Course Name: Power Electronics Applications in Power Systems

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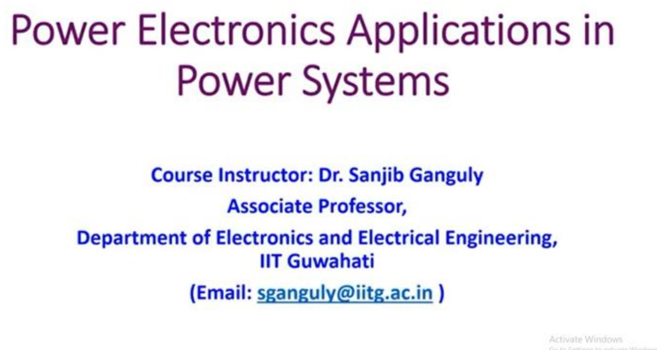


Lec 15: Harmonics in TCR and Three-phase TCR configuration

So welcome again in my course power electronics application in power system. In my last lecture, I discussed or I started discussion on this special type of power electronic compensator which is usually shunt connected compensator. It is a power electronic based and it is named as static var compensator. And I also discussed that the static wire compensator is not a single kind of device, it consists of a family of similar kind of compensators. Then, I started discussion on a specific type of static var compensator which is named as thyristor control reactor or TCR in short. Now, what is TCR? In TCR we have a bidirectional switch and this is connected to a reactor and this is connected altogether to a particular bus, wherever we are intended to locate it.

And if you look at this, my last lecture, I discussed the basic operating principle. I also discussed the voltage and current waveform under different types of switching conditions. And as I said, there are three different types of switching possible. One is the switches can be fully turn on or can be fully turn off or can be partially turn on.So, when the switches are of partially turn on, then we have this voltage current relationship, which is derived in this particular page. And you can see that this current waveform that is I of t, when these switches are of partially turn on are not sinusoidal, rather they are of distorted sinusoidal. So, when some signal is distorted sinusoidal, then we need to have the harmonic analysis, okay. And in my last lecture, I also derived or I also have shown you how to derive the fundamental component of the, this I of TCR. What is I of TCR? This I of TCR is basically representing the fundamental current drawn by this TCR when it is connected to a particular bus of a power system.

Now, this is the fundamental current and this figure shows you if we vary this firing angle alpha, how this particular fraction which is function of this firing angle alpha is varying. So, this fundamental current will vary according to this alpha. So, you can see it is function of this alpha and it will vary according to the firing angle. So, if we vary the firing angle, so fundamental component of this TCR current will vary, so as the other types of harmonics which exist in this TCR current, this will also vary. Now, so therefore, in today's lecture, I primarily discuss these harmonic characteristics of TCR. In particular, I will discuss how these three phase TCR look like and their harmonical behavior. So, in this particular lecture, we will discuss harmonic behavior, harmonic behavior of TCR. So, as I have shown you that the main reason of this harmonic current is the partially turn on condition of the switch of the TCR. And this is I explained in the last lecture as well. Now, we need to find out what would be the harmonic current that would exist in this TCR when it is operated as a partially conducting mode.

So, this harmonic current expression can be written as I of n alpha is equal to V divided by omega L multiplied by 4 divided by pi multiplied by sin alpha cosine n of alpha minus n cos alpha sin n alpha divided by n multiplied by n square minus 1. n is equal to 2k plus 1 and k a is equal to 2k plus 1. 1, 2, 3 and all this positive integer. So, if you put k is equal to 1, 2, 3, then what would be this n values? So, it would be 3, it will be 5, it will be 7 and so on. So, you can see all this odd order harmonics will exist in TCR current.

When this harmonics will exist, the TCR would be operated in partially conducting mode. And this partial conducting mode is the main control action that we can take in a particular TCR. So what we need to do is that we need to take care of or we need to mitigate some of these harmonics. Otherwise, the presence of this TCR will distort the line current wherever it will be placed. So, there should be some mitigation devices as well with this TCR which can mitigate that some of the dominant harmonics.

So, in order to mitigate this dominant harmonics, we will also see this how this three-phase TCR is constructed and taken care of. So, here we will also discuss the three-phase TCR. So, in the last example, in the last lecture, whatever I discussed, that is, this TCR is of a single-phase type. Now, as you know, our power system is essentially of three-phase. So, we need a three-phase TCR.

And three-phase TCR is constructed keeping in mind this harmonic mitigation as well. Now, we have to see that how different order of harmonics affect this line current drawn by this TCR and in which way we can mitigate them. Now, this TCR, this three-phase

TCR is constructed with, it consists of three identical single-phase TCR. So, three-phase TCR consists of three identical single-phase TCR and one single-phase TCR will look like this. This is what a single-phase TCR.

So, we need 3, this type of identical 3-phase TCR to construct a 3-phase TCR and whenever this 3-phase TCR is constructed, we also keep in mind the mitigation of harmonic as well to some extent. So, usually this 3 identical single-phase TCR are connected, 3 identical single-phase TCR are connected in delta. There is a specific purpose of keeping its construction as a delta, I will come to that. And apart from that, so each reactor is splitted into two halves to prevent full AC voltage appearing across the thyristor switches. Now, whenever this three-phase TCR is constructed, one thing we keep in mind that we need three identical single-phase TCR unit and they are connected to be delta.

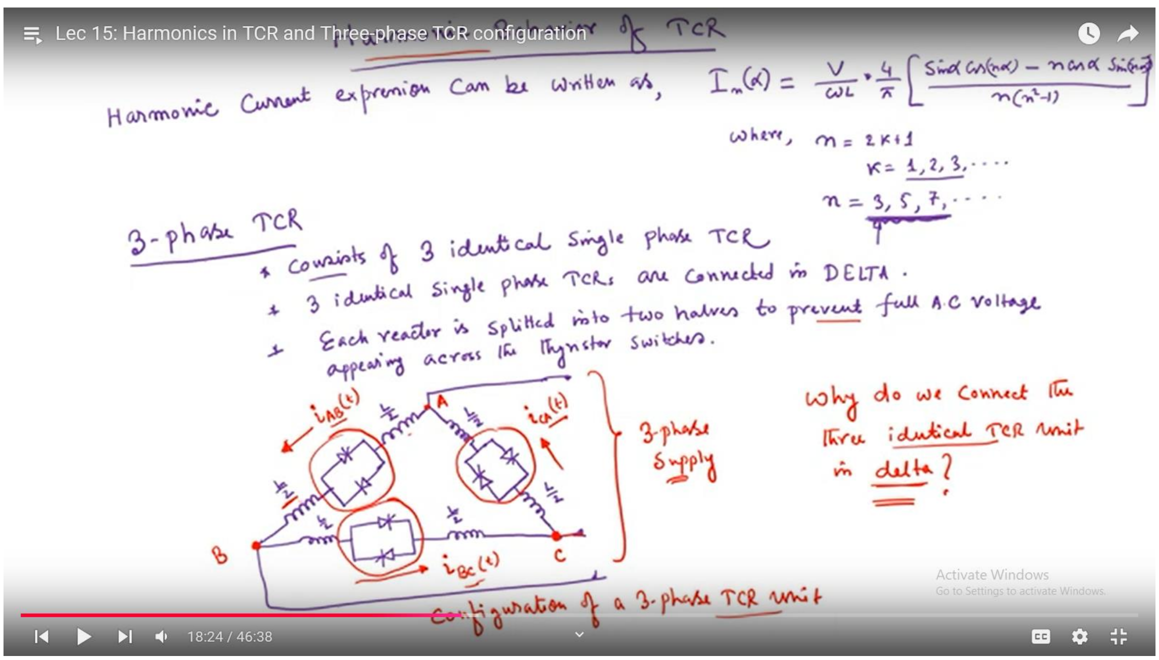
And unlike this single-phase TCR, this single-line diagram which I have shown over here, actually the three-phase TCR, what it does is that it splits this reactor into two halves and keeps it both sides of this bidirectional switch. It is something like that. Let me draw this. It will be understood then. So, one single-phase TCR looks like this.

This is a bidirectional switch. This is one half of the reactor, this is another half of the reactor. So, if this reactor reactance is x by 2 or if its inductance is let us say L by 2 and then this will be also L by 2. So, that overall this inductance of this reactor is L. Then this is one for one particular this TCR unit, then another TCR unit will be connected in delta with this like this. Here also this is inductance of this reactor is L by 2. Inductance of this reactor is L by 2 as well. And there is another single-phase TCR like this. This is bidirectional switch. This is the inductor and the inductance are half of this.

And now, these are connected to these three different phases. So, this is what, this is where we have three-phase, three-phase supply or the bus at which this 3-phase unit is placed. Now, look at this single line diagram. So, this is basically this not single line diagram, this is rather a configuration of a 3-phase TCR. So, configuration of a 3-phase TCR unit. Now, here you can see this is a bidirectional switch that is all a bidirectional switch and this is a bidirectional switch ok. They are in different this limbs of this delta connected 3-phase TCR unit and this is one half of this reactance and this is another half of the reactance. So, basically the reactance is splitted into two halves to prevent the full AC voltage appearing any of this thyristor switch at any instant of time ok. And this is how the configuration of the three-phase TCR. Now, the question is why do we why do we connect the three identical TCR unit in delta.

This is where we will try to find out that why this specific type of connection is, why not other type of connection possible. There are other types of connection possible, but usually this configuration is used. There is a specific reason. First of all, these three units should be identical, so that this whole TCR unit can act as a balanced source of reactive power. It is not a balanced source, I should say it is a balanced sink of reactive power because it absorbs the reactive power from the system.

So, if any unit is of different rating and then the absorption of this reactive power in all the three phases would be different. So, it will no longer be a balanced then. So, that is why we need three identical TCR unit to be connected. Now, regarding the specific connection that is delta, why it is so? I will come to that. In order to understand that, we need to go for harmonic analysis. And this is exactly is the goal of this lecture. Now, so as I said in this lecture, there are three different types of harmonics exist in the TCR current and we will discuss some of the harmonics. So, let us start with this third harmonics, where n is equal to 3. So, let us start with third harmonics. Now, how this third harmonics behaves? Suppose at any instant of time, the current drawn by these three, because you know that this configuration is drawing certain amount of current. Suppose this point is A, this point is B, and this point is C.



Then this unit which is connecting this point A and B, suppose it is drawing a current at any instant of time is A B, I A B of t, ok. And this unit which is connecting this point B and C, suppose it is drawing a current which is represented by I B C of T and this is drawing a current of I CA of T. So, look at this representation, this current I am representing in this small letter. So, and it is, these are time dependent. So, these are instantaneous current only. Now, we will analyze and as you understand that this IAB(t), IBC(t) and ICA(t), these are not perfectly sinusoidal, if we operate the switches in partial conducting mode. Now, when it happens, so we need to understand that there are some harmonics. So, we will try to understand the pattern of the harmonics and how these harmonics fundamental behavior are. Now, to do so, let us start with this triplen harmonics or third harmonics.

We call it also triplen harmonic. It is a kind of triplen harmonic. Now, suppose at any instant of time, this third harmonic is represented by i a b 3. This subscript c is representing the triplen harmonic. This is of t. Now, suppose it is represented by i 3 cos 3 omega t plus phi 3, where phi 3 is the phase angle difference. This phi 3 can be negative. It is, in fact, is negative. Then, this IBC 3 of t would be equal to i3, i3 is the peak value of this instantaneous current cosine 3 omega t plus phi 3 minus 3 multiplied by 2 pi by 3. Now, as you know that this fundamental component of three single phase unit, they are separated by 2 pi by 3 angles. So, this is known to us for a balance source. And if we have a balance load or in fact, we consider that this is a balance load, then this current drawn by the load will lag some angle and each of the current on different phases will be 2 pi divided by 3 angles apart to each other for fundamental component.

When it is a third harmonics, so they are 3 multiplied by 2 pi by 3 angle separated. So, when you have so, so this becomes this IBC 3 T becomes identical or equal with IAB 3 T. Similarly, ICA 3 T would be equal to i of 3 cosine 3 omega t plus phi by phi phi 3 phi 3 is the angle which is the separating or which is the angular difference between the voltage and the current drawn by this TCR and this is plus or minus 3 multiplied by 4 pi by 3. 3, either you can make it plus 1 multiplied with 3 2 pi by 3 or you can make it minus 3 multiplied by 4 pi pi, both the results will be same. Now, this will be also identical with this i a b 3. So, what we find over here is that, this third harmonic current are, currents are equal and in same phase, ok. So, that is, that this analysis gives us that this I a b 3, I a b of t is equal to IBC3 of t is equal to ICA3 of t. So, when it is so, then we can comment like this, that third order harmonic, third order harmonic current are equal and they are in same phase. When it happens so, then these currents are of additive.

3rd and Triplen harmonic current in 3- phase TCR

$$i_{AB3}(t) = I_3 \cos(3\omega t + 3\phi)$$

$$i_{BC3}(t) = I_3 \cos\left(3\omega t + 3\phi - 3 \times \frac{2\pi}{3}\right) = i_{AB3}(t)$$

$$i_{CA3}(t) = I_3 \cos\left(3\omega t + 3\phi - 3 \times \frac{4\pi}{3}\right) = i_{AB3}(t)$$

From above equations, $i_{AB3}(t) = i_{BC3}(t) = i_{CA3}(t)$

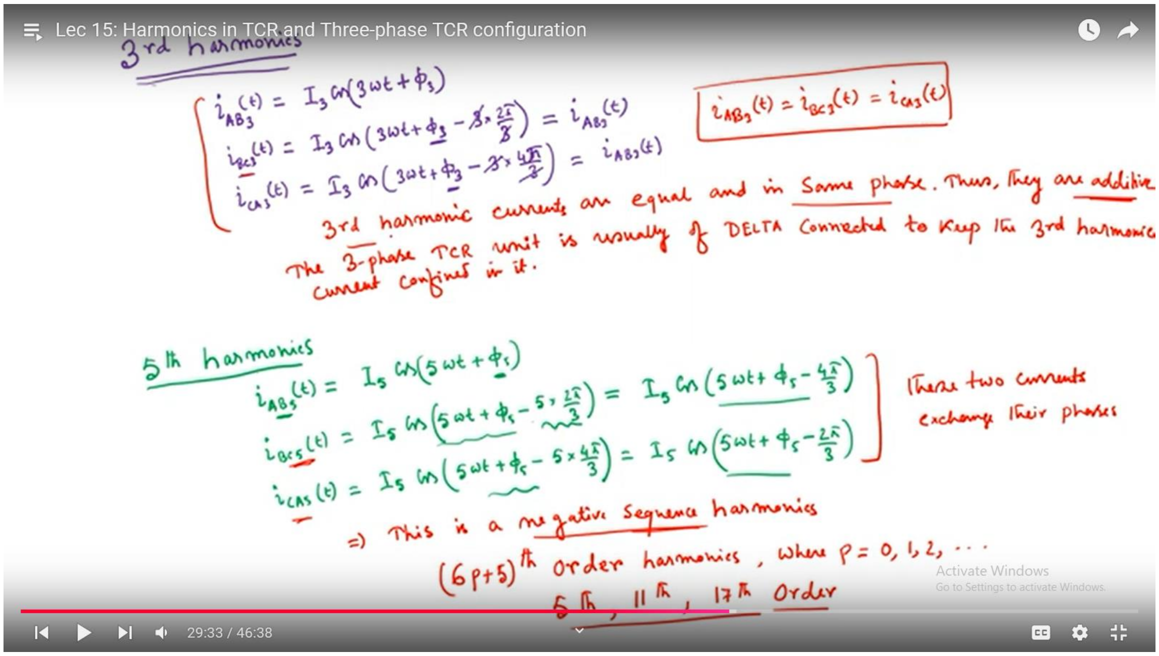
So, thus, they are additive. So, thus, they are additive. So, when they are additive, we can make a specific connection to confine it and that is exactly done by this delta connected circuit. So, this delta connection is primarily done to keep this third order harmonics or any triplen order harmonics to be confined within this delta link and this line current will be free from this triplen link. So, the three-phase TCR unit is usually of delta connected to keep the third harmonic current confined in it. So line is free from the third harmonic current.

And this will be true for any triplen harmonics or any harmonic which is of order of multiplied by 3. So this will be, this will happen for third harmonics, the ninth harmonics and so on. So, we can take the mitigation process to avoid the triplen harmonics which may appear in the current line current by constructing this three-phase TCR as a delta connected system. Then let us go for this next order harmonics which is of fifth harmonic. So, similar to this, if we consider that IAB5 of t, it is representing the instantaneous fifth order harmonic of any particular limb of this delta connected TCR unit, then let us represent it by in similar way, I of 5, it is the peak value of this particular current multiplied by cosine 5 omega t plus phi 5, where phi 5 is the phase angle difference between this current with the this similar order voltage.

Now, this I b c 5 t will be equal to I f 5 cosine 5 omega t plus phi 5 because we have considered identical 3 TCR unit and we also need to have this identical this firing angle control of this all this 3 TCR unit then we will have this which will be equal to 5 multiplied by 2 pi by 3 and not this. This and this i C A 5 of t will be equal to i of 5 cos 5 omega t plus phi 5 minus 5 multiplied by 4 pi by 3. Now, if you do this calculation, then you will be arriving at this is equal to i5 cosine 5 omega t plus phi 5 minus 4 pi by 3. And this is i5 cosine 5 omega t plus phi 5 minus 2 phi by 3. You try this, you split this 5 multiplied by 2 by phi 3 and then you do this further simplification, you will come up with this and similarly, if you do this, you will come up with this.

Now, what we can see over here is an interesting fact that here this I_{BC} 5 and I_{CA} 5, they are basically interchanging the phases, the phase sequence as compared to the fundamental current. So, that is why we call it the negative. So, this is a negative sequence harmonic. Harmonics, why it is a negative sequence harmonics? Because these two currents, they are, these two phases, these two currents exchange their their pages. So, that is why it is a negative sequence harmonic and this will be true for all this 6P plus fifth order harmonic and this will be true for all this 6P plus fifth order harmonic, where P is equal to 0, 1, 2, etc.

So, that means this will happens to be true for 5th order harmonics. Then if you put P is equal to 1, then it will be 11th order harmonics. And if you put P is equal to 2, then it will be the 17th order harmonic and so on. So, these harmonics are will be similar in nature and they are of negative sequence harmonic. So, we cannot do immediate mitigation procedure like this third order or triplen order harmonic.



5th Harmonic in 3-phase TCR

$$i_{AB5}(t) = I_5 cos(5\omega t + 5\phi)$$

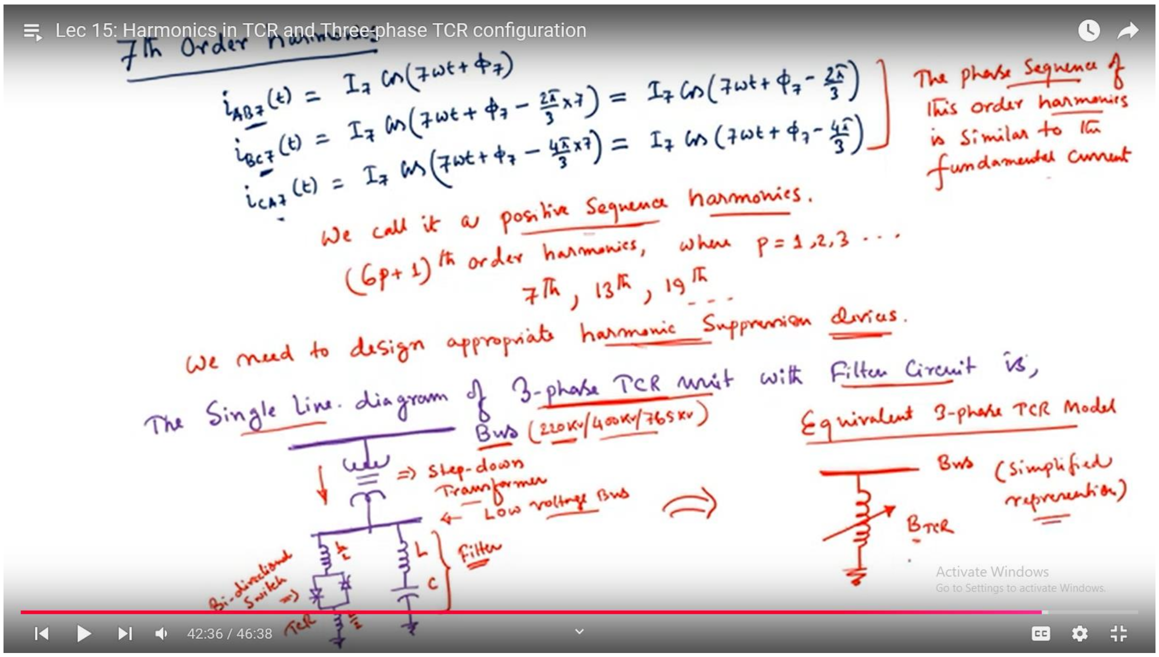
$$i_{BC5}(t) = I_5 \cos\left(5\omega t + 5\phi - 5 \times \frac{2\pi}{3}\right) = I_5 \cos\left(5\omega t + 5\phi - \frac{4\pi}{3}\right)$$

$$i_{CA5}(t) = I_5 \cos\left(5\omega t + 5\phi + 5 \times \frac{2\pi}{3}\right) = I_5 \cos\left(5\omega t + 5\phi - \frac{2\pi}{3}\right)$$

- 5th Harmonics currents results in change of phase sequence with respect to fundamental.
- Thus, it will rotate in reverse direction than fundamental component.
- In power system we call is **negative phase sequence**.
- Same will be true for any $(6p + 5)^{th}$ order harmonic. Where $p = 0,1,2,3 \ldots.$ (5th, 11th, 17th…………)

But what we need to do? We need to mitigate this harmonic and we should have some mitigation technique which can suppress this harmonic current. And then we will see that this needs to be, to have a filter which could should be designed to mitigate this order harmonics. Specifically this higher order harmonics so that that total harmonic distortion should be within the limit. Then we will go for next order harmonic which is of this seventh order harmonic. Now, in 7th order harmonic, if we analyze, then IB 7 of t is equal to, if we write it as a I of 7 cosine 7 omega t plus phi 7, where this phi 7 is the angular difference, it is negative in fact, then this IBC 7 of t is equal to I of 7 cosine 7 omega t plus phi 7 minus 2 pi by 3 multiplied by 7.

Similarly, i C A 7 of t is equal to i of 7 cosine 7 omega t plus phi 7 minus 4 pi by 3 multiplied by 7. And if you simplify these two, then what we will get as this will come out to be I of 7 cosine 7 omega t plus phi 7 minus 2 pi by 3 and this is I 7 cosine 7 omega t plus phi 7 minus 4 pi by 3. So, what you can see is that this phase difference between IAB and IBC is 2 pi by 3 and between IBC and ICE is again 2 pi by 3 and this is similar to the fundamental component. So, what we can write, so the phase sequence the phase sequence of this order harmonics is similar to the fundamental current.



<u>7th Harmonics in 3-phase TCR</u>

$$i_{AB7}(t) = a_7 cos(7\omega t + \phi_7)$$

$$i_{BC7}(t) = I_7 \cos\left(7\omega t + \phi_7 - 7 * \frac{2\pi}{3}\right) = I_7 \cos\left(7\omega t + \phi_7 - \frac{2\pi}{3}\right)$$

$$i_{CA7}(t) = I_7 \cos\left(7\omega t + \phi_7 + 7 * \frac{2\pi}{3}\right) = I_7 \cos\left(7\omega t + \phi_7 + \frac{2\pi}{3}\right)$$

- 7th Harmonics have similar phase shift to fundamental which results in **positive phase sequence**.
- Same is true for $(6p + 1)^{th}$order harmonics Where $p = 0,1,2,3 \ldots..$

(7th, 13th, 19th…………)

That is why we call it a positive sequence harmonics. So, why we call it positive sequence harmonics? Because its phase sequence is exactly similar to fundamental component. I hope that you understand what is phase sequence. Phase sequence means the, in the order in which the phase current or phase quantities are rotating, okay. So, if we have three different phases named as A, B and C and if A rotates ahead of B and then B rotates ahead of C, then of course the phase sequence is A, B, C. Or if it is, it could be ACB as well, if this, the rotation will be in sequence of A, C, phase A and phase C and phase B.

So, this is what the concept of phase sequence. So, here we have the positive sequence harmonic that is seventh order and this, the similar harmonic, similar order harmonics which are of 6p plus 1. Actually this would be 6p plus 5 and this is 6p plus 1 order harmonics. So, where p is equal to 1, 2, 3, etc. So, this similar positive sequence harmonics you can get with, if you put p is equal to 1, that is 7th harmonic. If you put p is equal to 2, that will be, so 7th harmonic and then we will have 13th order harmonic, we will have 19th order harmonics they will be similar this positive sequence harmonics okay.

So, if I summarize the whole analysis that we cannot analyze all the different types of harmonics, but you can see that we can categorize these harmonics either it could be this third order harmonics or it could be fifth order harmonic or it could be seventh order harmonics and many different types of harmonic will follow either third order harmonic. We call them a triplen harmonic or fifth order harmonic or seventh order harmonic. Now, all odd harmonics would be present because as already told you this current here you can see the specific nature of this symmetry in this current, harmonic current of this TCR is drawing will not generate this any even order harmonics. But odd-order harmonics would be present. So, what we need to do is, we need to have a specific device to suppress that.

So, overall this, now what we will do, we need to design appropriate harmonic suppression devices. And we know that this filter could be one of them. So, filter could be one of them. Now, if we consider all these harmonics, then the single line diagram of the equivalent circuit of the three-phase TCR will look like this. So, the single line diagram of three phase TCR unit with filter circuit is as follows so it is something like that we have a connecting bus suppose this is the bus at which this three-phase tcr is to be connected and of course we need some step down transformer like this.

Why we need step down transformer? Because one of the advantages of shunt connected compensator is that we can eventually step down the system voltage level to much lower voltage level. And therefore, the shunt connected device would be rated to much lower voltage as of the system voltage. And this step down transformer, this is a step down transformer, this is a step down transformer. This is a step-down transformer which acts as a liaison between this single-phase TCR, this three-phase TCR and the bus at which this three-phase TCR unit would be placed. Now, then what we will have? We will have this a low voltage bus. This is high voltage bus. This is low voltage bus. And then we will have this single-page TCR unit or single-line diagram of a three-page TCR unit like this.

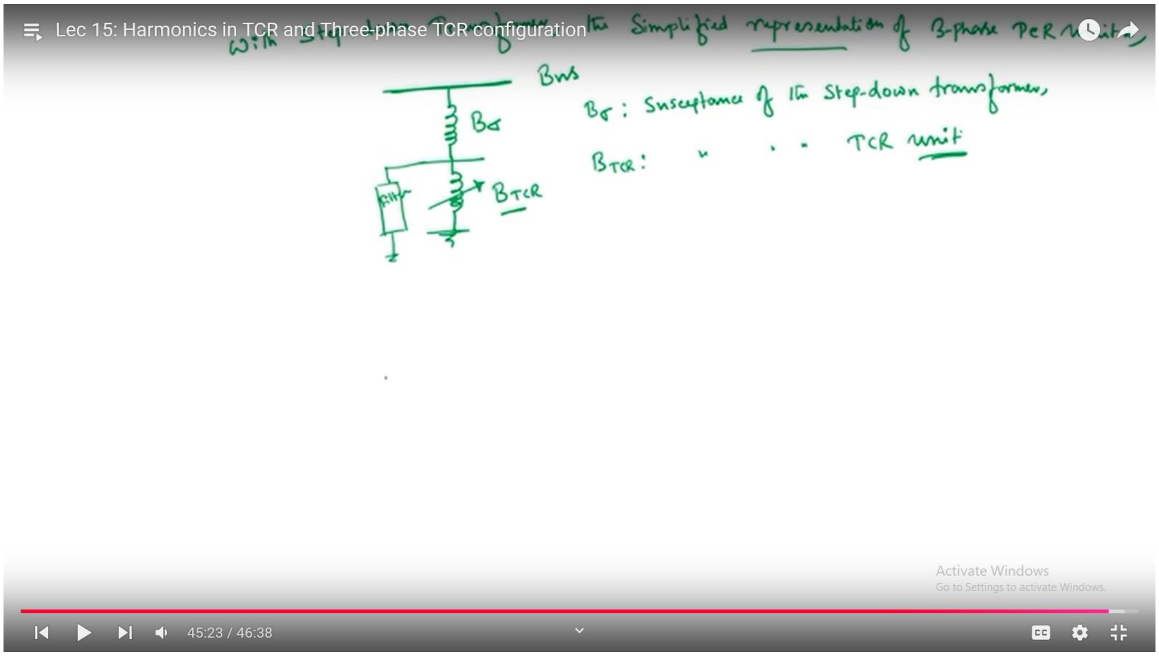
This is L by 2. This is L by 2. This is also L by 2. This is bidirectional switch. This is not sufficient presentation of a three-phase TCR unit because we need some filter circuit in order to suppress this type of harmonic. So, we should also represent single line diagram of a filter and this could be a LC filter like this or could be any type of filter. This is a LC filter. So, this is basically the filter circuit which is specifically designed to suppress some of the higher order harmonics so that the current which is drawn by this TCR unit is free from the harmonics that is basically appearing because of the partial conduction mode of the switches.

And this is what the representation single line diagram representation of a three-phase TCR unit. And the role of this step down transformer is to step down the voltage level. Suppose this bus voltage is 220 kV or maybe this 400 kV or maybe 765 kV as per the transmission level voltage in India. But here this is a low voltage, low voltage bus.

The voltage level will be much lower than this voltage level. So, that overall this TCR unit, so this is basically TCR unit and this is basically the filter unit, both would be not much costlier. So, that is what the idea behind this. Now, one thing I should also tell that we represent this single line diagram of a three-phase TCR unit along with this LC filter because of this harmonic current presence in this particular TCR and we need to suppress some of the harmonic currents. But we also need to understand that in actual representation in modeling of this TCR, there is something like which represent this fundamental current of this TCR unit. So, what we can represent this model of a 3-phase TCR is something like this, the equivalent model 3-phase TCR model is something like this.

This is what the bus at which this TCR unit would be placed and this is a variable susceptance. This is a variable susceptance whose susceptance value can be changed with by changing firing angle control of the thyristor. So, this is what the simplified model, this is a simplified simplified representation and we will solve many numerical problem considering this simplified representation. Now, this B TCR basically represents this overall susceptance of this TCR unit and it is variable because we can vary this susceptance by controlling the firing angle. Now, when you represent this simplify, when you will represent this, we are ignoring the presence of step down transformer.

Otherwise, so this is without step-down transformer. Now with step-down transformer, so with step-down the simplified representation of three-phase TCR. The unit is something like that. We have a, this is what the bus at which this TCR unit is to be placed. This is a susceptance. We will model that this is a susceptance of the step down transformer. This is represented by let us say B sigma. So, B sigma is representation of of the step down transformer. And then we will be having the variable susceptance representation of the TCR.



So, this is what B TCR. So, B TCR is the susceptance of the TCR unit. Many times we will represent this overall TCR with this simplified model and we can solve many numerical problems with this. So, this is what the simplified model of TCR, but of course, you should understand that there are you know LC filter also. If you consider this LC filter, so it will be something like here, we will be having LC filter also. So, this is what the filter representation But as this TCR unit is in parallel with this filter, while solving this mathematical problem, we can ignore even this filter, filter impedance or filter susceptance.

But this is how we can represent this three-phase TCR in a very simplified form. With this we will discuss the control characteristics, the dynamic characteristics of the TCR in the next lecture and we will proceed further with this. And this would be the part of the next lecture and this is the end of this today's lecture and thank you very much.