Economic Operation and Control of Power System

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Lecture – 36

So, good morning and welcome you all for the NPTEL online course on Economic Cooperation and Control of Power Systems. Today is a very important topic, we will discuss about real time case study on reactive power dispatch. First we will take you through different reactive power compensating devices, then we will take up some case studies and very interesting case studies and let us see how reactive power plays a crucial role in maintaining voltage stability. So before that let me walk you through different sources and sinks of reactive power in a power system network. So the first very important equipment or integrated part of a power system is transmission line which connects between generating stations to the demand side, the distribution system. Th transmission line, it depends on the load current, the transmission line can act as a sink or source of reactive power.

So whatever the load is connected, more industrial loads, induction motor loads are present, then naturally the transmission will need to carry this reactive current. So and there is something called as surge impedance loading, I hope you are very familiar about this aspect. So surge impedance loading is just expressed as VLL^2, surge impedance loading is equal to divided by Z_0, where Z_0 is known as the surge impedance. So what is the expression for Z_0? It is nothing but square root of R plus j omega L, G plus j omega C.

Because in a transmission line, L and C dominates R and G, the resistance and conductance usually ignore R and G, so you would come out with something called as square root of L by C. So this is the input impedance as seen by the transmission line actually. So for infinite line, this is the input impedance, the surge impedance or the characteristic impedance. So and this decides typically what is the net reactive power flow. In the sense if loading, there are three basic conditions.

If loading is greater than surge impedance loading, loading is equal to surge impedance loading, loading is less than surge impedance loading. There are three possible cases. So if loading is greater than surge impedance loading, then what happens? If it is more inductive oriented loads. That means now if you draw the voltage profile, this is between sending end and the receiving end, this is sending end and the receiving end, let us say, for a length. So the sending end voltage is same as the receiving end voltage if loading is equal to surge impedance loading.

That means we call it as operating power factor is unity. So if loading is greater than surge impedance loading, then eventually the voltage drops down for a length of line. This is loading greater than surge impedance loading. But if loading is less than surge impedance loading, then it is typically called as Ferranti effect. The receiving end voltage could be higher than the sending end voltage.

So if loading is greater than surge impedance loading, you are operating at lagging power factor. You are operating at lagging power factor. This is something called as unity power factor. And if loading is less than surge impedance loading, here is the case loading is less than surge impedance loading. And here you have the power factor is leading, leading power factor.

So above surge impedance loading lines absorb reactive power and underground cables have high capacitance and hence high natural load. They are usually source of reactive power under usual loading conditions. So what is transformer? Transformer as you already know, it has some leakage reactance. So leakage reactance will be anyway there because it draws some minimum finite current to establish the working flux within the operation of a transformer. If you remember the operation of a transformer, just walk you through little bit, not too much emphasis on the operation of transformer.

You can say this as a simple core type, though in actual sense the primary and secondary winding are present in both the limbs. We call this as limb. This is something called as yoke. The horizontal plate is called as yoke and vertical plates is called as limb. So let us say this is your primary side, V input and this is your secondary side, V output.

Now this is a magnetic material. Usually we use ferromagnetic type, ferromagnetic. There are four types of materials. One is ferromagnetic, second is ferrite cores are there, paramagnetic is there and there is something called as diamagnetic material. Four types of materials.

Here we use ferromagnetic type because its permeability is very high. So we can use various types of materials, cast iron, cast steel, all this is, but typically we use CRGO silicon steel, cold rolled grain oriented silicon steel type of material which has many superior magnetic features, high permeability and low hysteresis coefficient and all these things. So we can reduce the hysteresis loss and all. So typically what happens if you connect the primary, you excite, you need to excite the transformer. We call it as charging of a transformer actually.

So when you connect to the primary source, so it would draw some current. Actually let us say there is no load connected. As you see here there is no load I am connecting at the secondary side. So in the primary side you are connecting this transformer to the some voltage source. It could be LV, HV, that is immaterial for us.

It could be LV or HV either. So what happens there is some current which is flowing through the primary winding. So and because of which there is MMF which is being produced. What do you mean by magnetomotive force? This is called as MMF, magnetomotive force. It is nothing but number of winding times current.

That is it. And now there is some number of windings are there. There is a wound across this limb and then there is a current, finite current which has been pulled because of which there is a magnetomotive force present. So now like EMF is opposite to, it is equivalent to EMF in the magnetic circuit. So now there is a flux which is produced. Flux is nothing but MMF by reluctance.

Similarly you have current is equal to voltage by resistance. So there is reluctance. What is the expression for reluctance? So these are some fundamentals that you need to be very familiar at any given point of time. Reluctance is something but length by Ua, length by area. So now you have this reluctance and because of which there is also MMF and there is reluctance because both are finite.

So I am speaking about practical transformer. It is not ideal transformer. So there is some flux which has been established. It is a finite flux. And this flux completes path over the core.

There is a closed path for the flux and then you apply Fleming's right hand rule and you get the direction and the flux direction is typically upwards and it goes like this assuming the current is clockwise here. Now this flux will also link with the secondary winding. So because transformer is a static device, so that sort of EMF which is induced is known as statically induced EMF. There are two types of EMF induced. Static induced EMF and dynamically induced EMF.

And in rotating machines because there is rotation, we call it as EMF induced, dynamically induced EMF. Any machine that you consider but transformer is a static device. You fix it to one pole. There is no rotation part and henceforth we can also say that transformer efficiency is far far higher than any rotating machines because there is no rotational losses happening. Now anyway this transformer is present and how the EMF is produced because there is sinusoid time varying flux linking upon constant or immovable conductors.

Time varying flux touching upon the stagnant or stationary conductors produces an EMF which is known as statically induced EMF. And there is Faraday's law of electromagnetic induction which helps us to understand EMF gets induced which is minus n d phi by dt. So there is a rate of change of flux because input voltage is sinusoidal, time varying flux, current is sinusoidal, flux will also be sinusoidal, time varying. So now this EMF is been induced at the primary side which is called as self-induced EMF and the same flux which is produced due to the current flowing in the primary side is also linking the secondary side. And the EMF induced in the secondary side is known as mutually induced EMF.

Now the transformer the fundamental principle why it operates is mutual induction basically. Now there is EMF which is induced and then if you connect a load what happens? There is a current because there is a closed path again and there is a current which is flowing. Let us say this is I2. There is a current which is flowing and there is number of windings present at the secondary side. Then there is an EMF present at the secondary side as well that is N2I2.

Now because effect opposes the cause that is what Lenz's law suggests. So if because effect opposes the cause now cause is this flux because of which EMF is induced. Now the counter flux is produced such a way that it would oppose the cause. So ultimately that EMF MMF produce in such a way the direction of current produces a flux which opposes this flux. Now because let us consider this is the main flux or working flux and there is another counter flux which is produced which opposes this main flux.

So we call it as N1. Now what happens if there is a let us assume there is a temporary reduction in the flux because there is opposition right. There is temporary reduction in the flux. Then what happens if there is a temporary reduction in the flux then E1 will also reduce because E1 is depending upon the flux main flux. If E1 reduces but voltage source is fixed there is an additional current which is pulled because there is a voltage difference now.

So E1 minus E1 dash. When additional current is pulled then again a net MMF increases at the primary side. So that additional current is known as I1 dash. So ultimately whatever is the you know MMF which is contracted from the secondary side will be compensated by the additional current which is been pulled from the primary side. So the net overall flux within the transformer core remains constant and steady throughout the operation of a transformer. Hence for transformer is also called as constant flux machine right.

But there is some flux which is present. There is some flux which is present. So that means we can assume that and because this flux is I mean produced because of the inductive nature because coil is present there is some reactive current which is been taken right. So that means they always absorb some reactive power regardless of their loading, some flux will be there because to establish the working flux. So this is what we understand from transformer.

So I just gave a overview of why this transformer is we cannot ignore the reactive power consumed by the transformer. It will be present. Then synchronous machines. When over excited they generate reactive power and when under excited they absorb the reactive power.

It is very simple right. When you over excite that means in there is a field winding because unlike induction machine synchronous machine is a doubly excited machine right. So there is a field current also there is a if you see there is a machine there is a stator and a rotor. To the rotor there is also a field winding which is connected right. There is a field source which is connected. So because of there is a current which flows through the windings present in the field circuit.

So we call it as IF is equal to VF by RF. This is the current because of the field current by varying the field current you can vary the excitation or the reactive power control can happen. When you over excite means what? There is a impedance there is a control actually. Let us say there is some rheostat for time being. So by varying this resistance you can vary the current. When you have to increase the reactive power from the synchronous machine generator what you need to do? You need to increase or reduce the resistance.

Reduce the resistance the current will increase. When current increases then there is over excitation. Then there is increased voltage right. So that means there is better ability to cater to the reactive power requirement. Henceforth if more inductive loads coming up then what they do is to maintain the voltage profile same at the nominal value they would increase the current or reduce the resistance at the field circuit.

And the other way around. If let us imagine there is high capacitive load or Fahrenheit effect or whatever reasons then you need to reduce the current by increasing the resistance at the field side. And everything is depending upon these expressions. It is very well known expressions. Active power depends upon the phase angle difference between two buses. Here there is a bus E at delta to which you are connecting a synchronous machine and there is another bus V at an angle 0 whatever.

So here delta assuming it to be greater than this 0 it is a positive number basically. So what happens there is a phase angle difference and because of which there is active power flow which is happening from the synchronous machine to the load. And similarly there is a reactive power flow and that depends upon this expression. If E cos delta is greater than V magnitude is what important. If E cos delta is greater than V then what happens there is let us say this is a slack bus for just for our understanding or whatever.

And this is some other bus. And then whatever is the voltage at this bus if it is higher than the voltage present at the receiving end bus then the reactive power flow would happen from the sending end bus to the receiving end bus. That is what we are saying. So it is magnitude of voltage which dominates the reactive power flow and the difference in phase angle which dominates the which active power. Now automatic voltage regulator tries to keep the terminal voltage constant and there is maximum armature current limit also. It is not like you know you have infinite capability to exercise.

So there is a limit ultimately it is driven by this expression P square plus Q square is equal to the overall apparent power capacity V into I maximum square. So there is some you know boundary limits. You can see here there is some boundary limit for the reactive power and real power inflow. Every machine has its own boundary and it depends upon rotor winding limited because when you reduce the resistance there is a limit to which you can reduce also because if current exceeds so much then the winding may burn up.

So that will lead to damage of the synchronous machine. You cannot allow that. So similarly the stator winding limits how much current the stator conductors can carry that depends upon the conductor size and other things. So there is a steady state limit and but you can see here both over excited region and under excited region it can operate in these two quadrants. It can observe and what do you say generate or inject reactive power also. So ultimately you see here during over excited system what happens active power this is megawatt you see here this is a unit for real power flow.

This is flowing from generator to the system. Let us consider it should be infinite grade and reactive power flow also is happening from generator to the system. And can somebody tell what is the operating power factor of the synchronous machine synchronous generator at this point of time. When the machine is over excited when a synchronous generator is over excited what is the operating power factor of the synchronous generator to the system lagging because the load is hungry for reactive power. The synchronous generator react operating power factor would depend upon the operating the sort of load is being connected. If load is hungry for reactive power it is injecting reactive power that means it operates as lagging power factor.

Let us say if load is capacitive load then what happens in order to maintain the voltage profile constant the machine would given a command with this in a closed loop control will be there AVR automatic voltage regulator in order to reduce the current then machine would go to under excited zone. Under excited operation means there is someone who is already injecting reactive power in the system and you calm down you reduce the reactive power injection. In other way the machine may be absorbing reactive power to maintain the voltage profile constant. So that means it will operate in a leading power factor zone because load is capacitive Now as I told field current is limited to a maximum value and so is the field voltage right.

Hence EV by XS is a constant term.

$$P^2 + (Q + \frac{V^2}{X_s})^2 = (\frac{E_{max} V}{X_s})^2$$

So and there is also end heating effect at under excitation there may be large amount of flux entering the stator core in a perpendicular direction. This causes increased eddy current losses also right. Then there is another device which is known as synchronous condenser. This is nothing but synchronous motor.

Let us discuss this a little bit. So before the recent advances static power compensator technique synchronous generator were after used a power factor correcting devices basically. It is a power factor correcting devices often adopted by industries because they have to pay high penalty if they do not manage their own reactive power. If they are dependent upon the sources generating sources and let us say there is a far distance and you have to pull the reactive power from a very long time and increases the losses and you are occupying the whole corridor transmission corridor. So there will be high penalty imposed on these customers.

So what they do is I need reactive power. Let me manage my own reactive power with my own equipments. So this synchronous condenser is very important equipment. The over excited synchronous machine works as a source of reactive power. It shows the phasor diagram and then since no real power is being supplied and angle between A and B is 0.

Basically they do not deal with the active power. They just manage their reactive power. And it is dynamical. It is not like static because the machine is rotating. It is dynamically varying the reactive power basically.

And it is nothing but a capacitor basically. It behaves like a capacitor. At no load over exit synchronous machine works as a capacitor hence the name synchronous condenser. What are the advantages? As wide range of field control can work as a shunt reactor when under exit. So both quadrant operation is also possible.

It can inject or absorb the reactive power basically. Disadvantage is increases short circuit capacity of the system because there is a rotating machine present. So if there is a fault they would also inject because you cannot suddenly control. There is a rotating mass inertia is there. So they will contribute for the fault current. That means the protection equipment the breakers and all their capacity need to be augmented.

Yes. So falling out of step with sudden changes in voltage. So loss of synchronism stability issues because synchronous machine wherever it is there rotor angle stability will come into play all these things. And availability of cheaper static compensator. There is it is not it is very cheaper solution as compared to the static compensators. And there is another device which is called as shunt reactors.

It is exactly opposite to the shunt capacitors. So what it does shunt reactors are used mainly to compensate the effects of line capacitance. So we basically play with these things R, L, C. If L is I will try to bring C to manage it if C is I will try to bring L to manage it. So that is where we play. So if there is high line capacitance you use inductors to sort out the issue that is it.

So particularly at low loads to limit over voltage if C is I because of Fahrenheit effect then you need to have some device which can consume the reactive power and the shunt reactors are brought into place. So they are usually required for extra high voltage line longer than 200 kilometres because where the Fahrenheit effect is more prominently seen. Yes. So a shorter overhead line may also require a shunt reactor if it is connected to a weak system if bus is weak and if due to some reason if there is a chance of high voltage then at the receiving side then you may have to adopt this. In case of an open circuit in the receiving end line charging current will increase E s significantly due to the large reactance.

The Fahrenheit effect there will be more prominent at the open circuit end. A shunt reactor may be prominently connected to the other end of the line connected to a weak system to limit the over voltage that is the essence. And there is shunt capacitors. They are usually they are used to supply reactive power and boost local voltages basically. They can be connected to a system either permanently or via switch.

There will be something like switch capacitor banks. You might have heard this is one of the very important you know. As reactive power compensating devices adopted widely across the system. So there is a combination of capacitors which are connected and as per the requirement they would get connected. Henceforth they are considered to be a switch capacitor banks. So permanently or via switch most of the industrial and commercial loads draw power at a lagging power factor because the whole transmission system is hungry for reactive power.

So shunt capacitors are more often seen than shunt reactors basically. Their requirement is more prominent in the system because you need to compensate for reactive power lagging reactive power. So shunt capacitors can be connected near the load to correct the power factor. We call it as sometimes you know there is also called as PFC right. You might have heard this power factor correction devices.

They are nothing but capacitors itself either connected in delta or star fashion. So because there is a penalty from Indian government if you do not operate power factor at least at

0.8 lagging right. So you have to pay the penalty. So what they do is they put these capacitors so that they would manage the minimum requirement of 0.8 power factor. So the main disadvantage of shunt capacitors is that their production of reactive power is proportional to the square of load because it is a shunt device. Any device which is connected to a shunt means between the line and the ground we call it a shunt device. So their operation and the power handling capacity is depending upon the voltage. Any series device it depends upon the current right.

The power is expressed in terms of current. Now what happens is whenever there is a reduction in the voltage due to some reasons if there is a drop in the voltage in the system because this capacity of the capacity of the capacitor banks also depends upon the voltage profile their net capacity will also reduce. Ultimately it is V square by XC right. So power is something but V square by XC. If V reduces then it drastically reduces the power handling capacity of these capacitors.

But at the same time that is the most essential time where you need to support the system. So this is one of the disadvantages of shunt capacitors. And there is another device which is known as series capacitors. So series capacitors are connected in series with the line conductors to compensate for the inductive reactance of the line. If because there is a high inductance present because ultimately P is nothing but EV by XS sin delta right.

Now if you reduce X for the same angle you can increase the power handling capacity right. Or in other way around if the delta need to be reduced you can reduce the delta also by simultaneously also reducing the XS. That means you can improve the power system stability. If delta reduces for the same power handling capacity, same power carrying capacity you can play around with delta and XS combination so that you can improve the system stability. Now suppose series capacitor is more often termed as stability improvement device actually right. So this reduces the effective reactance of the line and increases maximum power transfer capability.

The power exchange capacity can be increased. It also reduces effective reactive power loss. But there are some issues also with series capacitors. During starting of large induction and synchronous motors series resonance may take place at a low frequency right. Resonance happens because C is there in the line, L is also there because of inductor induction motors. There at some point of time there could be resonance that may be happening that is a problem. The remedy is to connect suitable resistance in parallel to the capacitor and there is something called as hunting of synchronous machine where synchronous rotor the rotor of a synchronous machine oscillates upon its equilibrium position.

It is not a good idea so to operate. So especially at light load due to high R by X ratio of the feeder and there is also issue with fault in the system. So because you just imagine if there is a fault and now because of series capacitance there is a reduction in the reactance, net reactance that is good during steady state operation because it that will improve the system stability and active power capability of the system. But during fault already there is less resistance in the flow of current. Now it will increase the fault current because of the presence of series capacitor.

They are rarely used in the distribution systems basically. However use of series capacitors in extra high voltage line is quite common since they help in economic loading of the line. So there sometimes they will also use this, I am just you know helping you understand how they would reduce, how they would solve these issues. There is something called as peer gap that may be also used if series capacitance is very much essential. There is something called as peer gap. What they would do is during normal operation that this peer gap is inactive and during fault condition this peer gap would start conducting.

So it would bypass the capacitor basically. So this is another thing that is used. So static wire systems. Static wire systems consist of static wire compensators, SVCs and mechanically switched capacitors or reactors. SVCs are shunt connected devices that have a static wire generator. The term static signifies the fact that there is no rotating component associated with SVS. A SVS can be taken as a combination of shunt capacitor and shunt reactor both of which can be controlled.

It is not only shunt reactors required at sometime it may be required shunt capacitors. Now you put a device which can you know have the combination of shunt capacitors and reactors and based on the requirement you activate any one of them or combination of them to maintain the system stability or system operating conditions. So ideally an SVS should be able to hold the terminal voltage.

So next device is known as STATCOM. I will just put it. Static synchronous compensator. It is a very quick operating device. It is nothing but you know a power electronics operated device or there is a point of common coupling there is a voltage line is there. What basically we do is of course there is some impedance.

There is some impedance present. What they basically connect is power electronics based switches. Let us say voltage source converter. So what they do is by switching these switches and by controlling in such a way that you can either inject reactive power or absorb reactive power based on the requirement. And because switches operate at a very high switching frequency, high switching frequency in terms of kilohertz. So if switching frequency is high the operation time will be very less in terms of milliseconds.

So switching frequency in terms of kilohertz so operating time will be in terms of milliseconds. So they can operate very instantaneously meeting out the requirement. If there is a sudden requirement of reactive power they can able to inject reactive power.

Henceforth we call it as fast acting devices, fast acting reactive power compensating devices. So I mean I will discuss some case studies how if there is a combination of slow acting reactive power device and fast acting compensating devices how they would how we can able to manage both of them so that we can able to meet out the expectation of the system during various operating scenarios. And then we will discuss about varieties of real time simulation tools and various case studies probably in the next class. Thank you very much. .