Course Name: Power Electronics Applications in Power Systems

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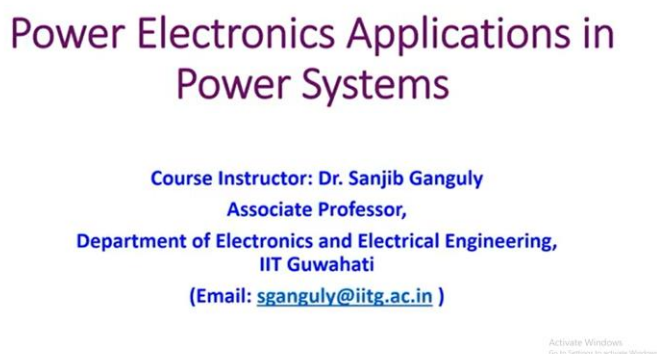


Lec 14: Thyristor controlled reactor (TCR)

Welcome again to all the learners to my course Power Electronics Application in power systems. So, in last few lectures, I discussed the basic requirement of power system compensation. Compensation means it is a reactive power compensation I am talking about. And you have seen that how a reactive power compensation at the midpoint of a symmetrical lossless long transmission line can be helpful in mitigating the over voltage as well as under voltage. Also we have learned that how a midpoint compensation for a symmetrical lossless long transmission line also helps in enhancing the power transfer capacity or by how it increases the power flow through a power transmission line. Those examples I have discussed with numerical examples in the last two, three lectures.

So, in this lecture onward, I will start the first type of power electronic compensator which are used widely in power system that is SVC that is called static var compensator. Let us see what it is. So, we will start static var compensator. So, what is static var compensator? It is, it is acronymed as SVC.

Now, what is static bar compensator? It is a shunt connected device. It is a type of shunt compensator. So, in the last lecture, I discussed how a shunt compensator impacts on power flow of a symmetrical lossless short transmission line. Now, if you want to model this type of shunt compensator. One example is SVC, that is static power compensator.

It is a power electronic based device. Now why it is power electronic based device, what it does, in which application of power system it is used, all these things I will discuss in very detail. This particular topic will continue in many lectures in the coming days. So, what is this static var compensator? So, it is a type of shunt compensation. Now, it is also a type of a device which uses the semiconductor switch or power electronic switch.

So, its basic schematic diagram, basic single line schematic diagram can be drawn like this. Suppose this is the bus at which this SVC is placed. It can also be the midpoint. So, what it has, it has a bidirectional switch or thyristor like this and it has a reactor. So, its single-line diagram is something like that of SVC.

What it has actually? It has a bi-directional switch, one is this, this is one switch, let us say SW1, this is another switch that is SW2. Then what are the purpose of these switches? These switches, you know, the difference of normal switch and a semiconductor switch is that normal switch can either be turned on or turn off, but the semiconductor switch can be turned on, can be turned off or can be partially turned on, that is what the difference is. And here also these two switches whatever is shown in the figure, they can be either fully turned off or they can be partially turned on. Now there are various types of this SVC, there are various types of SVC. The first one I will discuss that is called thyristor controlled reactor.

The first one which I will discuss, which will be discussed is TCR that is Thyristor Controlled Reactor. So whatever single line diagram I have drawn this is basically a type of TCR. So, this is a TCR type of SVC. So, what is the purpose of this TCR? TCR is a basically control reactor. Now, what is the purpose of having a reactor in a power system? A reactor you have seen that a reactor normally is used to absorb some amount of reactive power from a power network or power system.

Now what is the benefit of absorbing some amount of reactive power? You have seen I discussed this with numerical example that during light loading condition there is a surplus of reactive power due to the reactive power generation of the line capacitances and due to the less reactive power absorption by the load. So when we have a surplus of reactive power, so voltages of the line will get increased and the line will suffer from overvoltage. So, this is I discuss in my previous lecture. Now, during that time, we need some device which can absorb certain amount of reactive power, thereby it will mitigate the overvoltage. This is what exactly is done by using TCR.

So what this TCR does, it absorbs certain amount of reactive power from the bus at which it is connected. Suppose this is the bus at which this is connected. So this is what a line reactor. So at this bus, suppose this reactor is connected. So, what this reactor will do? Reactor will draw certain amount of reactive power from the bus. It will draw certain amount of reactive power from the bus and thereby it will help in mitigating the overvoltage. In normal power system in India, if you visit in several power, regional power grid, you will see we already have some fixed type of reactor at various locations, strategic location power grid, regional power grid. The purpose of those fixed reactor is to mitigate the overvoltage especially when there is a light loading condition. When the power grid is operating at light loading condition, this happens normally during midnight when we have a surplus generation from our thermal power plant, but we do not have that much of load demand. So there is a eventually gap of this load and generation and which causes certain amount of overvoltage.

And that overvoltage need to be mitigated by somehow, otherwise this overvoltage may cause serious problem of the line insulators and the associated accessory devices. So, here this TCR is a control reactor as I, you can see the name. It is a control reactor. So, the difference of the fixed reactor and the control reactor is that, this fixed reactor either you can turn on and turn off. The control reactor you can turn on, you can turn off, also you can partially turn on.

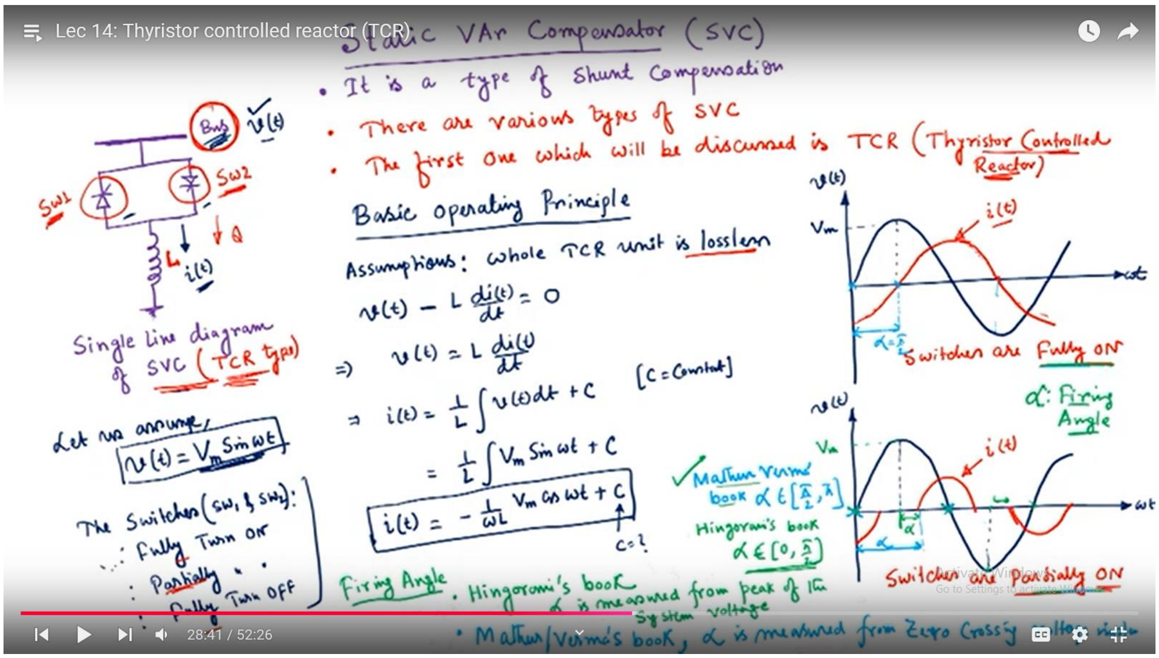
Now, what is the need of this partial turn on? You know that load throughout this power system is varying in nature. Load never be a fixed. So, sometimes load is very light during midnight, sometime load demand reaches to the peak value. For example, right now in India, it is a scorching summer. So, peak demand during evening, is very, very high, so extremely high.

So, but during midnight it is relatively less and so load is changing throughout a day with the season also. So, during this summer in the country like India is having peak demand, during winter our demand used to be less. So, load is a parameter which is always changing, it does not remain same. So, therefore, when the load is changing, the voltage conditions of the line will also get changed. Sometimes it, you will see there is an overvoltage, sometimes there is undervoltage as well.

So, we need the mitigation of both overvoltage and undervoltage. Now, depending upon the amount of overvoltage there in the network, this TCR can be controlled to operate so that we can mitigate that overvoltage. But if you keep it a fixed reactor, then this same reactor may cause serious undervoltage during peak load condition. Those things I hope that you should understand. Now, this is what the single line diagram of a TCR.

Now, what we will do is that we will draw this operating principle. So, basic operating principle. Basic operating principle. So here we will take assumptions, here also our assumptions will be, these assumptions we will consider throughout the course that the whole unit is lossless. So whole TCR unit is lossless.

Now, suppose this voltage at this particular bus is represented by this Vt, voltage at this particular bus is represented by Vt, so Vt represents instantaneous voltage of that particular bus. And the current flowing through this particular reactor is supposed I of t. So I of t is basically represents the instantaneous current. Now how this V of t and I of t they are related to each other? So, you know that if we apply KVL over this particular single line diagram or this particular network, then what we will get? This V t, V of t is minus this voltage drop due to this line, this line inductance, which is L di of t dt is equal to 0. So, what we can write that V of t is equal to L di of t dt.



Now, let us consider, let us assume that we have purely sinusoidal voltage source, which is represented by some peak voltage or maximum voltage V m sine omega t. So, here omega is your supply frequency, power frequency, V m is the peak value of this voltage. So, this is our source voltage or the voltage at this particular bus, at this particular bus, at this particular bus, where this, your TCR is connected. So, if you apply this, then what we will get? We will get, we can find out I of t is equal to 1 upon L integration of V of t d t. Now, there should be a constant if it is not definite integral.

So, what we can write, if we put this v of t over here, so then this will be 1 upon L integration v m sin omega t plus a constant, where c is an arbitrary constant, c is an arbitrary constant. Now, so this we can write it as minus 1 upon omega L V m cos omega t plus constant. So, this is what the expression of I of t. Now, what is I of t? I of t is the instantaneous current drawn by this TCR. So, here we just represent a TCR like a reactor where we have semiconductor switch connected, which is a bidirectional.

So, both sides of this voltage waveform, positive and negative sides, this can conduct. And therefore, we get an expression of the current flowing through this TCR from that. Now, what is to be done? We have to find out this arbitrary constant C. So, we have to find out the expression for C and we have to put it over here. In order to find out this constant C, what we have to do? We have to apply a boundary condition.

<u>Basic Operating Principle</u>

Assumptions: The whole TCR unit is lossless.

$v(t)$ = Instantaneous voltage at the particular bus to which TCR is connected

$i(t)$ = The instantaneous current drawn by the TCR

Applying KVL, $v(t) - L\frac{di(t)}{dt} = 0$

$$\Rightarrow v(t) = L\frac{di(t)}{dt}$$

Let us assume, $v(t) = V_m sin\omega t$ [V_m =Peak value of source voltage $v(t)$ and

ω = Power frequency]

Now, from Eq^n (2), $i(t) = \frac{1}{L}\int v(t)dt + C$ [C = Arbitrary constant]

$$= \frac{1}{L}\int V_m sin\omega t.dt + C$$

$$i(t) = \frac{-1}{\omega L}V_m cos\omega t + C$$

Now before I apply this boundary condition, let us see that how would be the voltage and current waveforms when you have this type of TCR unit connected to a particular bus. Now suppose we consider this supply voltage or voltage at the bus at which this TCS is connected is a sinusoidal source. So I can draw it. So suppose this is V of t, so it is basically represented a perfect sinusoidal voltage source. So this is what the V of t with respect to t or omega t.

Now this peak value of this is basically Vm. Now, let us assume that we have, as I said, these switches, these switches or I should write it here, the switches that are SW1 and SW2 either can be fully turn on, fully turn on or they can be partially turned on or they can be fully turned off. So, these are the three different modes of operation of the switches. Now, let us consider the switches are fully turned on, then what would be the waveform that you will get, this current waveform. So, if these switches are fully turned on, Then there would be a 90 degree phase angle difference when you have apply a voltage, purely sinusoidal voltage source across a pure inductive load or pure inductive element.

So here we assume that there are no losses, the unit is lossless. So only this reactor is having some inductance and when you have so, so As you know, if we apply a sinusoidal voltage across an inductive element, so it will conduct and this current will lag pi by 2 with respect to supply voltage. So that is what the waveform of the current. So this is what the waveform of the current when these switches are fully on. This is when the switches are fully on, fully turned or fully conducting.

So, that is what the, you know, plot of this voltage current or the voltage current waveforms of a TCR unit. It is very simple to understand for electrical engineering students. Now, what will happen when it is a partially turn on? So, let us draw this waveform once again. So, when the switches are partially turned on, this is supposed V of t, this is omega t, so this is the sinusoidal voltage source and this is what the peak value. So, when these switches are partially turned on, then how would be the waveform? This waveform will be something like this.

So, something like this. So, these are the waveforms for I of t when switches are switches are partially turned on, partially, partially on, let us write, partially on. So, that would be the voltage and current waveforms. So, that would be the voltage and current waveforms. And when they are off, you know that this, this waveform will come to this point and it represents, there is no IFT, IFT is 0. So, that is what the three different modes of operation of switches and since this TCR, it is a control reactor, so it is expected that it will be always, its turning on would be always controlled.

Now, the question is who is basically controlling this turn on of this particular switches? Here is a concept of firing angle. So, those who have a basic understanding of power electronics systems, they know that there is something called alpha. Alpha is called the firing angle or delay angle, which is basically controlling the turn-on instants of the switches. Now the question is how do we measure this or what is this particular firing angle from where to measure? Now here there is a difference. In different book they use different instance to measure this firing angle.

So, here basically I followed two different books. One is Hingorani's books, another is Mathur-Verma's books. So, this firing angle in Hingorani books, in Hingorani book, if you follow this Hingorani's book, it is a legendary book, then you will see this firing angle is measured from alpha, this firing angle, it is represented by the Greek letter alpha. So, here you will find alpha is measured from peak of the system voltage. So, what does it mean actually? So, here you see that this is the peak of that system voltage and this is the negative peak.

So, alpha is measured from this point, from this instant. So, here for this particular diagram, according to this Hinger and his book, alpha is this So, alpha is the angle measured from the peak value either positive peak or negative peak of the system voltage or of the voltage of the bus at which this TCR is connected. But if you follow this Mathur Verma s book, Mathur Verma s book. then you will see alpha is measured, alpha is measured from 0 crossing voltage, 0 crossing voltage instant. It means that according to this Mathur Verma's book, this is the zero crossing voltage, this is also the zero crossing voltage.

So, this is zero crossing and going to positive side, this is zero crossing going to the negative side. So, according to the Mathur Verma's book, so this is the measurement of alpha. So, if you look at this fully turn on condition, so I cannot show this value of alpha when we have this Hinger and his book because alpha is equal to 0 because it is measured from the peak value of the system voltage. It is measured from the peak value of the system voltage. However, from this in Mathur Verma's book, it is saying that since it is measured from the zero crossing voltage, so alpha is this, for this, according to the Mathur Verma's book.

Now, if it is so, then what would be the range of this alpha, what would be the range of this alpha? So, for Mathur Verma's book, Verma's book, alpha, the range of alpha is from, pi by 2 to pi. Because you know you can see that when at this instant when the thyristor is fully turn on alpha is equal to pi by 2 and for this partially turn on alpha is greater than pi by 2 and when it is fully turn off then alpha is equal to pi. So, that is what the range of the alpha according to the measurement if you follow the Mathur-Varma's book. However, in Hingorani's book, in Hingorani's book, Hingorani’s the range of alpha is equal to, so here you can see here alpha is equal to 0 which corresponds to the switches fully turn on.

So, alpha will belong to 0 to pi by 2. And here you can see the alpha, when alpha is equal to pi by 2, this, it is fully turn off. So, the variation of alpha according to Hingorani s book is 0 to pi by 2, whereas this variation of alpha or firing angle according to Mathu Verma s book is from pi by 2 to pi. So, either of this convention is to be followed. So, here I will follow this Mathur-Varma's convention. That means that we will consider that alpha is measured from the zero crossing voltage.

That means when the voltage waveform crosses zero voltage. So, you can see this happens once before it goes to positive, it happens another time when it goes to negative. And then it gets repeated because you know that all these voltage current signals are of periodic signals. Now, we will find out the expression of this arbitrary constant C by putting the boundary condition. So, what would be the boundary condition I should put? If we follow this Mathur-Varma's convention, that means alpha will start from this pi by 2 and it will go up to pi.

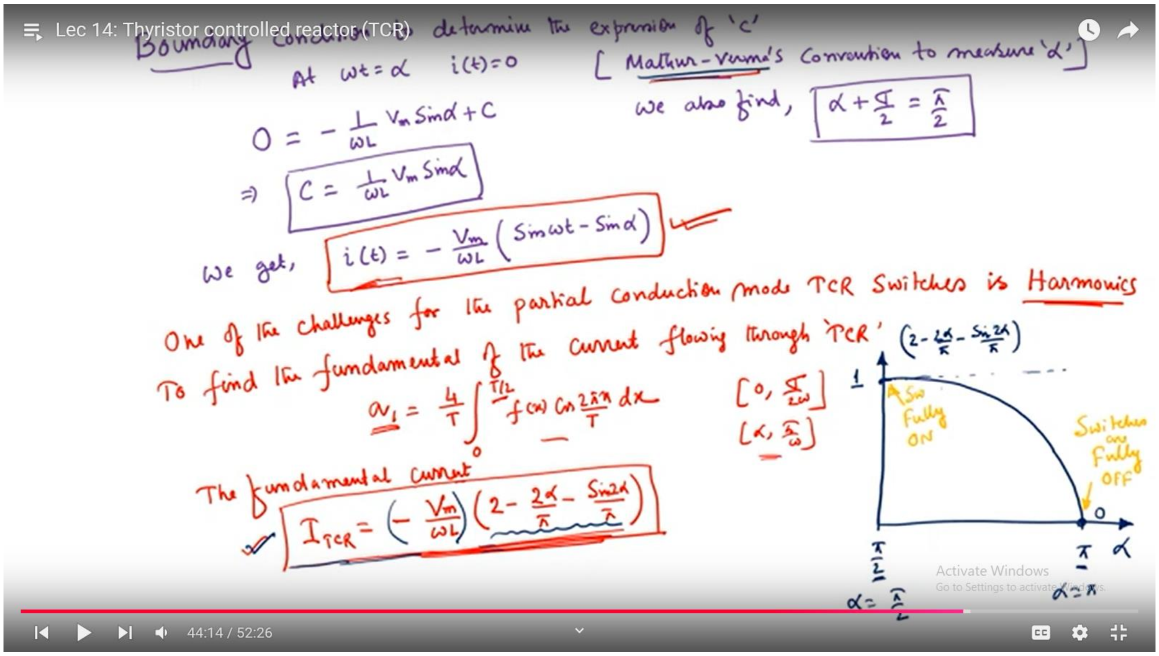
So, that means when you have this, this, this omega t is equal to alpha, omega t is equal to alpha, then you can see that according to this Mathur Verma's book, the current will start from 0. So, that means the boundary condition I should use, the boundary condition to determine the expression of the constant c. So, what boundary condition we will put that at omega t is equal to alpha i of t is equal to 0. This convention is according to Mathur-Verma's convention of measuring alpha.

Mathur-Verma's convention to measure alpha. So, we will put this into this equation and then we will find out this expression of this C. Before that I should tell another angle that is also used in this TCR when it is partially conducting or maybe fully conducting that is basically called this angle sigma. the Greek letter sigma represents the conduction angle, conduction angle. Alpha represents the firing angle and sigma represents the conduction angle. So, this is what sigma, and in this case, this is what the sigma is and so on.

Now, there is a relationship between alpha and sigma. What would be the relationship? You can see that alpha plus sigma by 2, that means up to this point, so this will represent alpha plus sigma by 2, this is nothing but the representation of angle pi by 2. So, many times we need to use this in order to find out various expressions. So, we can write, we also find the relationship alpha plus sigma by 2 is equal to pi by 2. So, this is where alpha is a representation of this firing angle, and sigma is the conduction. So, the firing angle plus half of the conduction angle is basically their summation is equal to pi by 2.

Now let us put this expression over here. When you put omega t is equal to alpha, i of t is equal to 0. So if we put it here, then this expression, then what we get? Left-hand side 0, right-hand side minus 1 upon omega L, Vm sine alpha plus c, that is equal to 0. So that means that c is equal to 1 by omega L V m sin alpha. So this is what we get from this boundary condition. But remember this boundary condition we use the convention of this Mathur-Verma where alpha is measured from the zero crossing instant of the supply voltage or source voltage.

Now, what we will do? We will put this expression over there. If you put this expression over here, then what we get? We get I of t is equal to minus Vm divided by omega L multiplied by sin omega t minus sin alpha. So, this is what the relationship that we obtain. Now, what is that relationship? This is the expression of the current flowing through this TCR when it is operating either fully conducting or partially conducting or even non-conducting. So, you can put the values of alpha appropriately, we will get the equation valid. Now, what we will see from the equation? What is the challenge of this particular, this current waveform that we get for NTCR? The main challenge you can see is that this I of t, unlike this V of t, is non-sinusoidal.



<u>Boundary condition to determine the expression of "C"</u>

At $\omega t = \alpha$; $i(t) = 0$ [Mathur-Verma's convention to measure]

Using the boundary condition,

$$0 = \frac{-1}{\omega L} V_m cos\alpha + C$$

$$\Rightarrow C = \frac{V_m}{\omega L} cos\alpha$$

Now, substituting the value of C we get,

$$i(t) = \frac{-V_m}{\omega L}(cos\omega t - cos\alpha)$$

But it is periodic, but it is non-sinusoidal, but it is periodic. Why it is non-sinusoidal? Because of this partial conduction or partially on mode of operation of the switches. However, when the switch is fully turned on, then I of t is of perfectly sinusoid. So, only this particular condition, when these switches are fully turned on, then you get the current perfectly sinusoidal. However, when there is a partial conduction mode of operation, then it is like a non-sinusoidal. Now, so therefore, when something is non-sinusoidal but periodic we can represent it in terms of Fourier series and there would be some harmonics exist and that is what one of the challenges.

So, one of the challenges, one of the challenges for the partial turn-on or partial conduction mode of TCR switches is harmonics. So, looking at this equation you understand that this is not a equation of a perfectly sinusoidal or perfectly sinusoid signal, but they are having some sort of harmonics. So, we need to find out this harmonics of this line current when we operate a TCR in partially conducting mode. So, we will find out this harmonics Also, most importantly that we need to find out the fundamental component of this harmonic current that is the line current flowing through the TCR reactor.

So, we have to find out also the fundamental. So, what is to be done? So, we need to have a harmonic analysis, also we need to find out the fundamentals. So, if we analyze it harmonic if we do this Fourier analysis then we will see that even harmonic should be not present because there will be half wave symmetry of this waveform that I have shown over here in this voltage-current waveform. So there would be no odd harmonic but there will be no even harmonic but there would be odd harmonics. So what is to be done is that what is the main challenge is to find out the fundamental So, to find the fundamental of the current flowing through TCR. What is to be done? We need to have Fourier analysis and as you know that we can find out this a coefficient fundamental a coefficient by 4 by t integration of 0 to t by 2 f cos 2 pi x divided by T dx.

So, in that way, we can find out the fundamental component of this coefficient A1. Similarly, we can find out this all odd harmonic coefficient also. And if you find out, then what we will get, the fundamental current fundamental current would be equal to I TCR. I am using this capital sign to represent the fundamental minus V m divided by omega L multiplied by 2 minus 2 alpha divided by pi minus sin 2 alpha divided by pi. So, this is I personally obtained through this, from this particular integration.

Now, the question is how do you do this integration? So, what you can do is that you can split this 0 to t by 2 into two this ranges, one is from 0 to sigma by 2 omega, this is one range. Another is from alpha to pi by omega. If you use this properly, then you will come up with this expression. Remember, if you follow this Mathur's Verma book, then there is a typo in a particular edition which I have followed. But if you do it, this integration correctly, you will be coming up with a fundamental current expression like this.

So, if you wish that I can show you in very detail how this integration has been done, but right now I am just leaving it for you to find this fundamental current from this particular expression from this particular waveform. So, if you do this intrication correctly, you will surely arrive at this fundamental current. So, from this fundamental current, what we will see is, that we can plot this fundamental current with respect to this alpha. So, let us plot this with respect to alpha. So, this is I of TCR, which represents the fundamental current flowing through the TCR and this represents alpha.

And as you know that we are following this Mathur-Verma's convention where the range of this alpha is pi by 2 to pi. So, that means we will keep this range from pi by 2 to pi. Now, simply if you use this particular expression in any language you know, for example, MATLAB or C++ or whatever, and if you plot this waveform, here I am just neglecting this negative sign, and if you plot this particular expression over here, then what we will get that this plot I am it is not ITCR plot rather it is the plot of this 2 minus 2 alpha by pi minus sin 2 alpha by pi. So, this is what the function which is a function of this alpha. So, if you plot this in MATLAB then what you will get the plot would be something like So, that means when alpha is equal to pi by 2, this expression, if you put alpha is equal to pi by 2, this expression would be equal, this will come out to be 1.

When alpha is equal to pi, then this would be equal to 0, this will be equal to 0. When alpha is equal to pi, you can verify from this particular expression that whether this is happening or not. Now, if you multiply this, this is nothing but a fixed multiplier. If you multiply this accordingly, you will get the plot of the fundamental current with respect to alpha. So, for any value of alpha which is in between pi by 2 to pi, you can find out what is the fundamental component that you will be getting. Of course, you can see when alpha is equal to pi by 2 that means, near to this region when alpha is equal to pi by 2, it is this I t is basically operating fully conducting mode that means, switches are operating in fully conducting mode.

The fundamental component is higher. However, when it is operating in partially conducting mode, so its fundamental value gets reduced and when you increases this alpha further like this, if I increase this alpha further, then let us what will happen? So, if you increase this alpha further, so you know the amplitude of this will also get changed like this and then it will be 0 when it is fully turned off. That means according to this Mathur-Varma's convention, if you consider this alpha is varying from pi by 2 to pi, if you keep on increasing alpha, that means you are going from fully conduction mode to fully non-conduction mode. That means here at this particular point, it is operating at fully conduction mode, fully turn-on. Here it is fully off, which are fully on, and which are fully on, of course that switches are fully on, switches are fully on and switches are fully off.

So, this is something that you need to understand. So, as we go in go on keep on increasing the value of alpha, you are basically reducing the fundamental current of the TCR. So, in many times we need that, when we have this slow change of this load, changing from this very light load condition to full load condition, we need this partial mode of operation of the TCR. For example, when this line is operating in light loading conditions, the thyristor switches should be fully turned on and then if the load keeps on increasing, load is kept on increasing, as this alpha value or this firing angle value should be increased, so that this var amount that the TCR is absorbed is getting reduced. So, that is how it will work. Now, what could be our remark? So if I summarize this whole analysis, then you will see that, so first of all, if we write this ITCR expression once again, so this is nothing but minus Vm by omega L multiplied by this 2 minus 2 alpha divided by pi minus sin 2 alpha divided by pi.

Now, if we consider that 1 by omega L, what does it represent actually? It represents, what is omega L? Omega L basically represents the reactance of the line. So, it is x L, if you represent the reactance of the, not reactance of the line, I should say it is the reactance of the reactor of the TCR. So, x L is TCR Now, what is 1 upon this reactance? This is basically B L. So, that is called TCR susceptance. So, the reciprocal of the reactance is susceptance. So, this can be written as minus V m B L multiplied by 2 minus 2 alpha by pi minus sin alpha 2 alpha by pi. Now, here Vm is always constant. But remember, if we consider it Vm, then basically this ITCR will represent the peak value of the fundamental things. Now, if you divide it by this root 2 both side, then that will represent this RMS component. Now, the question is, if we consider that this equation, then what we will see that basically this TCR is nothing but a susceptance, whose susceptance value is getting changed with this firing angle that is alpha.

So, that means, first remark will be TCR acts as a variable susceptance because this B L is not getting change, but the multiplier of the B L that is this will getting change according to this alpha. So, if we consider that overall susceptance of this is B TCR, then the B TCR would be equal to B L multiplied by 2 minus 2 by 2 alpha by pi minus sin 2 alpha by pi. Now you can see this B TCR is varying with alpha. So that is why we wrote that TCR acts as a variable susceptance.

Now we can write the susceptance of TCR changes with firing angle firing angle that is alpha. So, susceptance is changing of the firing angle. What would be third remark? Third remark will be in addition to the fundamental, there are exist in TCR current. So, in addition to the fundamental, there are various harmonics exist in TCR current. Those harmonics will, regarding those harmonics, we will discuss in my next lecture. But if we summarize up to what we learn is, if you look at, if we go back and look at work out, you can see that we are talking about SVC.

SVC is not a single device, rather it is, it consists of multiple different types of shunt compensating devices. And one of such device is TCR. Now, what is TCR? It is a thyristor control reactor. Now, what it actually works, it controls the current drawn by this particular reactor. How it is controlled? By controlling the turning operation of the switches, which are bidirectional switches available there.

Now, what is the advantage of having so? The advantage is that when we change the turn on operation of the switches, what we will see? We will see this TCR acts as a variable susceptance and its susceptance changes with this firing angle. So, rather if this susceptance is getting changed, so the current drawn by the TCR will also get changed.

So, as the reactive power absorption that is happening to this TCR also will get changed. So, that is what the whole means summary of this today's lecture. In the next lecture, we will see the harmonics, various harmonics of this TCR currents and the several remedial measures to mitigate those harmonics.

Also, we will try to understand the effect of those harmonics and then we will study the remedial measures. So, up to this, for this particular lecture, then thank you very much for your attention. Thank you.