Course Name: Power Electronics Applications in Power Systems

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Power Electronics Applications in Power Systems

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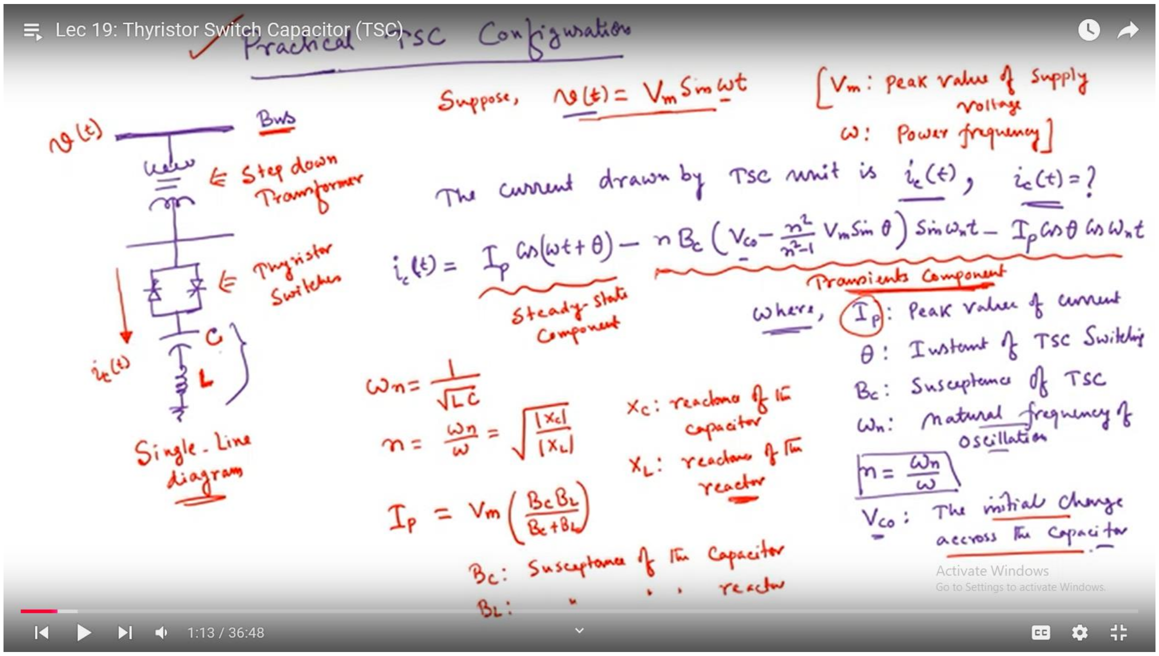
Lec 19: Thyristor Switch Capacitor (TSC)

So, welcome again in my course Power Electronics Application in Power Systems. So in the last lecture, I discussed a specific type of static wire compensator which is thyristor-switched capacitor, right? So I will continue to that. And I will also discuss the operation of thyristor-switched capacitor or in short, it is named as TSC in more detail, and also I will discuss some of the practical problems in implementing this TSC in a practical power system. So, let us proceed with this. So, if you look at this my discussion for practical TSC configuration, it consists of this a step down transformer just for stepping down the voltage level from the system or transmission level voltage to a much lower voltage at this particular bus. And then we have a bidirectional switch, we have a fixed capacitor, we have a small reactor.

The role of the reactor is to primarily restrict the current during switching and also to restrict the high di/dt value during the switching, okay. So, this is the single-phase configuration of TSC. This is single-line diagram that constitutes this single-phase, single-phase TSC. Now, of course, we will discuss about this three-phased TSC.

Before that, we will discuss on some of the practical problems in operating this TSC. One of the problems I already discussed in the last class or in the last lecture. For example, when this particular system is brought in into the system, then the current drawn by this capacitor or current drawn by this TSC unit is this, this is what the current expression. And if you look at this expression, it consists of two terms, one is steady-state component, and another is a transient component. Now steady-state component is the component that we desire for, but the transient component is the additional component and it makes that initial current during this turning-on operation is very high.



Practical TSC Configuration

Suppose, $v(t) = V_m \sin\omega t$ [V_m: Peak value of Supply voltage
ω: Power frequency]

The current drawn by TSC unit is $i_c(t)$, $i_c(t) = ?$

$$i_c(t) = \underbrace{I_p\cos(\omega t+\theta)}_{\text{Steady-State Component}} \underbrace{- nB_c\left(V_{co} - \frac{n^2}{n^2-1}V_m\sin\theta\right)\sin\omega_n t - I_p\cos\theta\cos\omega_n t}_{\text{Transients Component}}$$

Where, $\boxed{I_p}$: Peak value of current
θ: Instant of TSC Switching
B_c: Susceptance of TSC
ω_n: natural frequency of oscillation
$\boxed{n = \frac{\omega_n}{\omega}}$
V_{co}: The initial Change across the Capacitor

$$\omega_n = \frac{1}{\sqrt{LC}}$$

$$n = \frac{\omega_n}{\omega} = \sqrt{\frac{|X_c|}{|X_L|}}$$

X_c: reactance of the capacitor
X_L: reactance of the reactor

$$I_p = V_m\left(\frac{B_c B_L}{B_c+B_L}\right)$$

B_c: Susceptance of the Capacitor
B_L: " " " reactor

Let, $v(t)$ be the voltage of the bus to which the TSC unit is connected.

$$v(t) = V_m\sin(\omega t)$$

Where,

V_m = Peak value of the supply voltage

ω = Power frequency

When the thyristors are switched on, the current drawn by the TSC is:

$$i_c(t) = \underbrace{I_P\cos(\omega t+\theta)}_{\substack{\text{Steady-state component} \\ i_c(t)|_{steady-state}}} \underbrace{- nB_C\left(V_{C_0} - \frac{n^2}{n^2-1}V_m\sin\theta\right)\sin(\omega_n t) - I_P\cos(\theta)\cos(\omega_n t)}_{\substack{\text{Transient component} \\ i_c(t)|_{transient}}}$$

Here,

ω = System frequency

θ = Instant of TSC switching

$\omega_n = n\omega = \frac{1}{\sqrt{LC}}$ = Natural frequency of oscillation

B_c = Susceptance offered by capacitor

V_{C_0} = Initial voltage of capacitor (at switching instant)

I_P = Peak value of the current

$n = \frac{\omega_n}{\omega} = \sqrt{\frac{|X_C|}{|X_L|}}$; X_C = Reactance of the capacitor, X_L = Reactance of the inductor

$$\Rightarrow\ i_c(t) = i_c(t)|_{steady-state} + i_c(t)|_{transient}$$

From the circuit we have,

$$I_P = V_m\left(\frac{B_C B_L}{B_C + B_L}\right)$$

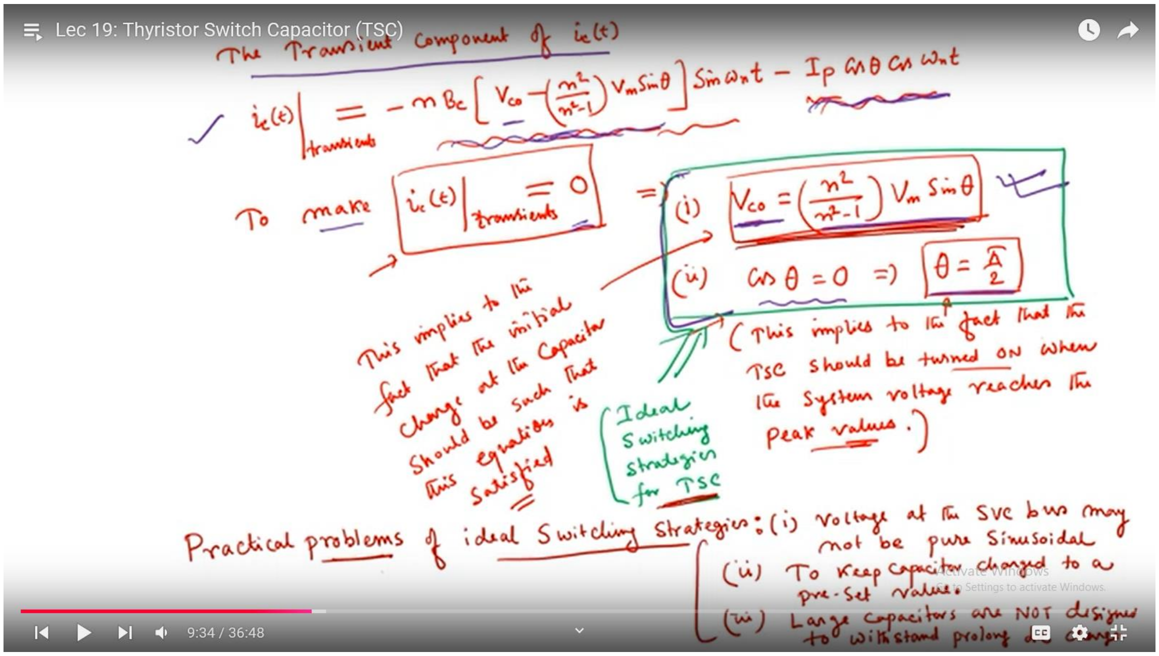
$$I_P = \frac{V_m}{X_C}\left(\frac{1}{1-\frac{X_L}{X_C}}\right) = \frac{V_m}{X_C}\left(\frac{1}{1-\frac{1}{n^2}}\right) = \frac{V_m}{X_C}\left(\frac{n^2}{n^2-1}\right) = V_m\left(\frac{n^2}{n^2-1}\right)B_C$$

Now we need to mitigate that and if you look at this transient component which I have written over here, you can see that we can make this transient component exactly equal to 0. If we have these two conditions satisfied, one is this, this VCO is equal to this, which means that. What is VCO? Already I discussed in the last class that this VCO is basically representing the initial charge across the capacitor. So, it is the voltage across the capacitor due to some leftover charge in the capacitor. So, if there is no initial charge on a capacitor, then, of course, the VCO would be 0. So, that means if the capacitor is initially uncharged, then VCO is equal to 0. But if VCO is equal to 0, that does not mean that this component would be 0. Rather, you can see that even if VCO is equal to 0, this component will be there. So, in order to make it 0, this condition has to be satisfied. This is the condition I discussed in the last lecture, which means that capacitor needs to be charged, precharged to these values, so that this component will be 0, this transient component would be 0.

Similarly, the instant of turning on should be such that this cos theta is equal to 0, which implies to that theta is equal to pi by 2, then there will be no this transient current for this particular component or of this transient current. But there are some practical difficulties to achieve that. So, what are the practical difficulties? So, these two conditions, these two conditions are called ideal switch, turning on and ideal switching condition. So, these two conditions are called ideal switching strategies for TSC. But of course, we have some limitations to achieve the ideal switching strategies for TSE which I am going to discuss today.

Then I will discuss what would be then the practical switching strategies to have a very lesser amount of transient or no transient. So this I am going to discuss today. So firstly, let us see what is the problem with this ideal switching strategy. The practical problems of ideal switching strategies are number 1, voltage at the SVC bus may not be pure sinusoidal. This is the limitation of ideal switching strategies. One is that the bus at which this particular TSC would be placed, at that particular bus, we may not have purely sinusoidal voltage. So that in fact in power systems, you never expect that any point you will get a pure sinusoidal voltage. So there would be some sort of distortion everywhere, in every country, wherever you may go. So, in power system voltage if you measure, it will not represent a pure sinusoid, it will be rather a distorted sinusoid. So, if it is so, then our practical switching strategy may not work.

Then what would be the second limitation? Now if you look at this particular expression, this particular expression says that in if you follow this particular strategy, we need to charge the capacitor to a preset value. There is a problem to charge the capacitor to a preset value before you connect it to this TSC unit, it is itself a problematic task. So the second problem or second difficulty with this ideal switching strategy is that to keep capacitor charged to a preset value. So, this needs additional charging circuitry, this needs additional control circuitry as well to keep the capacitor of the TSC unit to remain charged before you turning on this TSC unit. So, this is another practical problem or the limitation.



The Transient component of $i_c(t)$

✓ $$i_c(t)\Big|_{\text{transients}} = -nB_c\left[V_{co} - \left(\frac{n^2}{n^2-1}\right)V_m\sin\theta\right]\sin\omega_n t - I_p\cos\theta\cos\omega_n t$$

To make $\boxed{i_c(t)\Big|_{\text{transients}} = 0}$ $\Rightarrow$

(i) $\boxed{V_{co} = \left(\frac{n^2}{n^2-1}\right)V_m\sin\theta}$

(ii) $\cos\theta = 0 \Rightarrow \boxed{\theta = \frac{\pi}{2}}$

This implies to the fact that the initial charge at the capacitor should be such that this equation is satisfied

(Ideal switching strategies for TSC)

(This implies to the fact that the TSC should be turned ON when the system voltage reaches the peak values.)

Practical problems of ideal Switching Strategies: (i) Voltage at the SVC bus may not be pure Sinusoidal

(ii) To keep capacitor charged to a pre-set value.

(iii) Large capacitors are NOT designed to withstand prolong

Number 3, large capacitors are not designed to withstand prolonged DC charge or DC stress. So this means that when you charge a capacitor that is the TSC capacitor to a preset value before you bring it in service or before you turn on the TSC unit, this capacitor needs to withstand this DC charge for a prolonged time. And normally this capacitor is not designed to withstand that. So, that is a practical problem. So, therefore, this ideal switching strategies may not practically work because of this limitations.

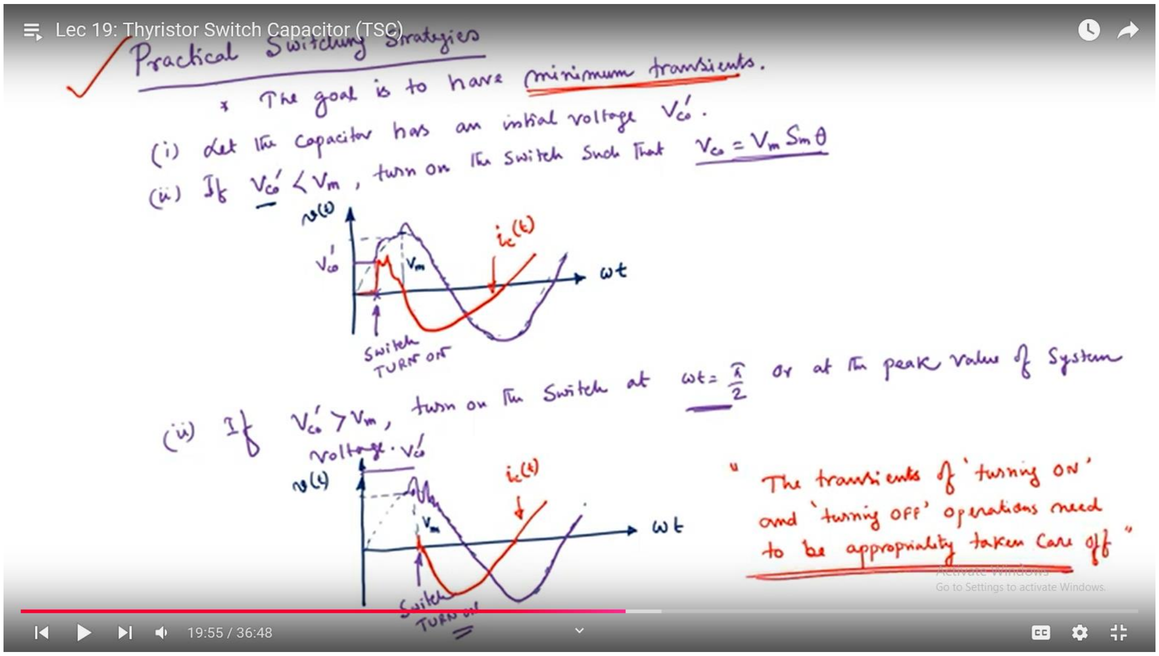
And we need to go for some practical switching strategies for this particular TSC. So, let us see what would be the practical switching strategies. So this practical switching strategies, the practical switching strategies may alleviate the difficulty that we may have in case of ideal switching strategy. So here the goal would be, the goal is to have minimum transients. So, in case of a practical switching strategy, the goal is to have a minimum transient, we cannot avoid the transient current but we can reduce the transient to an acceptable range.

So, that is what the main goal is. So, we have different type of practical switching strategies for TSC unit and I will discuss one or two of them. So, one of them is number one, let the capacitor has an initial voltage which represents the initial charge corresponding to VCO. So, let the capacitor has an initial charge, this we can do while turning off the capacitor or while turning off the TSC unit and we can keep the capacitor having some amount of charge left with that. That charge may not be equal to VCO, whatever I discussed, that may be equal to some value, let us say VCO dash, okay. V co dash is less than V m, here V m is basically the maximum voltage or maximum supply voltage of the bus at which this TSC unit is placed. So, if V co dash is less than V m, then turn on the switch such that V co is equal to V m sin theta. It means that suppose if I draw this waveform, suppose this is the waveform of the supply voltage V of t with respect to this omega t. This is suppose the sinusoidal voltage source, we assume that it is sinusoidal. Now, what will happen if it is non sinusoidal that I am going to discuss.

So, if it is sinusoidal, then suppose this VCO dash is and then of course, this is what you know this VM peak value of this is VM, this is VM. Now, if suppose V co dash is lower than that, then suppose V co dash is something somewhere here, then the instant of turning on a switch such that V co dash is equal to V m sin theta, then this will be the instant of turning on the switch, here we will turn on the switch, will be turned on. So, if we turn on the switch at this instant, then this voltage will be little bit of deviated and it will be then settled like this. And the current flowing through this ITCR will start from 0, will have some sort of settle down to here. So, this will be i of c, i c of t.

So, here we will have some minimal amount of transient before it is settled. So, that will happen if we follow this strategy. Then what would be the next strategy? Next strategy is if V co dash greater than V m, then turn on the switch at omega t is equal to pi by t or at the peak value of system voltage. So, this is in general difficult to achieve to turn on the switch in a particular instant, but what is done in practical situation is we will turn on the switch when the difference of this VCO dash and the peak value of system voltage that is Vm is less.

So, that is possible. So, that is somewhere near to the peak value of the system voltage. So, suppose if this is the system voltage if suppose this is the system voltage, then of course you understand that this is the V m, this is V m, this represents V of t, this represents omega t, and suppose this VCO dash is somewhere here, VCO dash is somewhere here. So, just find out wherever is the difference is less, it will be of course, at this peak value during that instant of time, let us turn on the switch. So this is at the instant we will turn on the switch, then what will happen actually this system voltage will be oscillating and will be set quickly settle to this value and current drawn by this TCR unit will be little bit of hurry and it will directly reach to the steady state value. So that is what it will have, that is what it will have I c of t.



Practical Switching Strategies

* The goal is to have minimum transients.

(i) Let the capacitor has an initial voltage V_{co}'.

(ii) If $V_{co}' < V_m$, turn on the switch such that $V_{co} = V_m \sin\theta$

(ii) If $V_{co}' > V_m$, turn on the switch at $\omega t = \frac{\pi}{2}$ or at the peak value of system

" The transients of 'turning ON' and 'turning OFF' operations need to be appropriately taken care off "

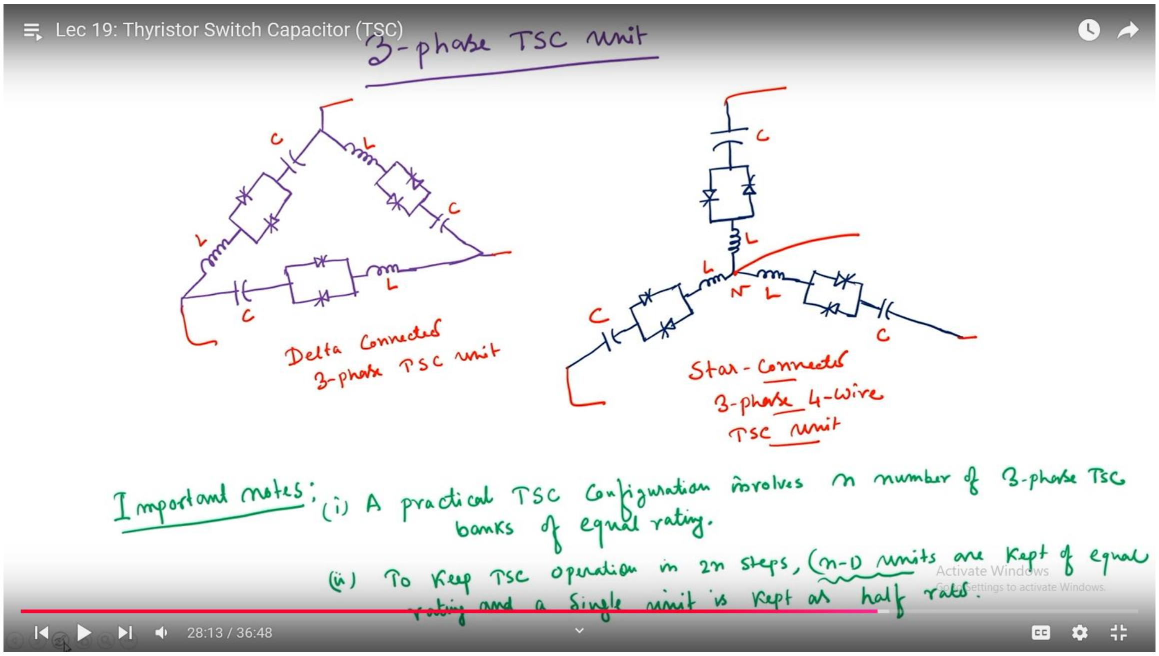
So, these are some practical switching strategies and that can be followed to have a minimum transient. Again I am saying that minimum transient we cannot avoid the transient fully, but we have the minimum transient. But at this point, you should have an idea that the major bottleneck of having this capacitor in SVC is that it is turning on operation, it is switching operation, it will cause this some sort of transient like this. And the operator needs to have a suitable control strategy to minimize the transient. Other than that, this turning on and turning off operation both would be, both would be difficult or both would be challenging.

In fact, not only, I only discuss this turning on operation of this TSC, but the same thing will follow when you turn off the TSC from the supply. So, during that time, if you turn on the switch, suppose when the capacitor voltage holds the system voltage or its peak, and then if you turn it on at the condition when the system voltage again hits the negative peak, then there would be a twice of the peak voltage that would appear across the switch which will be not a favorable condition. So, this is something you need to understand at this moment. Other than that this TSC operation would be as similar to as this TCR operation, but this transient needs to be properly taken care of. So, the summary of this is that the transients of TSC, the transients of turning on and turning off operations need to be appropriately taken care of.

This is the main goal of designing and developing the control strategy of TSC. Other than that, its basic operation is similar to TCR, but since it is having a capacitor, so one needs to have a proper strategy to turn it on and turn it off. So, when it will be kept on for a prolonged time there will be no issue, but basically we are designing this TSC as you can remember and its advantage over this fixed capacitor is it is turning on and turning off operation. But this may create some sort of transience to the system, so this needs to be properly taken care of. So, this is one of the you know the take-home message that one should understand at this point.

Then, next I will discuss three-phase configuration of TSC unit, three-phase TSC unit. So, we have seen a single-phase TSC unit will look like this. This is a single-phase TSC unit. This whole constitutes a single-phase TSC unit. And a three-phase TSC unit will consist of similar single-phase TSC units in all the phases. And this either to be connected in star or is to be connected in delta. A three-phase TSC unit looks like this. If it is delta connected, it looks like this. So, there would be a small reactor. There would be a bidirectional switch like this. Then, there will be a capacitor over here. Here also, we will be having a capacitor and one bidirectional switch. I am assuming it is a thyristor, but it could be any semiconductor switch, you can understand. And here also we will be having a small inductor, then a bidirectional switch, then a capacitor. So, this is I am drawing only the three-phase TSC unit, but one needs to understand that this is to be connected to a step-down transformer to the actual point where it is to be connected to the network.

So, there would be a step-down transformer, then this TSC configuration and that constitute the whole TSC unit, three-phase TSC unit. So, this as you know, these are the small reactor. And the purpose of this small reactor is to limit the initial current and to limit this high value of di/dt which may appear across the switch due to this turning on or turning on operation. These are the capacitor units. And this, the choice of this inductor or reactor should be such that it can fulfill the basic requirement to reduce the inrush current or transient current of the system.



Important notes: (i) A practical TSC configuration involves n number of 3-phase TSC banks of equal rating.

(ii) To keep TSC operation in 2n steps, (n-1) units are kept of equal rating and a single unit is kept as half rated.

So this is basically a delta connected, delta connected three-phase TSC unit. But it also can be star connected like this. There will be a bidirectional switch. There will be a small inductor like this. And all the phases will have identical single phase unit. So, here is the bidirectional switch again. and we have the capacitor of the TSC unit. So, this configuration is basically a star connected 3-phase, it could be a neutral also, neutral could be available 3-phase 4-wire So, this is what the neutral of this TSC unit three-phase four-wire TSC unit. So, these are the capacitors, identical capacitors, this will be three identical reactors. So, this constitutes this star connected three-phase Fourier TCS unit. And the all the practical SVC unit as already I have discussed are of this three-phase unit like this.

And remember this all would be connected to the secondary terminal of the step-down transformer which already I have discussed. So, this will be connected to the secondary terminal of the 3-page transformer and this 3-page transformer can be either star delta or delta star or similar configuration to suppress this triplen harmonics and to have various issues involved in it. So, this is what a practical TSC configuration. However, I need to tell you that a practical TSC configuration constitute of many identical 3-phase TSC unit not a single TSC unit rather many identical TSC units. So, the important note is a practical TSC configuration involves n number of three-phase TSC banks like capacitor bank of equal rating.

But sometimes to keep TSC in two n steps, n minus 1 units are kept of equal rating and a single unit is kept as half rated half rated. Suppose this n minus unit n minus 1 units having a susceptance rating of the capacitance as this B, then one number of unit is having a rating of the capacitance is B by 2. This is just to increase the number of operations to, from n to n minus 1. Otherwise what will happen, if you have 3 units for example, you will have 3 different steps of operation. First is you can turn on this first unit, then the next step will be you turn on the first unit as well as second unit and the first step will be you turn on the first unit, second unit and third unit simultaneously.

So, these are the three different steps of operation possible, if we have three identical TSC units. However, if we have a three identical TSC units and one TSC unit which is rated half of the actual rating of the one of the TSC unit, half in the sense that half of the susceptance. Then you may have some intermediate step, one is you turning on this each of the unit once and another time you turning on and turning off the half rated unit that will extend that whole range of operation from n to 2n. So, that is something one need to understand. And that is basically followed in practice that in order to have a reliable operation, there is not only a single unit of 3-page DSC is kept.

Rather, there are multiple TSC units, we consider n number of TSC units are operated simultaneously, out of which one, each of them n minus unit would be of equal rated and one unit will have a susceptance, half of the susceptance of the other units. So, that is something one needs to understand. Another thing I should mention over here is that, so here we talk about the steady state transient a lot, but we did not talk about the steady state component much. So, we discussed that this transient component is one of the major attention of this practical operation of the TSC unit, but also the steady state unit needs to be appropriately taken care of. So, you can see that this steady state unit will have this peak value of the current, which is equal to I p is equal to V m.

This constitutes the susceptance of BC and BL constitute the susceptances of the capacitor and the reactor. And as we know, this n which is basically representing the ratio of the natural frequency of the oscillation to this power frequency. So, therefore, if you just put this x c information that is this information over here in this particular expression. So, what we will get this particular component that is this particular component, this B C multiplied by B L plus B C multiplied by B L, if I write B C multiplied by B L, which is basically representing this series combination of the susceptance of this capacitor and this inductor unit.

So, this capacitor and this inductor unit are in series. So, therefore, when you consider their susceptance, so the effective susceptance, so the effective susceptance will be this. Effective susceptance will be this. Now, if you look at this, this can be written as n square divided by n square minus 1 multiplied by vc, which is very important because you can see that this we can bring from this expression and from this expression. If we just put these two expressions over this particular expression, you will get this. So, overall susceptance in the steady-state of this single-phase TCR unit is basically having a factor n square divided by n square minus 1.

Now, what is n? This n is the ratio of the natural frequency of oscillation to the power frequency. Now, here some design consideration is taken care of. Now, if you plot this n square minus n with respect to n, if we plot this n square divided by n square minus n, this factor only with respect to this n, then what we will get when n is equal to 1. n equal to 1 means this your natural frequency is exactly equal to power frequency which will normally not happen as per our design consideration. So, if it happens then this factor would be where this factor would be infinity.

And so, if you go for the other values of this n, n is equal to 2, n is equal to 3, n is equal to 4 and n is equal to 5 and so on. So, what we can see that this factor will die down and it gets settled to some value. So, that is why So, this design of this B L that is this susceptance of the reactor unit is to be designed such that this n is always greater than 3. Because if n is lower than 3, then there would be very high steady state current appear, or that will be very high steady state current that would be drawn by the TSA unit, which is not desirable, of course. So, therefore, this VL, design of this VL is very crucial here.

So, it should be such that this factor, this n square divided by n square minus 1 should not be very high value. So, that is why the normal practice n is chosen to be above 3. It should be chosen to be above 3. It means that this L and C units would be resonant, which would be higher than, 3 times higher than the power frequency.

It should be at 150 hertz in India or maybe at 200 hertz. So, this is another prime importance. Note that, one can understand from this TSC operation. So, this is all about this TSC operation and this is the practical configuration of this TSC unit, a three-phase TSC unit. And, then one thing that is left is the discussion of this TSC along with this TCR, which is our goal at the very beginning that we set over here. So, this is only left over, other than that I have completed all this relevant discussion on this static var compensator.

Only thing is that, this TSC-TCR which is a very sophisticated form of this static var compensator that is left over in discussion. So, a TSC-TCR consist of a TSC unit, a three-phase TSC unit which may consist of multiple subunits and a TCR unit, three-phase TCR unit which also constitute of multiple three-phase TCR units and they constitute together as a TSC-TCR and this TSC-TCR is the most sophisticated type of the static bar compensator and regarding which I will discuss in the next lecture. So, apart from that I completed this part of the static var compensator, and for today thank you for your attention again. Thank you very much for your attention. Thank you.