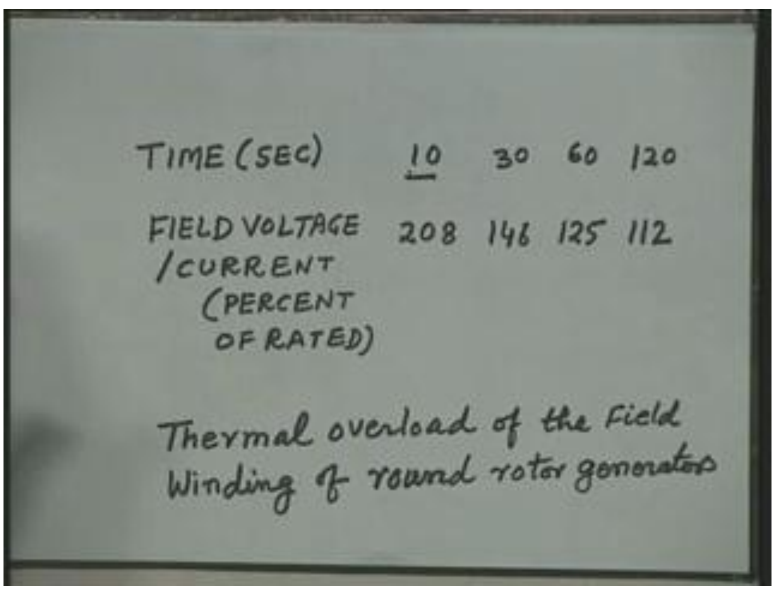

Now this table shows the time in seconds verses the field voltage of the current in percent of rated value right that is from this graph we have just picked up some values and that shows actually that if the applied voltage is 2.08 per unit or 208 percent of the rated value it can withstand for 10 seconds. If it is 146 percent right it can withstand for 30seconds, if it is 25 percent more than the rated value it can withstand for 60seconds and 12 percent more than the rated value withstand for about 2 minutes is 120 seconds.

Now this is the this is the thermal characteristic of round rotor generator, turbo generator, round rotor turbo generator because these characteristics are going to be different for different machines but typical machines this has to be provided by the manufacturer then the next important limiter and the protection function is the voltage-per-hertz limiter, voltage-per-hertz limiter. Now here we all know that the the flux produced in the core is function of the terminal voltage that is we we have a standard emf equation right therefore, the voltage is related to the flux and the frequency okay.

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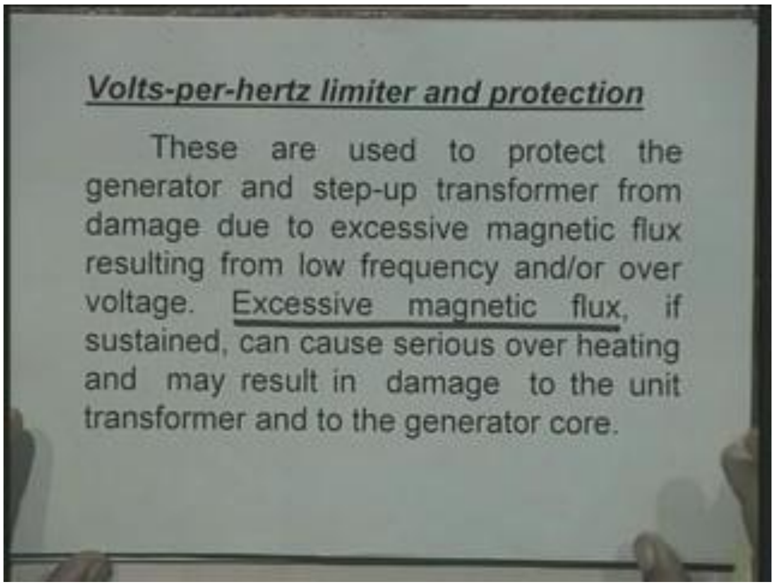

Now suppose we are operating and at a situation where frequency drops and voltage rises, voltage becomes more frequency becomes less. Okay it means v by f becomes more under that situation the the operating flux will become more it will increase and when the flux increases it will cause additional core losses right and therefore there is a necessity to provide the protections against such eventuality, one simple example is that when standard generator is you know disconnected from the load or actually the load is thrown off.

At that time the there is tendency for the machine to speed up and the frequency rises voltage also rises right and in case the v by f ratio is beyond a certain permissible value then this limiter will come into action and take necessary, you know action right. Therefore, basically this is provided to safeguard the generator from the excessive magnetic flux. Now not only the generator actually the transformer which is connected to the generator is also effected when when a v by f ratio is more than certain value.

Now the ratio of per unit voltage and per unit frequency referred to as volts per hertz is readily measurable quantity that is proportional to the magnetic flux that is v by f ratio but here the ratio is taken the voltage is expressed in per unit frequency is also expressed in per unit right and that ratio v by f not the absolute value, this per unit ratio reflects the over fluxing of the synchronous generator this is also called over fluxing.

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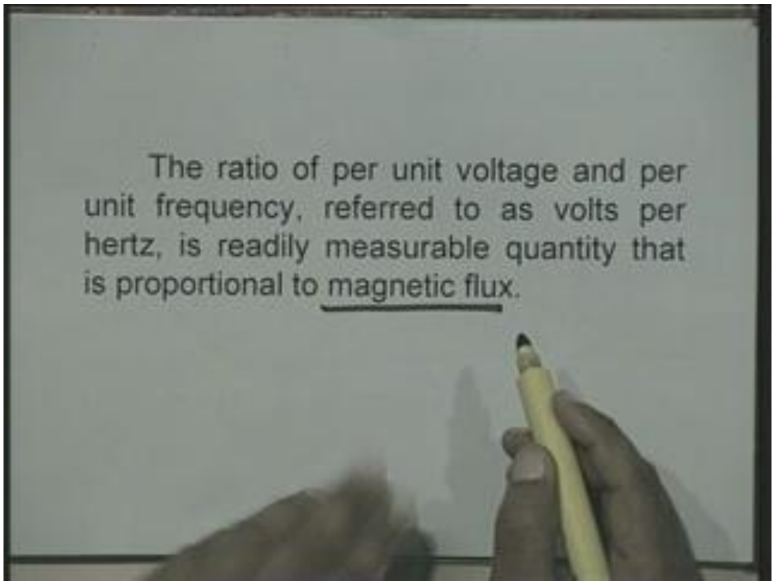

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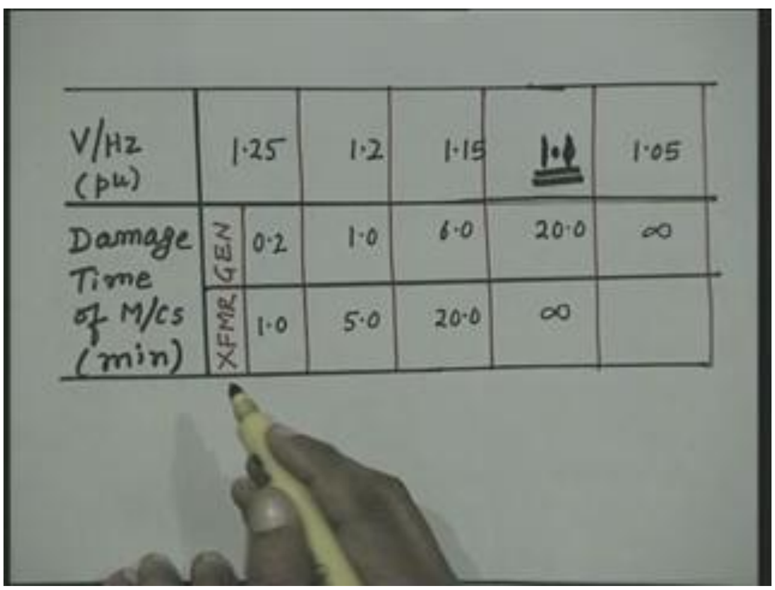

V/Hz (pu)		1.25	1.2	1.15	1.1	1.05
Damage Time of M/cs (min)	GEN	0.2	1.0	6.0	20.0	∞
	XFMR	1.0	5.0	20.0	∞	

Here this table shows the voltage per hertz in per unit you can see it is a this is 1.051. I think this this is slightly mistaken, no this is 1.25, 1.2, 1.15 this may be 1.1, okay this is 1.1 correction 1.1, 1.05. Now here damage time of the machines right damage times are given in minutes here. The time is expressed in minutes instead of putting in seconds here write is in minutes.

Now damage time for generator and transformer are separately mentioned here that is in case this ratio V by hertz or voltage per hertz is 1.25, the the generator can withstand this for .2 minutes if it is 20 percent more than for 1 minute, it is if 15 percent it is about 6 minutes, it is 10 percent it can be withstand for 20 minutes and if it is 5 percent more than infinite, this is the capability that is if this V by f ratio right in per unit is 1.05 then there is nothing to worry. For the transformer the permissible times are more, we can easily see here that instead of .2 here it is ones minute for 20 percent ah V by f right ah 1.2 times V by f is 5 minutes 1.15 it is 20 minutes and 10 percent is infinite right. Therefore, based upon this permissible values right the setting of the limiter or the voltage per hertz limiter settings are decided.

Now this ah field shorting is very special provision which is provided on the synchronous generator. Especially when when we have the the excitation systems where we use the rectifiers to supply the field current because you will you will see that we have two categories of excitation systems ah one is AC excitation system where the output of the AC excited is rectified and given to the field winding.

Similarly, the static excitation system right. We take the terminal voltage terminal current rectify and give the field current to the synchronous generator right. In these 2 types of excitation system we cannot make the field current to reverse because rectifiers are provided therefore, the field current cannot reverse and under certain situation, certain situation it is desirable to allow the current to flow in the reverse direction particularly during pole slipping or during short circuit conditions where in the stator carries the stator carries the dc component whenever the fault occurs at the terminal of synchronous generator right. The the voltages which are produced in the field winding of the synchronous generator right if they try to drive the current in the reverse direction.

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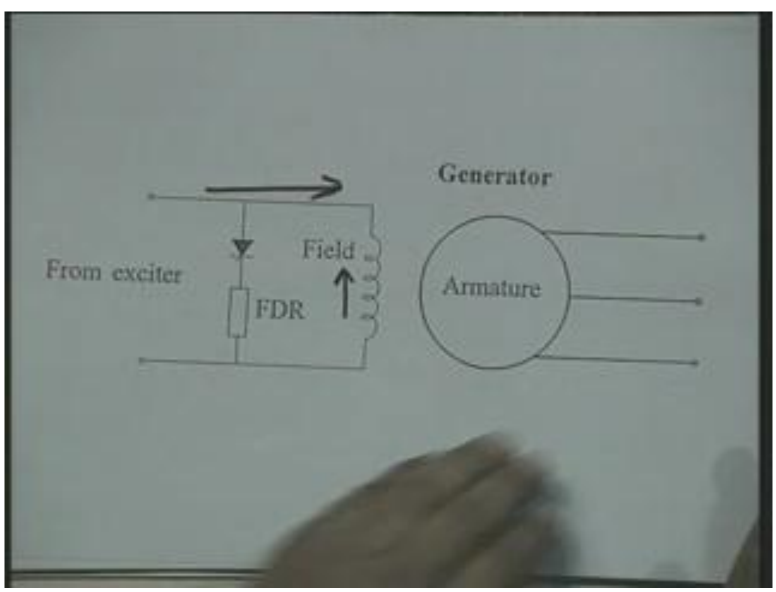

In case we do not have this provision then the voltage produced will be very high which may damage the field winding of the synchronous generator and therefore there are two different circuits which are provided, one is that across the field winding you put a thyristor control field field discharge resistance right that is this resistance is always provided actually along with the excitation system right and the moment actually the voltage across the field winding becomes more than a certain set value then this thyristor is switched on right and it will allow the current to flow in the reverse direction right.

Otherwise actually the the the field current is flowing say in this direction okay and this thyristor is off therefore, this there is no current flowing here and this field current cannot reverse it cannot flow in the reverse direction it will flow only is in this direction. Now suppose the due to some ah faults on the terminals of synchronous generator right in the field winding some voltages are produced which have this type of polarity and in case this the in case actually the this we provide a path for the reverse current to flow then this voltage will not go beyond a particular limit. If this path is not provided then this voltage becomes high and it is dangerous to the life of the synchronous generator field winding.

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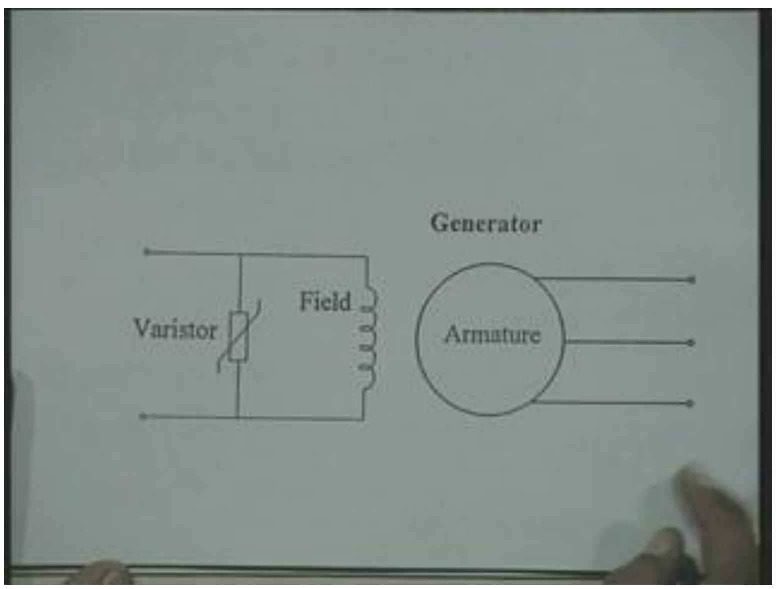

Another arrangement is that use make use of varistor, varistor which is a non linear resistance when the voltage across this circuit is below set value or some less value then it offers infinite resistance and when voltage goes beyond certain value it offers low resistance and therefore it allows the field current to flow in the negative direction right. They are the two arrangements which are provided as a special ah protection for the field winding of the synchronous generator. Therefore with this I can say that we have discussed the various control and protection functions provided on the synchronous generator excitation system it is not it is synchronous generator excitation system.

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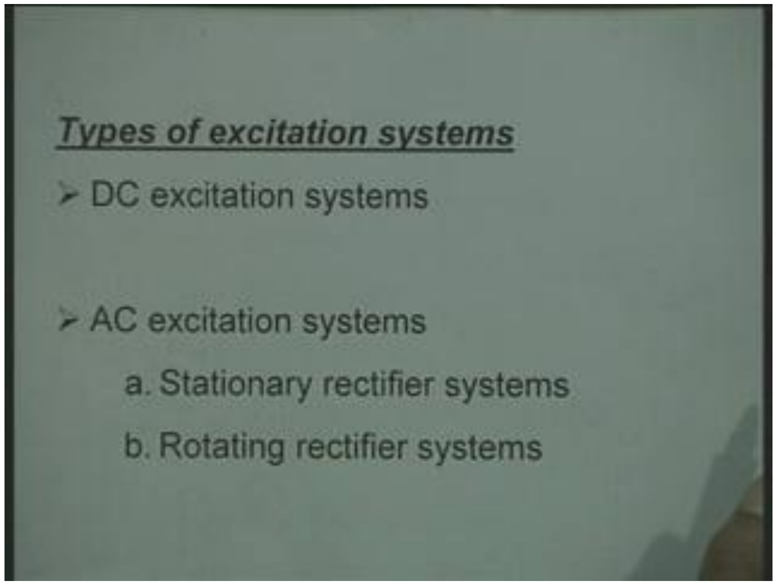

Now we will briefly talk about the different types of excitation systems. Excitation systems are broadly classified into 3 categories DC excitation system, AC excitation system and static excitation systems. The excitation power required for a synchronous generator is of the order of 2 to 3.5 kilo watt per mega watt rating of the machine or per MVA rating of the machine.

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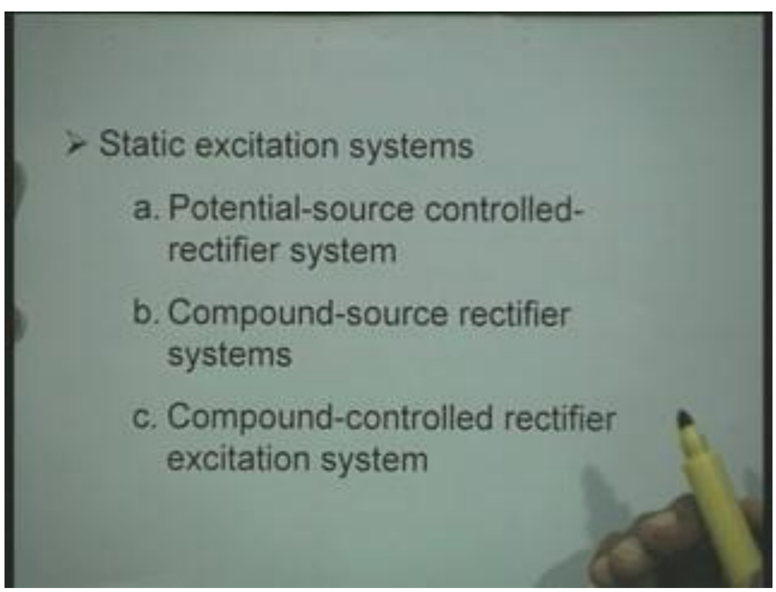

The DC excitation systems were the oldest of all the excitation systems and the main limitation of DC excitation system is the amount of power which can be delivered and the commutation is the main problem in the excitation system, the more the current to be delivered, more is the commutation problem. The in nineteen sixties the DC excitation system has been superseded by AC excitation systems in AC excitation systems we have 2 different type of excitation systems ah stationary rectified systems and rotating rectifier systems while we study excitation systems we have different types of arrangements, one is the potential source controlled-rectifier system, compound-source rectifier system and third is the compound-controlled rectifier excitation system. Now this figure shows the schematic diagram of a DC excitation system.

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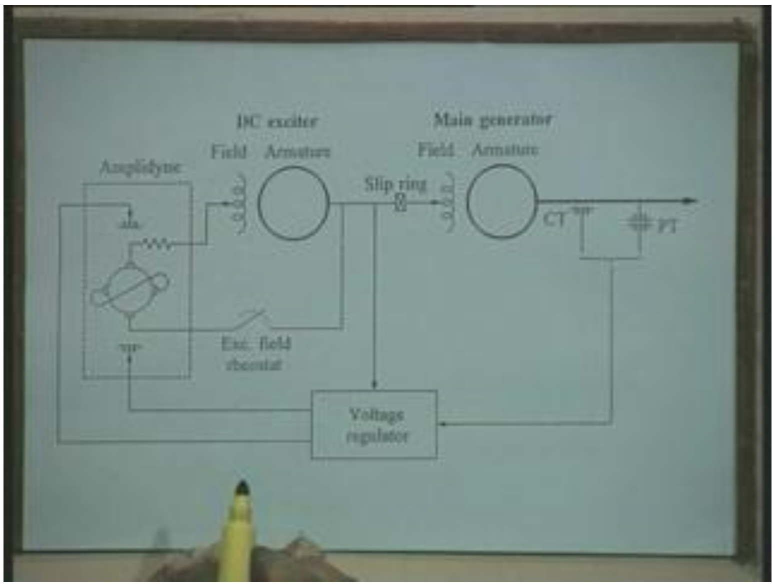

The this the DC generator is the source of power for supplying DC current to the field winding of the synchronous generator. If you see here then this represents the DC exciter this is the armature this is the field winding the output of the DC generator is feeds the field winding of the synchronous generator through slip rings. The DC exciter may be driven by the turbine shaft or by separate motor also and this may be self excited or a separately excited machine. The the voltage regulators may be a rheostatic type or they magnetic amplifier or amplidyne time and this type of excitation systems are still existing in many of the power plants and therefore, modeling of this DC excitation system is also important. We shall discuss the modeling of DC excitation system separately. Now this diagram shows the AC excitation system.

In AC excitation system the the field power is obtained from AC exciter, the AC exciter is a AC generator and this AC generator may be driven again by a separate motor or by a shaft of the turbine. Generally in this AC exciter is driven by the turbine shaft itself. Now here in this arrangement we are using the stationary diode arrangement that is the output of the AC exciter is rectified with the help of stationary diodes and the DC current is fed to the field winding of the synchronous generator through slip rings.

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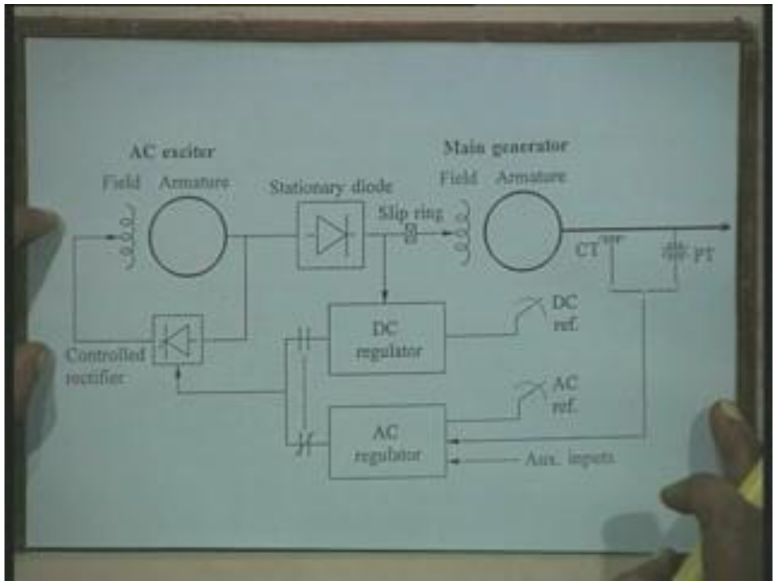

Now here when we use the non control rectifiers then the output of the exciter is regulated by controlling the field current of the AC exciter therefore, if you see here in this diagram then the AC regulator adds to control the firing angle of the control rectifier and it regulates the output of the AC exciter. The another arrangement which is ah possible is that we use stationary controlled rectifier that is instead of using the stationary uncontrolled rectifiers as is shown here. We can use the stationary controlled rectifiers other arrangement is exactly the same as in the previous case.

Now once we use this stationary controlled rectifier then the output of the excitation is adjusted or controlled by controlling the firing angle of the controlled rectifier here itself that is this AC regulator will directly control the firing angle of the stationary controlled rectifier and this AC exciter provides out AC output, AC output and the control output is obtained by rectifying the ah this DC ah AC output to DC but in a controlled fashion.

The other arrangement is exactly similar to what we discussed in the earlier case. Now in these two arrangements which we discussed for the AC exciters, AC exciters the armature of the AC exciter is stationary and field system is rotating while the field of the synchronous generator is getting it supply through slip rings. Therefore, in this AC exciter we have still the presence of slip rings and the another ah alternative arrangement which has been used is where we do not make use of slip rings and that is called the brushless excitation system.

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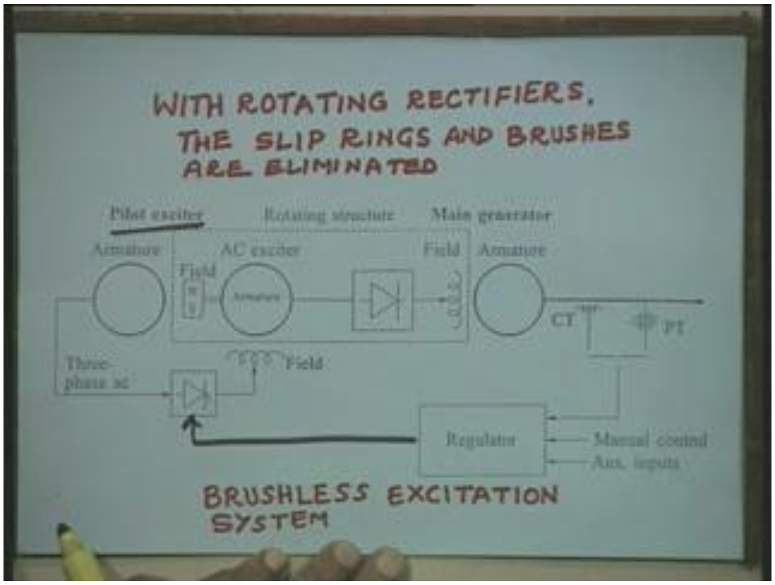

In brushless excitation system we have AC exciter uncontrolled rectifier and the output of the AC exciter is fed to the field winding. Now the armature of the alternator or the armature of the AC exciter is made rotating right the rectifiers are also rotating the field system is rotating and therefore, we can see here that armature of the AC exciter, the rectifiers and the phase field system they are rotating and they are connected rigidly without having any slipping contact. The excitation of the AC exciter, how do you provide the excitation for the AC exciter? The AC exciter excitation is provided by using a pilot exciter, this pilot exciter has the a permanent magnet field system right and the armature is stationary.

Now in this arrangement the rectifiers are not accessible to us because they are rotating and therefore, we cannot have controlled rectifiers in the brushless excitation system the control of the excitation system is achieved by controlling the field current of the AC exciter that is the AC exciter gets its field current field current through a controlled rectifier that is the AC regulator this is the AC regulator.

This AC regulator acts on the controlled rectifier which are provided here and we supply the controlled field current in the AC exciter and in this arrangement. We will be in a position to control the output of the exciter by controlling the field current of the AC exciter. However, another problem is that the the field voltage and field current cannot be measured directly that is since this field system is rotating rectifiers are rotating and therefore, there is no way directly to measure the field current directly and therefore if you want to get the information about how much field current is flowing this can be obtained indirectly by measuring the field current of the field current of the pilot exciter in the not in the AC field field current of the AC exciter that is the output of the pilot exciter.

The major advantage of this type of excitation system is that we do not have slip rings and once we do not have slip rings right the problem of maintenance of the slip rings. The carbon brushes flashovers all these things are eliminated the excitation systems whether we use a stationary rectifier excitation system or brushless excitation system the dynamic performance of these two systems have been found to be practically identical therefore from the point of view of performance. There is no special choice whether we choose a stationary rectifier excitation system or brushless excitation system both these arrangements provide the similar dynamic performance. Now we briefly talk about the static excitation system.

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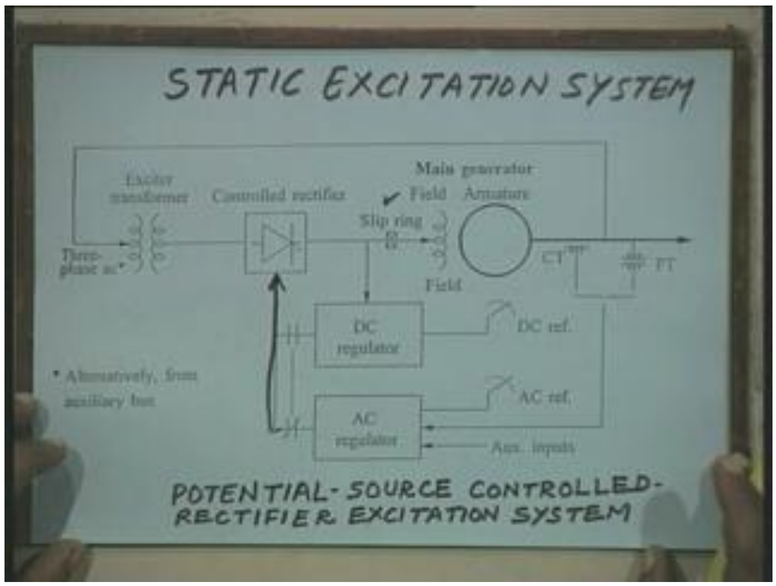

The static excitation system now this figure shows the schematic diagram of a static excitation system. In a static excitation system, the excitation power is derived derived from the terminal of the synchronous generator or from the auxiliary bus of the power plant. Now in this arrangement the the we make use of this exciter transformer the input to the exciter transformer comes from the terminal of the synchronous generator itself and output of this exciter transformer is rectified using the controlled rectifier and this output is fed to the field winding of the main generator or main synchronous generator through slip rings. Therefore, in this static excitation system, we do require the slip rings the control is the output of the excitation system is controlled by controlling the firing angle of the controlled rectifiers that is the AC regulator directly acts this is the AC regulator. This AC regulator directly acts on controlled rectifiers and we get the regulated current in the field circuit of the synchronous generator.

Now one major advantage of the static excitation system is that we do not have any rotating part so far the excitation, excitation or the excitation system is concerned another thing is that the the the response time of this static excitation system is very low that is they are very fast there is one more arrangement of static excitation system.

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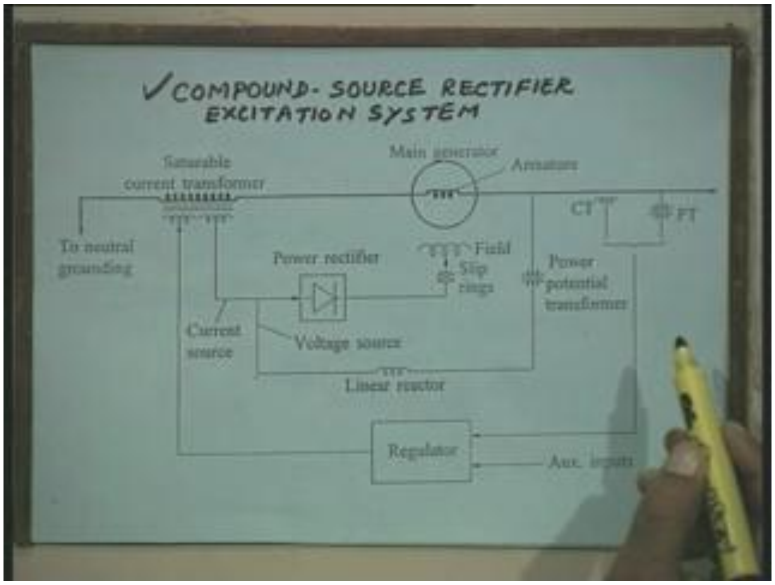

Now here this is the main generator to get the required field current instead of making use of only potential or power potential transformer to get the required field current. We make use of an arrangement which is called compound source rectifier excitation system here here. The field current in the main generator is made function of the terminal voltage of the synchronous generator and the load current therefore, if you see here in this arrangement that we make use of a transformer which is called saturable current transformer this saturable current transformer is connected in the neutral circuit of the main alternator then we can obtain a quantity proportional to the load current. We can obtain a quantity proportional to the terminal voltage these two quantities are these terminal voltages and load current, they are appropriately combined and we get an output which is fed to the fed to the power rectifier and the the output of the power rectifier field gives the field current to the synchronous machine field winding.

Now the major advantage of this is that whenever suppose a fault which occurs at the terminal of the synchronous generator. If we use a simple static excitation system using the exciter transform only then when the 3 phase fault occurs or some sort of fault occurs at its synchronous machine terminals right then the voltage available to this transformer becomes 0 or it dips then this will affect the field current of the excitation system now in this arrangement. When the voltage at the terminal synchronous generator dips but simultaneously current becomes high right.

So that, we will be in a position to maintain the field current even under the disturbance conditions. With this I will conclude the that we have discussed today is that the various control protection and limiting functions of the excitation system and different type of excitation systems. We have also seen the limitations of DC excitation system, the merits of AC excitation system and particularly the merits of brushless excitation system, the today in major power plants; major power plants the excitation systems are either AC excitation systems or static excitation systems. Thank you!