Pulsewidth Modulation for Power Electronic Converters
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Lecture - 03
DC - AC converters

Welcome back to this lecture series on Pulsewidth Modulation for Power Electronic Converters. As we were, this is the third lecture here in the first two lectures we were discussing a few things about electronic switches and DC to DC converters. We are in the process of discussing various power electronic converters here.

So, first we have been discussing numerous power electronic converters before heading towards pulsewidth modulation of power electronic converters. In the process of discussing power electronic converters, we have seen that you know we need certain electronic switches and how we can convert power into using electronic switches.

So, the first example that we saw was that of DC to DC converter and today we are going to look at DC to AC converters.

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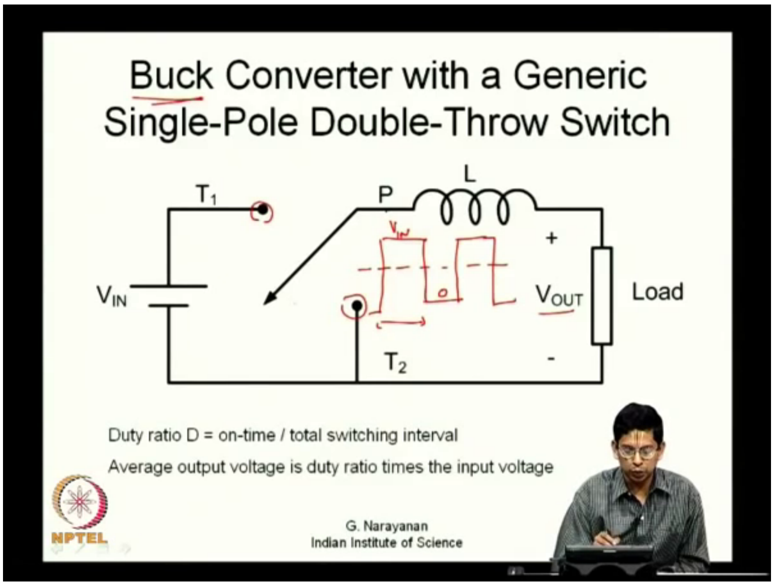

Before looking at DC to AC converters, let us have a quick recapitulation of what we saw about DC to DC converter. Because DC to DC converters are the most fundamental converters and the understanding that we develop with these converters could be extended to many other converters. Now, what I have shown here is a buck converter which we discussed the other day.

Buck meaning its output voltage V out, the average output voltage V OUT is less than the input voltage; so, it is a buck converter. Given certain input voltage you arrive at any output voltage which is lower than the input. So, how do we do that? We have a single pole double throw switch shown here, this node P is the pole and there are two throws. This P is either connected to throw T 1 or connected to throw T 2, it is connected alternatively between T 1 and T 2 alternately.

So, whenever you connect the pole P to T 1; the voltage here is high, the entire V IN gets separate here. And whenever P is connected to T 2 what you apply here is 0, so either V IN or 0 gets separate here; so, you go on repeating this cycle. So, what you get is such a pulsed square waveform, now this has certain average value and this is the average voltage that we require for the load, the average voltage dropped across the inductor is 0 so the entire average goes through the load.

The inductive filter serves to smoothen the current as we saw before. We can also have an additional capacitance connected across the load; for further smoothening of the current and I mean to smoothen out the load voltage 2. So, the output voltage here is basically the duty ratio times, the input voltage as we saw. If you want a higher output voltage what we do is; this width of the pulse divided by the total time interval, we have to increase what is called as the duty ratio, we should increase that you will get higher output voltage. If you reduce the duty ratio, you are going to get lower output voltages now.

So, this is a buck converter where; which has been shown with a single pole double throw switch generic switch now. We have to realize the single pole double throw switch electronically and how do we do that?

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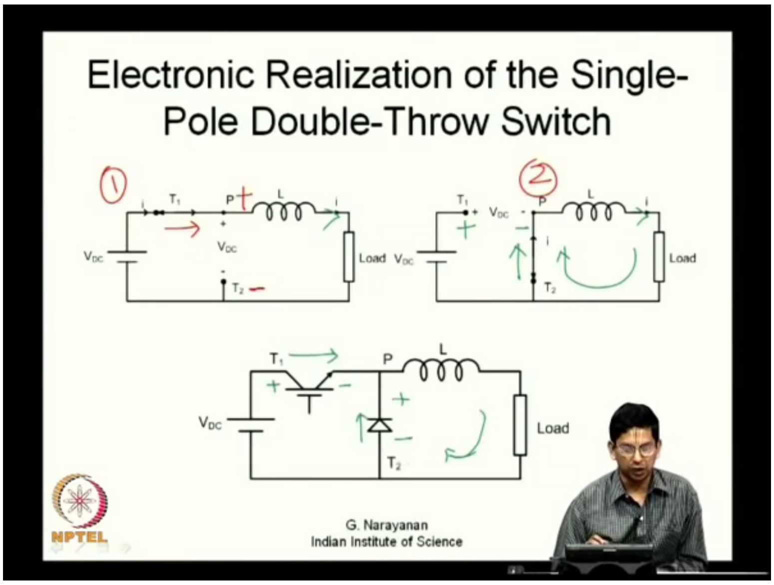

So, we look at the two states of the DC to DC converter, let us call this as state 1 and let us call this as state 2 what happens in state 1 pole is connected to throw 1 and in state 2, this pole is connect to throw 2. In the so called state 1 there is current flowing from throw 1 to pole as indicated in this direction. Then this pole to throw 2 what happens here is, it is blocking certain voltage.

What is the polarity of this? The pole P is positive with respect to the throw T 2; that is the polarity of voltage which it is required to block. Now when you go to the state 2 what happens is pole P is connected to throw T 2. So, here the conduction is from throw T 2 to pole P because what is being flowing is; the load current, the load current flows in this direction. So, the load current is free-wheeling now and that conduction is from T 2 to pole P. So, here what happens? P to T 1 is now blocking certain potential and that potential is the polarity such that T 1 is positive with respect to P, this is the kind of potential that you have here.

Now, how are we going to realize this? So, these are the requirements that we have. We need a switch between pole and throw 1, which can conduct in one particular direction namely from throw 1 to P. And we need a switch which can block a potential which is where T 1 is positive with respect to P that is what we need. And you see that a transistor perfectly fits the bill, so it can conduct in this direction. In state 1 the transistor conducts in this direction and similarly a diode what fits the bill for the other one.

So, in the so called state 1 a transistor conducts in this direction and the diode blocks with this polarity. And in the so called state 2, you have the transistor blocking like this on the diode conducting like this.

So, you have a transistor that is connected between P and T 1 and you have a diode that is connected between P and T 2. Whenever the transistor is turned off, the diode gets turned on that is because of the energy stored in the inductor; it gets turned on. And whenever the transistor is turned on, the diode is turned off. So, you basically do not need to have any other control device here, an uncontrolled switch will do; this point now this is what we saw the other day.

So, we are recapitulating it today because it is important for us to do so, because we are going to extend this to DC to AC converters now. So, this is what we found with DC to DC converter; I mean a buck converter, the next thing is a boost converter.

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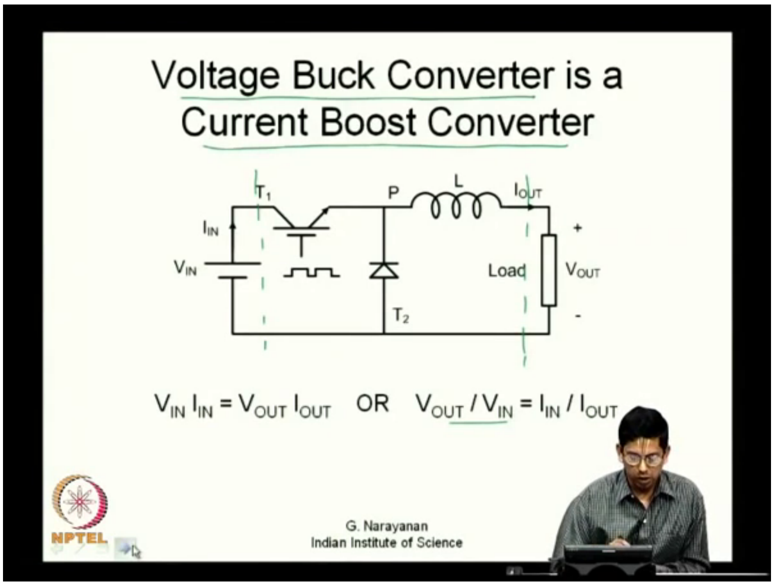

So, this is again a buck converter which is shown here; now you give such kind of a gating signal to this transistor, you give such kind of gating signal so that T 1 gets connected to P and when this getting signal is low, T 2 gets connected to P and it goes on like this. And you get a pulsed waveform here and the current is smoothened by the inductor and so on and you can also have an optional capacitance here.

So, now what we are going to look at here is; this is a voltage buck converter, the output voltage is less than the input voltage. Now let us look at this we have a supply, we have a load. So, between the supply and load we have basically switches and the passive elements for filtering. Let us say these are all ideal, the power that flows into this converter is V IN times IN; that is the input power.

What is the output power? It is V OUT times I OUT; if the converter is ideal that is if the switches are ideal and the passive elements are all ideal, there are no losses then you have V IN is equal to V OUT times V IN; IN is V OUT times I OUT; that is power balance, the input power is equal to the output power. If you rewrite this; V OUT by V IN is equal to I IN by I OUT. So, V OUT by V IN if this is less than 1, then I IN by I OUT should also be less than 1.

So, if you have; if the voltage is bucked then the current gets boosted. You have V OUT lower than V IN, you will have I IN lower than I OUT or I OUT greater than I IN. So, if it is a voltage buck action this is because of this power balance here. If the output voltage is less than the input voltage, the output current will be greater than the input current. Therefore, a voltage buck converter; what we commonly call as a buck converter is actually a voltage buck converter and this is actually a current boost converter.

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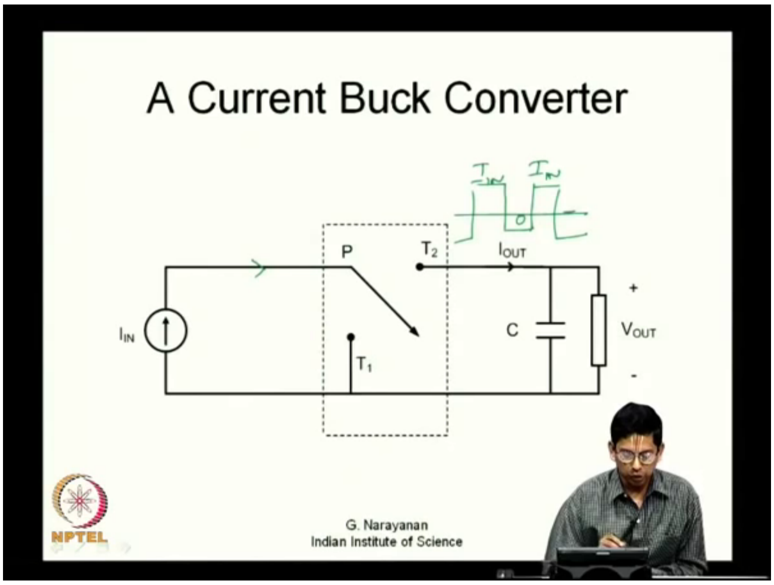

Now, if you want basically a voltage boost converter; what you need is actually a current buck converter. So, this is what I have drawn now; so, this is a current source here and there is a current buck converter now. There is a constant current flowing through this line whereas, if you look at this I OUT what flows through this T 2, it only flows; there is a current equal to I IN; 0; this current is equal to I IN, this is equal to 0 or I IN; 0. You have such a pulsed current flowing through this now.

This pulsed current flowing through a resistive load will produce a pulsed voltage waveform. You can consider the; you smoothen the voltage waveform considerably by putting in a capacitance across this as we discussed the other day. Anyway what we are worried about is the output voltage; V OUT now.

So, now what we are trying to do is here the average output current is lower than the input current. Therefore, you would expect the output voltage to be greater than the input voltage; therefore, this is a boost converter now.

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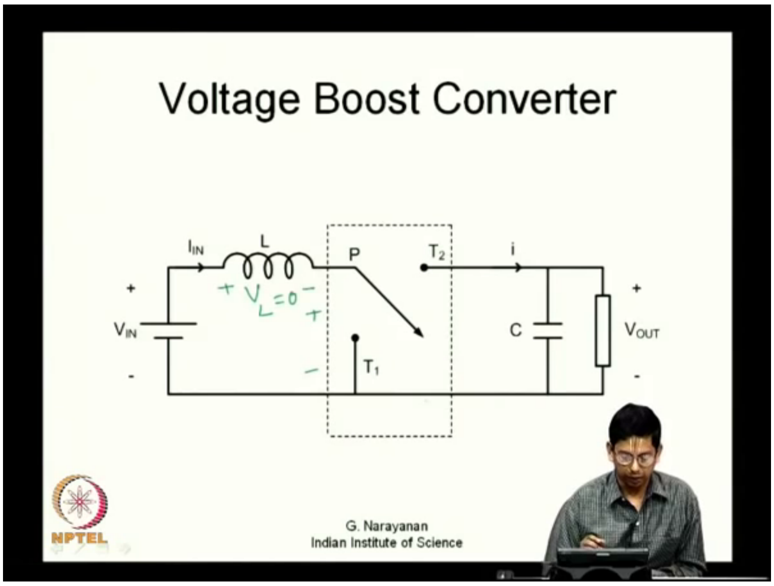

So, let us go on to the next step of replacing this current source with a voltage source and a series inductance. Now this is a voltage boost converter, now there is no average voltage that is dropped across an inductor. If you have a positive voltage during the during one of the switching intervals or during the on time or off time, it will be negative during the other time. In over switching interval, this voltage will get average to 0; the average voltage across this will always be 0 now.

So, you have nothing and so you have the same V IN available here and you will have a V OUT which is going to be greater than that; because there is a current buck action and there will be a voltage boost action now. So, here you also have a single pole double throw switch, as we had in a buck converter but it is connected a little differently now.

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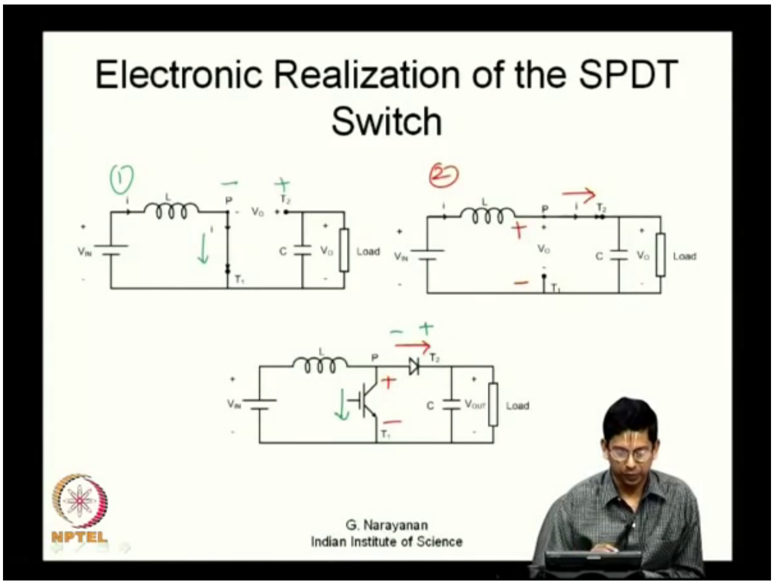

So, let us move on further and see how this single pole double throw switch in a boost converter be realized. The approach is similar to what we saw in case of a buck converter. So, in the so called state 1 we have this pole P connected to throw T 1 and this is the direction of conduction, then this is the voltage blocking requirement on the part of P to T 2. Now if you move over to state 2, the direction of conduction is from P to T 2 and the potential block is P positive with respect to T.

So, these are your requirements you have to find out devices which will satisfy these requirements now. As we can see very easily, if you have this state 2 you have a diode here; the diode can conduct like this and the transistor can block a potential like this. Now if you want to look at the state 1, you have a transistor and the transistor can conduct like this and the diode can block as shown here. So, you can realize the single pole double throw switch using a transistor and a diode as shown here.

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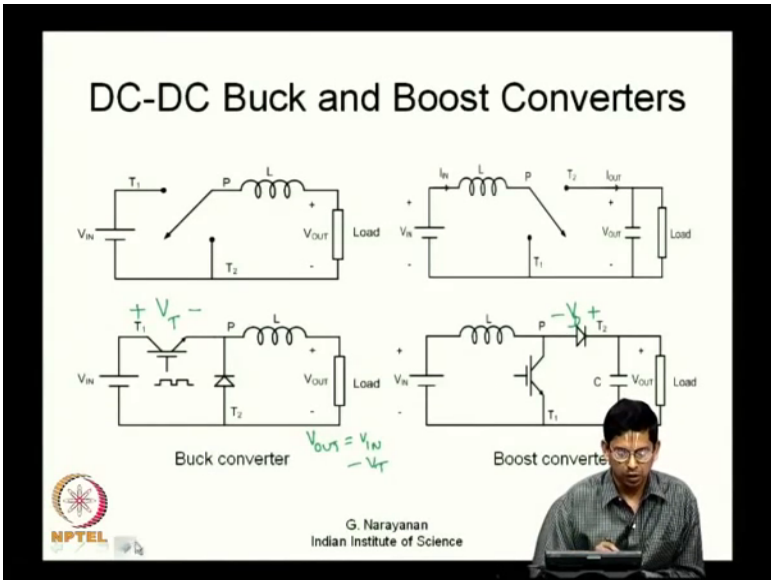

So, we have all of them put together, so essentially DC to DC this buck as well as boost converters have one single pole double throw switch now. And you see that this pole is always in series with the inductance because the inductive current should not be opened and you should always provide a path for the inductive current flow through

So, P is either connected to T 1 or T 2; so, the current through L or the current through P always has a path to flow through; either through T 1 or through T 2 the same story here also it is connected that will differently now. So, here because of this chopping action; you turn on and turn off the average output voltage is less than the average input voltage in the case of a buck converter now. If you look at the voltage polarity, whenever the transistor is off this T 1 is positive with respect to P or the collector is positive with respect to emitter.

So, you have certain average voltage V T with this polarity that is dropped and your output voltage is V OUT is basically V IN minus V T; V OUT is equal to V IN minus V T is what you have and there is a buck action. On the other hand, if you look at the boost converter there is no voltage dropped across the inductor now. Whereas, if you have a diode a diode blocks voltages of this polarity and when it is on ideally the drop is 0.

Therefore, the average voltage dropped has this polarity; the cathode positive with respect to anode. Now what happens here is your V OUT is the sum of this V D plus V IN and you can see that the output voltage is greater than the input voltage and you have boost action now. So, we have both the buck and the boost converters available for us here, both have single pole double throw switches as shown here.

And the single pole double throw switches you look at the conduction and the voltage blocking requirements between every pole and every throw and you come up with an appropriate electronic realization, which is one transistor and a diode as shown in these two cases now.

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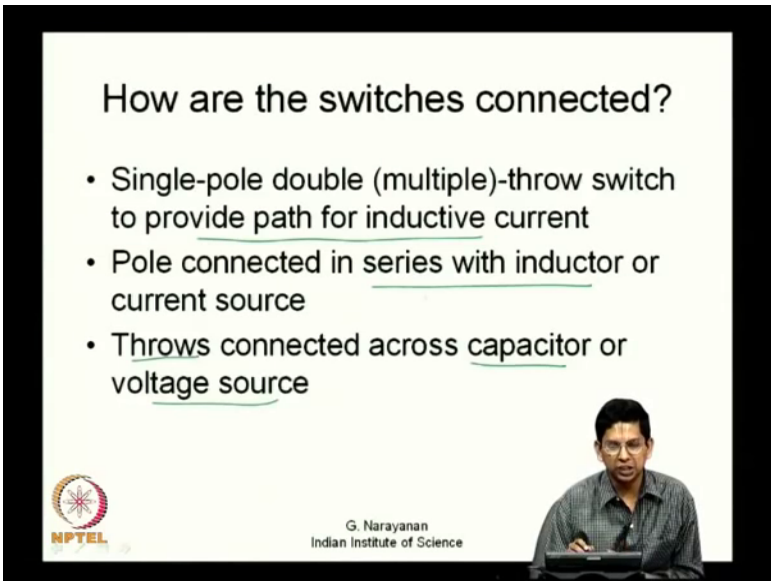

So, here we find certain rules here what do we find about how switches are to be connected; what do we find? We find a single pole double throw switch is used; why is it used? To provide path for inductive current, there is a inductive current and it has to you know be provided with the path, it cannot be opened.

Therefore, you provide for the path or for the inductive current flow throw; I throw 1 throw or other throw now, so you have a single pole double throw switch. Now the pole is always connected in series with the inductor or a current source and you look at the throws, they are connected across the capacitor voltage source now.

So, this is what you commonly find; so you once again you connect the pole in series with the inductor or current source. So, the inductor current or current source it has a path to flow through, it will either flow through T 1 or through T 2; this is what will happen now. If you look at more complex cases than buck converter or a boost converter what you may find is; you may not find a single pole double throw switches, you may find a number of single pole double throw switches.

And also there are cases where you will find not single pole double throw switch, but single pole multiple throw. For example, single pole triple throw switch we will look at those examples today a little later now. So, you this is how you basically connect switches in a converter, so you can realize; one of our first attempts would be to realize a converter using a network of single pole multiple throw switches. And then go about electronically realizing each single pole multiple throw switch; that could be an approach to coming up with any power circuit that may be necessary.

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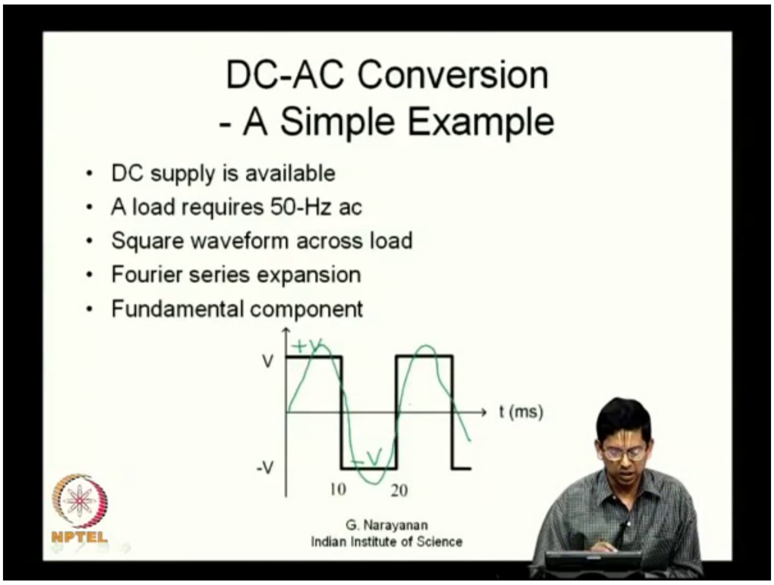

That may be useful for us; we are going to look at this simple example for a DC to AC conversion which is our main topic for today. This was something we briefly discussed on; in the first day or in our first lecture. So, let us say we have DC and we need an AC that is we have a load which needs 50 hertz AC, this is very very common we like for example, when you power supply is failed you just have a DC battery, you have a load which requires (Refer Time: 16:04) and you want to feed it now; what do you do? You use an inverter that is what we call as an inverter, I mean which is part of a UPS.

Now, let us look at what is a simplest possibility, what you can do is apply the DC voltage directly across the load for some time, say 10 millisecond and apply a minus V across the load for another 10 millisecond time and go on repeating the cycle. Now this is a 20 millisecond or 50 hertz cycle, you can expand this is a Fourier series and you will find that this has a fundamental component like this. There are other harmonics which can be either filtered or ignored. So, this is; it is a starting point for DC to AC conversion it is a very very simple example now.

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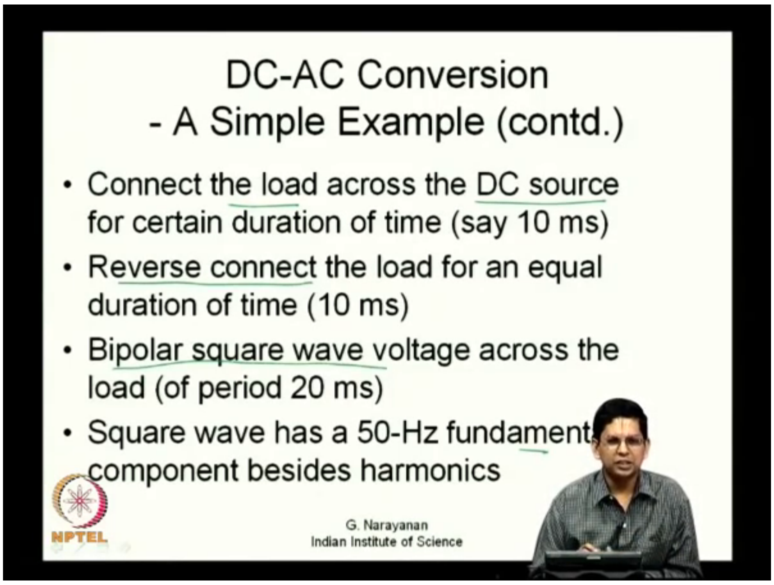

What are we doing here essentially is; we are connecting the load directly across the DC source for some duration of time. And what are we doing? We are reverse connecting the load for certain duration of time. You connect the load for some 10 milliseconds, reverse connect for 10 milliseconds, you connect it for 10 milliseconds and reverse connect you go on doing this way. So, you get some plus V and minus V, plus V and minus V across the load and a square waveform as we saw before.

So, you will get a bipolar square wave now; this square wave has a 50 hertz fundamental component; though it also has harmonics now, which can be filtered or ignored now. So, this is a starting point for DC to AC conversion now; we can certainly do better than that.

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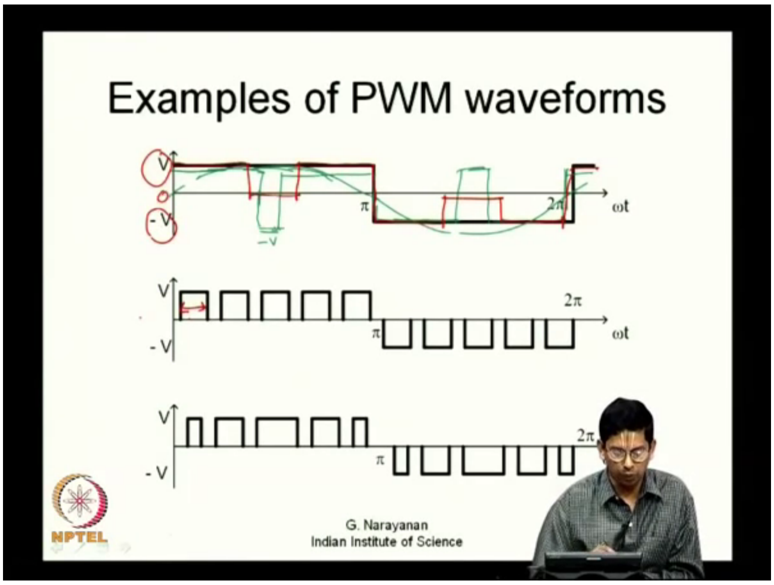

Some examples are here; now let us say this is what we have, it is a square wave. Now it has a fixed fundamental voltage; that is determined by this V, whatever is this V now. If you want to change the fundamental voltage of the square wave, the only way to do this is to change V; that is like operating an inverter with a variable DC voltage; which is not what we do commonly these days.

So, we try and operate it with a fixed DC voltage now. So, this amplitude cannot be modified; in fact, the amplitude cannot be any higher than this, but you can reduce this amplitude. How can you reduce this amplitude? Let us say you apply this V and for a short duration of time, you can have a notch like this. Similarly, the negative half cycle you can apply minus V as shown here and for a short duration of time, you can apply plus V like this; you can go on with the cycle.

This green waveform is similar to the original waveform which was; I mean the black one except that it has a notch. Now what happens, it is minus V whenever you have this notch here. So, the fundamental voltage is kind of reduced here, you get a different value of fundamental voltage. You can by varying this notch width for example; you can vary the fundamental voltage.

Now this notch what we are doing is; we are applying plus V and we are applying minus V. So, if you look at the interval during this notch; this period the interval pertaining to this notch, what you need is actually a sinusoidal wave which is as shown here. This is the desired one, what you are actually applying is this minus V which you are; like this there is a substantial error between what is applied and what is needed. What is needed is a sign wave and which is almost close to its positive peak and what you want is; you know what you manage to apply is minus V.

So, there is a very big difference between what is needed and what is applied during this interval of time, so it is better to apply a slightly different kind of a waveform. So, let us say you apply the same plus V here; there is a notch as shown by the red colored waveform there is a notch. But during this notch, the voltage applied is only 0 it is not equal to minus V.

The same way you go around; you apply a notch, so what have we done now we are applying a notch during which the voltage is equal to 0 or not equal to minus V. This way we may be able to produce same amplitude, but the instantaneous error between the desired waveform namely the sine wave and the actual applied waveform; namely this pulsed waveform you can see that it is not very different, it is much less than what it was before.

So, what we normally want to do is we want to apply either plus V or 0 during the so called positive half cycle of the waveform and we want to apply minus V or 0 during the. so called negative half cycle of the AC waveform that we decided to. So, it need not be one notch; it can be many notches or it can be seen as several pulses as indicated in this waveform here. You can see that there are several pulses now and these determine; there is some amount of fundamental voltage and the width of these pulses can be controlled. If you control the width of these pulses that I have indicated here, you will be able to adjust your amplitude of the sine wave or the fundamental component of this waveform.

Now, you can also do better by modifying the widths; I mean modulating the widths in a particular fashion here. So, by doing all this you will not only be able to control the amplitude, you will also be able to reduce the harmonics substantially. This is what we will be trying to do in a more systematic fashion and at greater depth in the later lectures to do now.

For now what we are looking at is what is it that we expect the power converter to do? What kind of converter is required for DC to AC inversion? That is our question. So, that is what we are looking at, so this converter should be capable of taking an input V; DC input V and producing an output which is either equal to plus V or equal to minus V or equal to 0; that is what we want.

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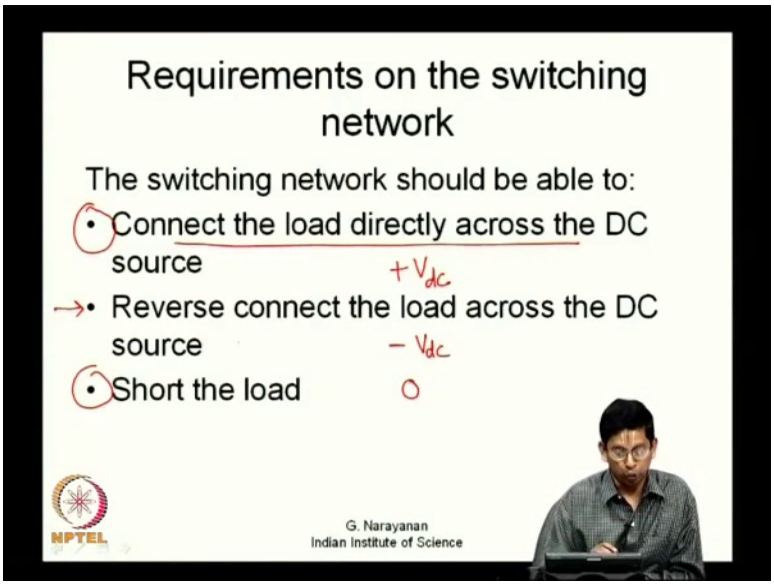

So, the switching network should be capable of connecting the load directly across the DC source; that is you are producing an output equal to plus V. If you call V DC as the input voltage, DC input voltage it should be capable of applying plus V DC between the two output terminals. Again this switching network should be capable of reverse connecting the load across the DC source that is; it should be able to produce apply an output voltage of minus V DC also.

It should be able to short the load which means the output voltage is 0, it should be capable of doing these three. In the case of DC to DC converter for example, in the case of a buck converter; we saw that we wanted the network to be able to connect the load across the source. And we also saw that the network was required to short the load, but this is now different.

In the case of DC to AC conversion; what we want is we also want a negative voltage to be applied; we also want the load to be reverse connected across the source whenever it is necessary now. So, these are the requirements on the switching network; so, how should the switching network look like here?

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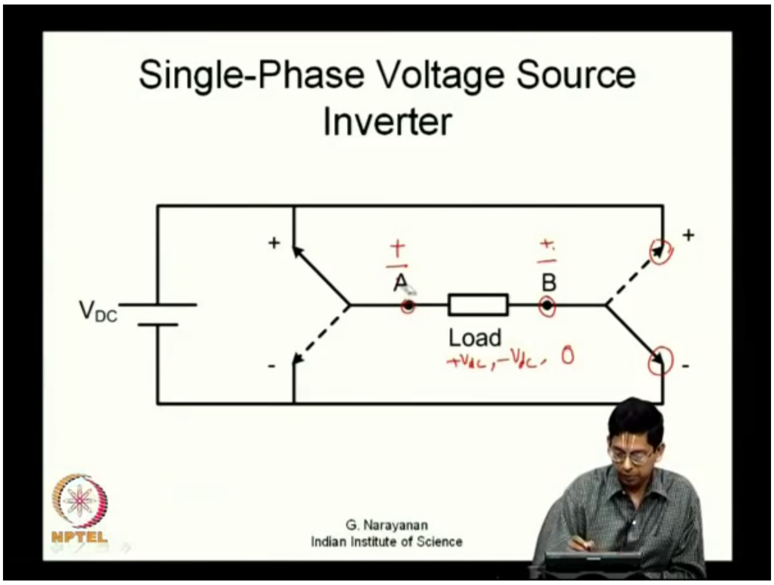

We have something like this; this is load. Let us presume that the load is inductive that is how many loads are; it is R L or it can be an active load where some resistance inductance and there is also certain (Refer Time: 23:38) is here now that is the kind of load we are looking at and there is certain amount of inductance in this load now.

So, what are we going to do here? So, these load what you want is you want to apply either plus V or minus V or 0 across this. One simple way to do that is to have a single pole double throw switch like this where the pole is connected to A and the two throws are connected across plus and minus, so A can be either positive or negative.

Similarly you have B; so now this B this is another single pole double throw switch, the pole of that switch is connected to the other load terminal B and the two throws are connected across the power supply; the DC supply. So, B can also be positive or negative it can be either connected to the positive bus or negative bus and so you have all these combinations. A can be positive, B can be negative which would mean you can have plus V DC applied across the load. A can be negative, B can be positive which means you can apply minus V DC across the load.

How about 0? A can be positive and B also can be positive that will make it 0 and also A connected to negative and B connected to negative; that will also give you 0. So, you can short the load in two different manners; by connecting both the poles through the top throws or both the poles through to their bottom throws, so there is an option that is available here.

As far as if you look at this option what matters is; the state of the switch is different, but the output voltage is the same. So, we will use this in kind of coming up with certain modulation methods later on. So, now let us say that we want to do this now, this is the kind of switching network that we want and this switching network satisfies the requirement that we are talking about. What is the requirement? It should be capable of applying plus V DC minus V DC or 0 across the load, which it is capable of doing so; so it is doing fine now.

The next point is to issue is how do we realize the single pole double throw switch? That is our next question now. How do we realize that? Let us just say we have; let us clear a part of it; we need to find out what are the conduction blocking requirements? Now this is load what you apply here is this is an AC load; what is produces on the AC side of the inverter, it is an AC load. So, the current here is really bidirectional; what you really have is a bidirectional current. During the positive half cycle, the current flows in one direction and in the negative half cycle, it flows in the other direction.

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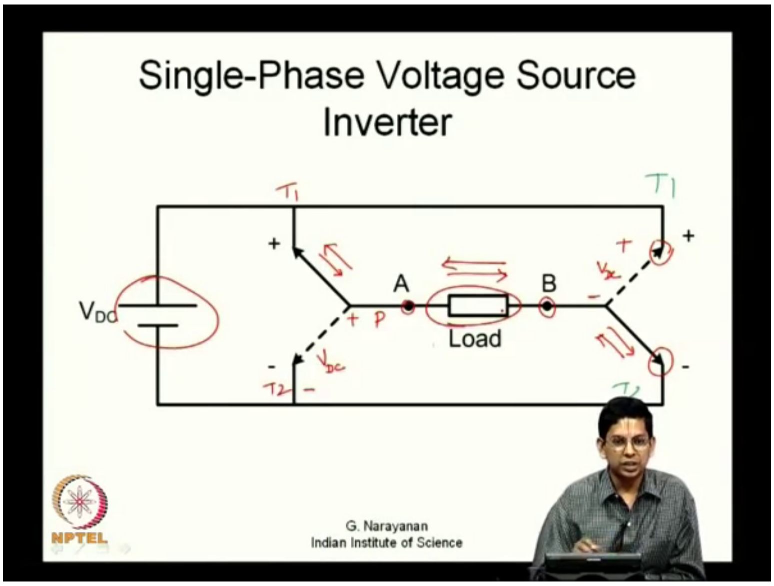

So, what you want to do is; to connect A to the positive throw or the negative throw as you wish, independent or irrespective of the direction of current. The current may be flowing from left to right or right to left, you want to connect A to plus; that is what let us say you have done now. So, between A and let us call this as this is pole P and let us call this as T 1; between P and T 1.

What do we want? We want a switch which can conduct in either direction. The direction of conduction will depend upon the load current; so, we want a switch which can conduct in either direction. When the pole P is connected to throw T 1 like this, what happens between P and T 2; obviously, the switch between P and T 2 is off and it is blocking certain potential. What is the polarity of that potential? Since A has been or the pole P has been connected to the top throw.

So, what you have is, this is connected to the positive DC bus voltage. So, this is point is positive and the throw T 2 is connected to the negative of the DC bus and the entire DC bus voltage gets separate across that. What you get between P and T 2 is the entire DC bus voltage and P is positive with respect to T 2; that is what we find here. This is the kind of conduction blocking requirements we want now.

Now let us look at this side, here let us say this B or this pole is connected to the bottom throw. So, here also you need this switch to conduct in both the directions depending upon whatever is the load. Now since the pole is connected to the bottom throw, here the pole is at a negative potential and the throw is at positive potential and this is blocking a potential V DC as shown here now.

So, both the top switch that is between pole and the top throw or between the pole and bottom throw, the requirement is just the same; that is the switch should be able to conduct in both the direction. And it should be able to block a potential of a particular polarity, the top pole to throw; if you consider the top pole to throw, the throw voltage will be positive with respect to the pole. If you connect the bottom consider P and T 2; then it has to block a potential where P will be positive with respect to T 2; this is the requirement that you want now.

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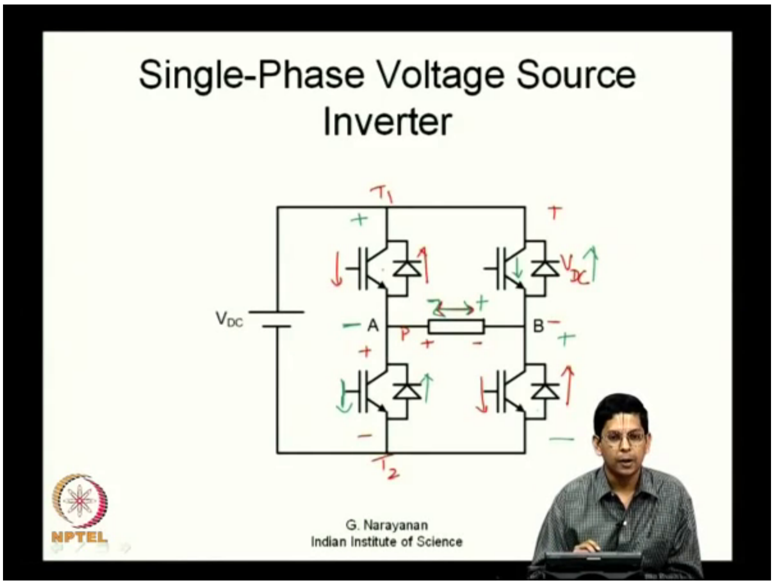

So, you want to come up with a particular set of electronic switches now. What you do? Is you can have a switch like this. So, you can have a bidirectional conduction here, you can have a bidirectional conduction; any direction the load current might be flowing now.

So, if the load current is in one direction; the transistor will conduct. If the load current is in the opposite direction this can conduct and let us say this switch is also on correspondingly depending on the load current direction, the transistor will conduct or the diode will conduct. And when you have such a state, what happens? A the load terminal A or the pole of this single pole double throw switch, this leg is a single pole double throw switch, this is pole to throw; this is pole P, this is throw T 1, this is throw T 2.

So, you have a bidirectional conduction between P and T 1 and P, the potential at P is now equal to the positive, it is connected to the positive terminal of the DC source now.

So, what happens to the switch between P and T 2? It blocks a potential like this. So, essentially the transistor is blocking, a potential where its collector is positive with respect to emitter. Similarly, what happens here? This is been conducting, so therefore B is at negative potential and this is at positive potential, this is blocking a potential like this.

This is in one of the states. Let us say when the output voltage is equal to plus V DC. Since this is connected here, the load is like this A is connected to the positive bus, B is connected to the negative bus and we have plus V DC applied here. Now let us look at a scenario where minus V DC is applied, I am indicating all this in green colour. The load current once again is a bidirectional current, it can be either flowing in one direction or the other direction.

So, now which switches are on; the top switch is on and this bottom switch is on now. So, you have the top being on; so this is plus and this side is minus; this is the potential that is applied now. When the top is on, this has to conduct and this has to conduct depending upon whatever is the direction of current flow now. If the direction of current flow is like this, then the transistor conducts. If the direction of current flow is the other way the diode conducts.

Similarly here also you know it depends on the direction of current, the transistor conducts in this direction, and the diode conducts in the opposite direction. These are all bidirectional current switches, switches with bidirectional conduction capability. Now, what happens to the other two switches which are blocking a potential? So, this is connected to the positive bus, this is connected to the negative bus. So, this transistor is blocking a potential positive with respect to negative and here again it is blocking a potential which is positive with respect to negative now.

So, whatever we wanted here we are able to realize; what we want here is between a pole P and let us say throw T 1; we wanted a switch which has bidirectional conduction capability. And therefore, you have a (Refer Time: 32:14) and a anti parallel diode which has the bidirectional current capability. Then you want let us say between P and T 2 when P and T 1 are connected; P and T 2 should be able to block a potential with this polarity, you see that you can block it with this polarity.

Similarly, if pole is connected to throw T 2 you needed a bidirectional current carrying capability which you have here and you wanted the top switch to block a potential with polarity T 1 being positive with respect to P, which it does now. So, what we do here is now from a single, single pole double throw switch; we moved on to two single pole double throw switches. Because now you see the load has two terminals now, it has an AC load it can conduct in both the directions.

One terminal is connected to one of the poles, the other terminal is connected to another pole and the load is assumed to be inductive as I mentioned a little earlier now. And the two throws, they are connected across the DC bus; you see this throw T 1 here and the throw T 1 here also are connected to the positive terminal of the DC bus. Similarly throw T 2 and throw T 2 here or both connected to the negative terminal here.

So, the rule that any inductance or current source is connected in series with pole P and the capacitance or voltage source is connected across throw T 2 is what you are doing now. This is a switching network which can apply either plus V DC minus V DC or 0 across the load and it satisfies these conditions; that pole is connected to the inductance or current source and throws are connected across this. So, that is how we have come to this now and the next stage of this is realizing; I mean electronic realization of the single pole double throw switches, which is what we did just a while back now. So, let me just clear off all this so, that we see a clear picture of the inverter.

So, now you have a voltage source inverter which is been realized using some transistors; I mean or IGBT; let us say with the anti parallel diodes, this is what you have. Now, these such devices are commonly available and voltage source inverter is very very popular these days. So, we will look at how do you do further control etcetera as we go about now. What is clear is; you have these two, either the top is on or the bottom is on; this is a single pole double throw switch.

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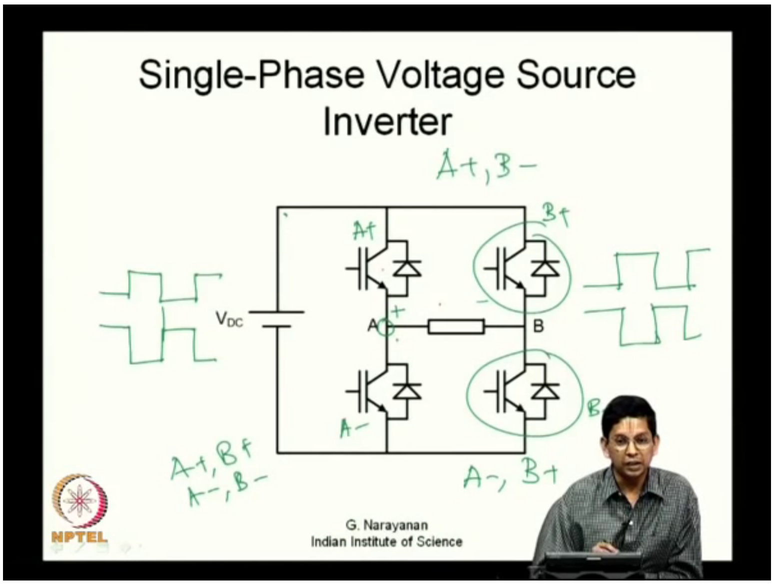

So, if the top is on the bottom has to be half and vice versa. So, if the top transistor in A is gated like this; the bottom has to be gated like this complementary to that, these two are complementary to one another. So, this is how they are gated; if the top is on then the potential here is equal to plus.

If the bottom is on, the potential at A is equal to I mean; A gets connected to the negative bus of; this the negative terminal of this DC supply. So, similarly when you have B; this B can be connected either to the positive supply or the negative supply, here also these two transistors are switched in a complementary fashion, the top transistor on the bottom transistor are switched in a complementary fashion. If the top transistor is switched like this, the bottom transistor is switched like this.

So, there is also something called dead time; that is the outgoing transistor is turned off slightly ahead of the turning on or the getting on of the incoming transistor, which is called dead time; we will ignore it for now, we will deal with it a much later in this course now.

So, you but as of now let us say that the transistors are they have instantaneous turn on, turn off; they do not actually, but we will ignore the switching transitions for the time being, we will deal with them as ideal devices. So, ideal devices do not drop any voltage; when they are on; do not conduct any current when they are off and their switching transitions are instantaneous.

So, these are the attributes of ideal switches and let us regard all these switches as ideal now. So, you will switch them like this and whenever A; the top and let us call this as A plus and let us call this as A minus. Let us call this as B plus, let us call this as B minus; so whenever you have A plus and B minus on, you have a particular potential that is V DC.

And whenever you have A minus and B plus or on, you have the output potential is equal to minus V DC. And whenever A plus and B plus are on or A minus and B minus are on, the load is simply shorted; what happens is a kind of free-wheeling; just the stored energy in the load continues to flow through that, there is no transfer of power between the DC source and load during that interval of time.

So, this is how you look at; this is a single-phase inverter now, what we want to see is also can we inward DC into three-phase AC?

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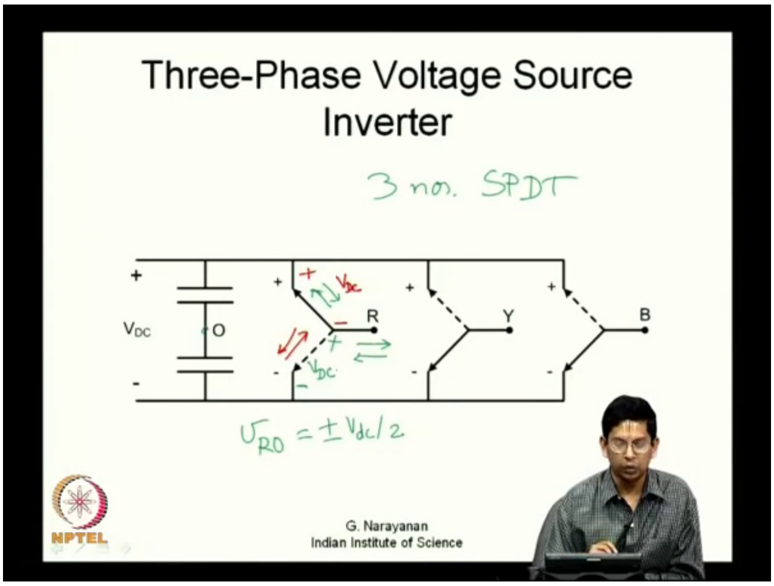

Because more often you need three-phase AC, what should we do now? Now the load does not have just two terminals, a single-phase load has only two terminals; which we called as A and B earlier. Now let us say there are three terminals and let us follow the notation R, Y, B; now we have three terminals. Now the load is presumed to be inductive, so every terminals of the load should be connected to a pole.

So, you cannot have just two poles; you must have three poles or you must have three numbers of single pole; double throw switches instead of two numbers that you had before now. This is what you mean by adding an additional leg, earlier the voltage source inverter had only two legs; the single-phase voltage source inverter because the load has only two terminals.

Now, you have three; so, you have an additional leg added in here now. The configuration is essentially the same now; the three-phase load is connected to these points R; which are indicated as R, Y and B here now. So, the midpoint of the DC is a convenient point for considering all our measurement, this point may not be available but analytically we want to express this potential R; potential at this pole R or at this pole Y or at this pole B with respect to some point of reference. And this O or the DC bus midpoint or the DC bus neutral as it is variously called is a convenient reference. So, we will say V, R, O for example, which means the voltage at this pole R measured with respect to O, this can be either plus V DC by 2 or minus V DC by 2.

If R is connected to the top throw; V R O equals plus V DC by 2. If it is connected to the bottom throw V R O is equal to minus V DC by 2; this is what we have in all the three legs. So, you have now a three face inverter; which has been represented in terms of single pole double throw switches. How do you electronically realize? It is pretty much the same as in previous cases now; so, this current R it can be in either direction. If you look at R, the current may be flowing either in this direction or it can be flowing in the opposite direction.

So, if R is connected to let us say the positive throw; this has to be capable of conducting in both the directions. Similarly, if it is connected to the bottom throw it should; once again be capable, but let us say R is connected to the positive throw; what happens to the bottom throw? Mean what happens between the pole and the bottom throw? There is a switch which is open, which is off and this switch is blocking a voltage and what is it blocking? R is connected to the positive terminal of the DC source. So, it is plus and throw is connected to the bottom of DC; so, it is minus; it is blocking a potential equal to V DC, the DC bus voltage V DC.

If you look at the other state of this single pole double throw switch; let us show that in red colour, where the pole is connected to the bottom throw. Then what you need is; the bottom switch should be able to conduct in both the direction and how about the top switch? The top switch is now off and this is positive, this is negative and it is blocking a potential of V DC; this is what you have in the top switch now.

So, what you need is once again you need a switch between the pole and throw; which can conduct in both the directions and which can block a potential of only one polarity, which needs to block a potential of only one polarity as we have indicated here now.

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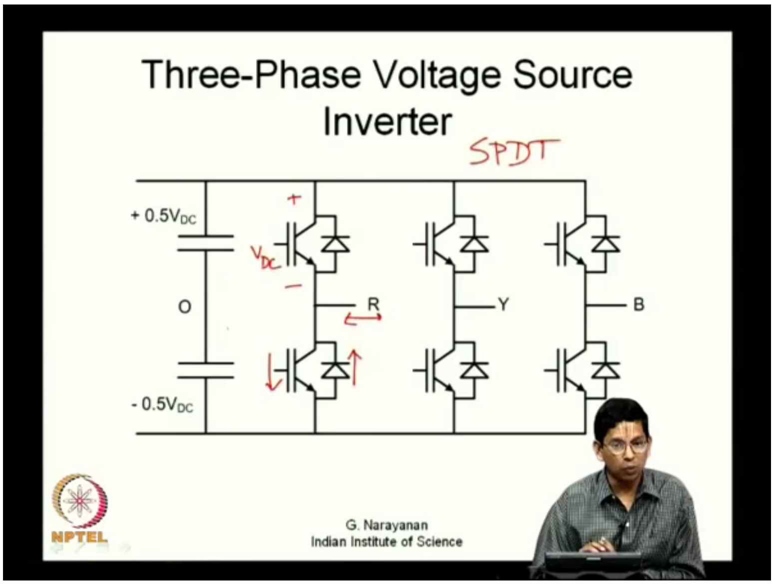

So, it is just same as the same thing that we used earlier, you have a top transistor with an anti parallel diode and a bottom transistor with an anti parallel diode; this will serve the purpose now. So, this for example can conduct in both the directions; the bottom transistor is on, this can conduct; the transistor will conduct in this direction or the diode will conduct in this direction depending on the direction of your load current here, whether it flows this way or that way.

And the top transistor if it is off, it will be blocking the DC bus voltage with such polarity as indicated here; the same thing applies to the other next two. So, here also what you find is basically the top and the bottom switches are switched in a complementary fashion so that every leg is a single pole double throw switch. And you have three numbers of single pole double throw switches here.

So, the poles are once again connected to the load terminals which are inductive; load being inductive and the throws are connected across the power DC supply. So, now this is a three-phase voltage source inverter; let us quickly take a look at three-phase current source inverter. What are we trying to do here? We want to produce AC from DC, but this DC is what you have is a DC voltage available and you want to produce an; you get an AC voltage output at that.

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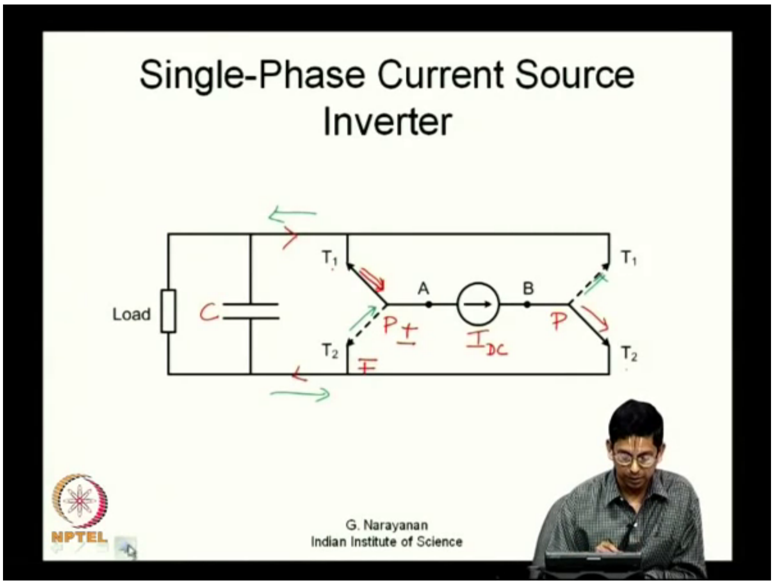

Now, what let us say; what you have is not a DC voltage source, but a DC current source what do you do, it is actually fairly simple. So, you look at this you look at a single-phase voltage source inverter; so what do you have here? You have a load here and you have the DC supply connected here. You just interchange these two, you get a single-phase current source inverter.

You have a DC current source I DC, the current source has two terminals and you should provide a path for this current to flow through. So, both these terminals are connected to poles, this is connected to pole of one of the SPDT switch and this is connected to another pole of another SPDT switch now.

So, this pole; this is also a pole, this is also a pole now. So, these poles they are either connected to the top throw T 1 or bottom connect or bottom throw T 2 at any given instant now. And T 1 and T 2 are connected together to one of the load terminal; sorry similarly the bottom two throws of the two SPDT switches are connected together and brought out as a single load terminal now.

So, what you now have is; the load terminals across the throws you have the load connected. And the load is now a voltage stiff load, I mean it is capacitive load; you have a capacitance C; a fairly big capacitance C connected across that. This is an AC capacitance now because it actually has an AC voltage across this now.

So, what do you want here? Basically you have a current source and this current source you are providing a path for this current source to flow through now. What you want here at this point is a bidirectional current; let us say you want current I to flow like this. So, if A is connected to the top throw; it will flow like this, if B is connected to the bottom throw it will flow like this and current will flow back this will be the direction.

Alternatively, let us say you want the current to flow in an opposite direction; let us say you want the current to flow in this direction. So, if you want the current to flow in this direction it flows here, so what you do is, it flows from T 2 to P then this current source on the next path is P to T 1 and back here. So, what you do is you are injecting an alternating current into this load circuit and this load as a capacitance connected to it in parallel to smoothen out the voltage waveform that you will get; as we discussed here very very I mean similar to what we discussed while we were discussing a voltage boost converter or a current buck converter now.

So, this is what you do now; you manage to pass an AC current through this now. So, this AC current; so, the voltage across this is also actually an AC voltage now. So, next step that you will have is to realize this switch now; one thing that we observe is the load current is this is not the load current, this is the source current, it has a fixed direction. So, if you look at between any pole and throw, what you need is now a uni-directional current conduction, you do not need a bidirectional current flow; as you needed in a voltage source converter.

It is now a unidirectional source, but how about the voltage blocking? So, let us say that this pole is connected to the top throw and the current is flowing as indicated here. So what happens? Pole is connected here and what happens between this pole P and throw T 2, the load voltage appears across that, the load voltage it can be of either polarity. So, the load voltage can be this positive and throw 2 negative or it can be pole positive and the throw 2; I mean pole negative and throw 2 positive, it can be of either polarity.

P may be positive with respect to T 2 or P may be negative with respect to T 2, it depends on what the load voltage is at that instant. So, what you need is between P and T 2, a switch which in its off condition can block a voltage of either polarity. So, now what you once again need is a two quadrant switch, but in a voltage source what we needed was a two quadrant switch, in terms of the current conduction.

Now, what you need is a two quadrant operation in terms of the voltage blocking; you want a switch which can conduct in only one direction, but it should be capable of blocking voltages of either polarity; so, what do we do now?

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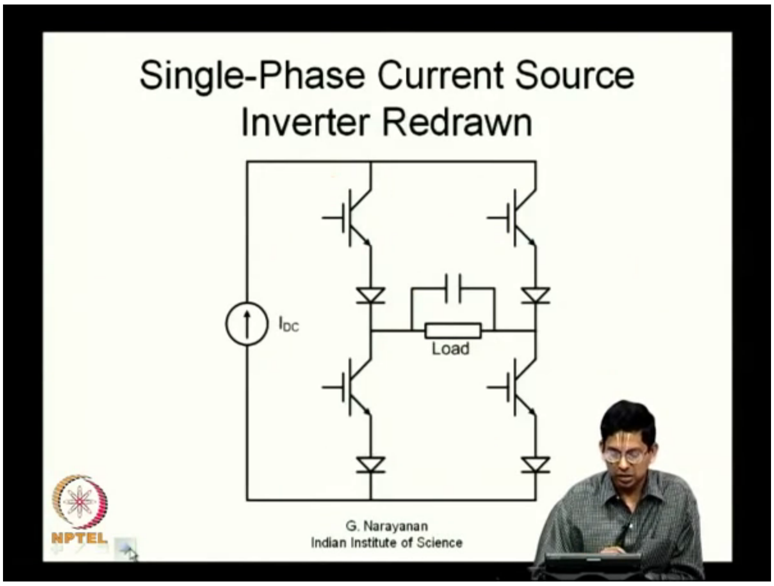

Let us say this is a simple option; a thyristor is actually a natural option. A thyristor can actually conduct in only one direction and it can block, a potential in the off state and I mean if it is a reverse bias; it will block a potential as indicated here. If it is forward biased, it can still block a potential as long as it is not fired on. So, a thyristor is a two quadrant switch as we discussed in the very first lecture, which is capable of conducting in one direction, but blocking voltage of either capability.

It is a natural option for such a current source inverter, but should you want to use a transistor or an IGBT; what you can do is you can connect a transistor with a diode in the so called anti series fashion as we discussed before. So, both of them conduct actually in the same direction and the transistor; if it is off; in the off state the transistor can block a potential with this polarity and the diode can block with another polarity.

So, together the combination of these two switches can block a potential of either polarity; as you know what a thyristor can do. So, this is what you need now and now you get that this is a current source inverter. So, if you have this conduction here; you will also have; if let us say these two switches are on, it will flow like this and the current kind of flows through this around this now.

So, again in this situation let us just erase this part, let us say the current is flowing like this. So, what happens here? It depends on this switch is off and it has to block a potential and it has to block a potential which is actually really bipolar in nature, it can be either positive or negative. So, this transistor is capable of blocking with this polarity and this diode is capable of blocking this polarity.

So, the two of them together can block any potential of either polarity, so you get a two quadrant switch here. The same situation here also, this can block a potential of this polarity and this can block a potential of this polarity; together the series connection of these two switches can block a potential of either polarity. So, now what you have is this switching network can allow a current equal to I DC to flow here.

It is not just I DC, it could be minus I D C; so, it can be plus or minus I DC that flows here and this current can also be 0; let us say if both these transistors are on then the current gets a path to flow around like this. Alternatively, let us say let us choose some other colour; if these two transistors are on then the current gets to flow like this, it does not flow through the load.

So, the load side current will be equal to 0; so like a voltage source inverter is capable of applying plus V DC minus V DC or 0, this is capable of injecting plus I DC minus I DC or 0 through the load; this is a current source inverter now.

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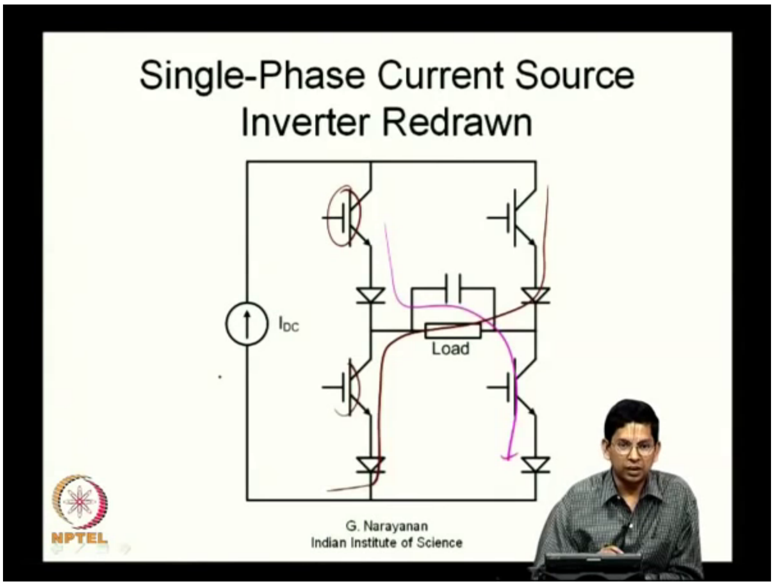

So, how can you have a three-phase current source inverter is one question. Before that let us just have this redrawn because this I have drawn it with some orientation, here I am just drawing it with a different kind of an orientation now. So, the current source is shown separately as a source and the load is shown connected here now. And you see that the current can actually flow in one of the directions the current can flow and if you will change it the direction; the current can actually flow in this direction back.

So, it is also possible for the current to be both these switches, the top and what is indicated is top and bottom can be turned on so that the current source is just shorted and there is no transfer of power from the current source or between the current source and the load now.

So, let us say you want to do your three-phase inverter now; how do you get a three-phase inverter is a question now.

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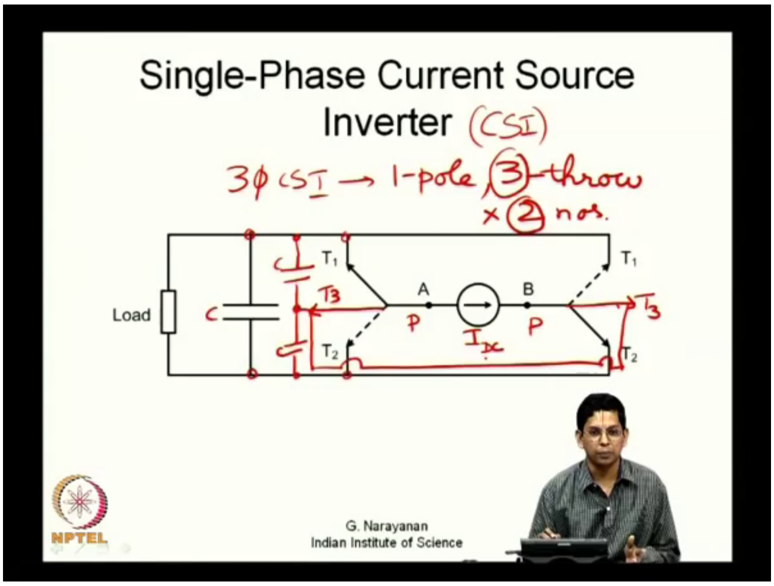

So, once again we are looking at single-phase current source inverter and what we need now is a three-phase current source inverter. So, what we need is a three-phase current source inverter, what is the difference between a single-phase current source inverter and a three-phase current source inverter? Is the difference in the DC source? No. Is the same DC source I DC that is going to be used in both, whether it is a single-phase CSI or a three-phase CSI. So current source inverter CSI; actually an abbreviation for that; so, whether it is a single-phase or three-phase it is the same thing.

So, it is the same current source; so, it has two terminals and these two terminals are connected to two poles now. So, you still need only two switches, but what you now have is instead of a single-phase load; you have a three-phase load. A single-phase load has two terminals which are connected to the two throws whereas, what you now need; what you now have is a three-phase load and you need three throws. So, what we have is we need an additional throw here; let us call this T 3; we also need an additional throw here in this switch; let us call this T 3.

So, just as T 1 throws T 1 of the two are connected together and throws T 2 of the two are connected together, the throws T 3 of the two should also be connected together. It will get a little clumpsy if I draw on this, but anyway let us just draw this and see how it looks. So, the two throw have been connected together and this becomes the third load terminal. So, you have 1 terminal, 2 and 3; you have 3 different load terminals available now. And you have capacitances across every two of them; you have a capacitance C that is connected across every two of those terminals. So, these terminals can be called as R, Y and B; if you wish.

Now, the loads can be connected across these capacitances. So, thus you get a single-phase I mean; I am sorry you get a three-phase current source inverter, it is still a DC source, but you have three-phase load and you have three capacitors connected to this now. So, for this for a three-phase CSI; what do you need? You need a single pole triple throw switch, how many in numbers? Two numbers; so why do you need 2 numbers? Because you have a current source with two terminals, why do you need 3 throws? Because your load is now a 3 terminal load; so, you need 3.

So, for a single-phase CSI; we just had two single pole double throw switches. For a three-phase CSI, we have two single pole triple throw switches as we have shown here now. You have two legs here and you have the single-phase load connected here, what you can do is; you can have another leg connected like this.

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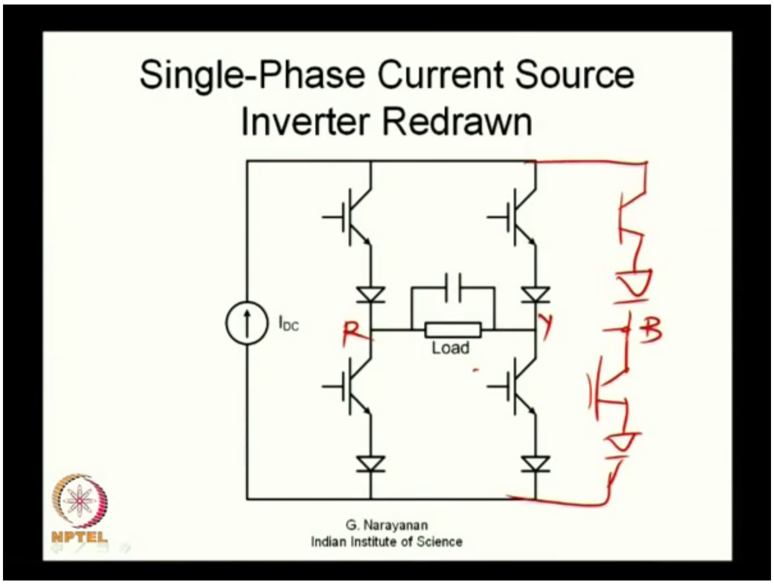

You have one more leg connected like this and this becomes an additional load terminal, you can have capacitance here. And similarly between these two terminals, you can have capacitance connected and load also connected here. So, you can change your single-phase inverter into a three-phase inverter; let me erase these load parts.

So, these are essentially the three terminals; this would be called your terminal. Let us say R; this would be become your terminal Y, this would be become your terminal B. So, this is a three-phase current source inverter, as I mentioned here thyristor is a natural choice for doing it. So, let us just summarize; so what we would have seen is; we have seen how voltage source inverter looks like and how a current source inverter looks like we have tried to derive this; starting from our understanding of buck converter now.

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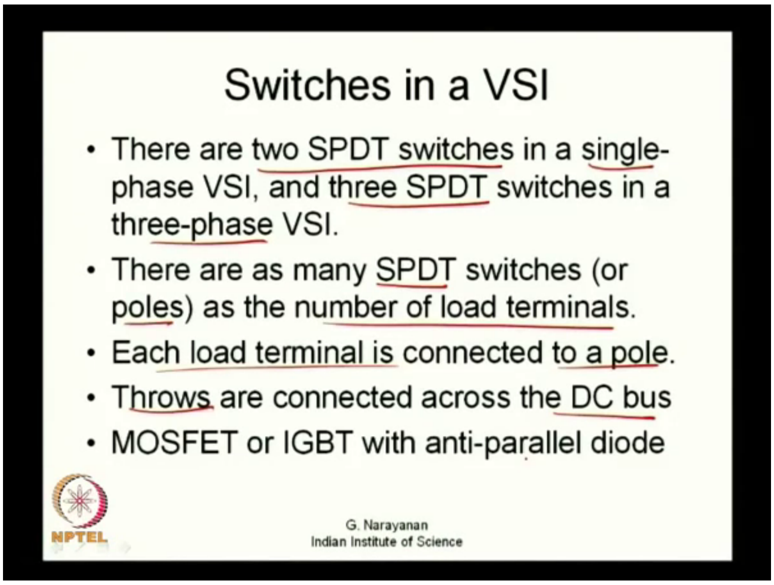

So, some points are made here; how are these switches are connected in a voltage source inverter? Here some observations we are summarizing. There are two single pole double throw switches; in a single-phase inverter. In a three-phase inverter, you have three single pole double throw switches. So, as I mentioned here; there are as many single pole double throw switches or as many poles, as there are load terminals.

In a single-phase load, you have two terminals therefore, you need the load is inductive. So, you need two poles or two single pole double throw switches, in a three-phase inverter you have a three terminal load. So, three poles or three single pole double throw switches now. So, each load terminals is connected to a pole as indicated here and how about the throws? The throws are connected across the DC bus; the DC bus should never get shorted and therefore, you always have the throws connected across the DC bus and what kind of switches you use? You either use MOSFET or IGBT with anti parallel diode.

So, these devices are; this is an IGBT with an anti parallel diode is capable of conducting in either direction and blocking a potential of only one polarity, the collector being positive with respect to the emitter now.

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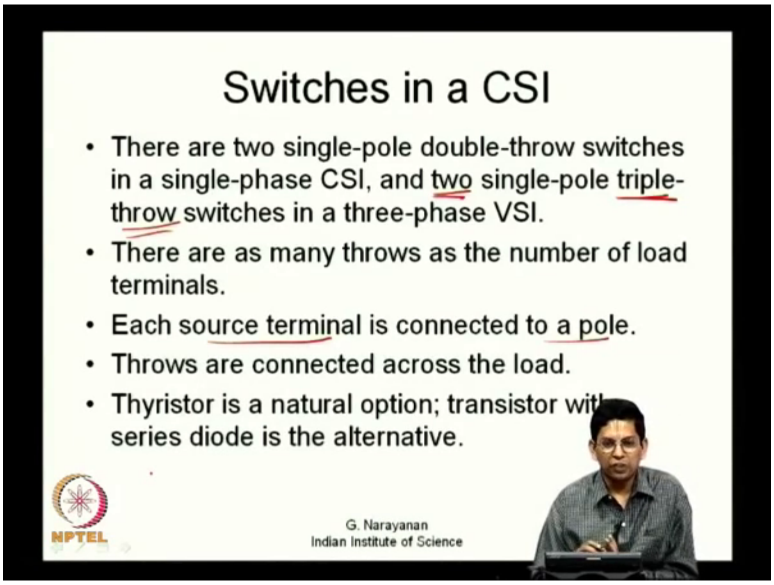

On the other hand, if you look at a current source inverter; what you need is you still need only two numbers of switches; it is a single-phase inverter requires two single pole double throw switches. If you go for a three-phase inverter, you still have only two, but you need triple throw switches. Because what happens, the current source are connected; each source terminal is connected to a pole and the throws are connected across the load, the load has three terminals and you have three throws here.

And in this case, what you need is in a current source inverter; you require a switch which can conduct in one direction, but should be capable of blocking voltages of either polarity and a thyristor is a natural option for such requirement now or such an application now. You can also alternatively use a transistor which has MOSFET or IGBT with a series diode to realize; this to this effect now. So, this is what we have seen now; so what we need is now like we saw DC to DC conversion, where we had to step down or step up a buck converter and boost converter; today what we saw was; we had DC to AC conversion.

The DC source may be available as a voltage source or current source and if it is available as a voltage source, what we want is the load voltage should have plus V or minus V applied across it or a 0. Similarly, current source should be capable of injecting plus sign, minus sign or 0 through that. So, we just saw a few possibilities and this kind of finishes the lecture for today and in a subsequent lecture, we will go to a slightly higher complex in a more complex DC to AC converter.

We will take up a multi level converter in the next lecture and thanks for your interest and your patience. I hope this was interesting to you and hoping to see you again in the next lecture. Bye.

Thank you.