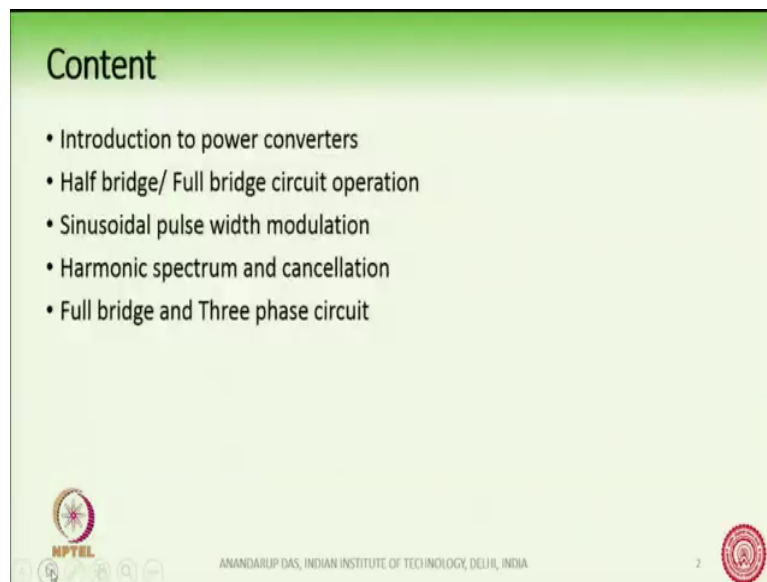


High Power Multilevel Converters - Analysis, Design and Operational Issues
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Lecture – 01
Basic Understanding of Converter - (Introduction to power converters)

So, we start with the first lecture of this course and which is Basic Understanding of Converters.

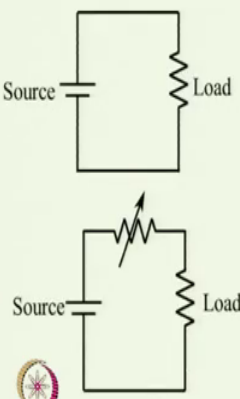
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So, in this one in this section, we will cover the basic introduction to power converters. We will study half bridge, full bridge circuit operation, a little bit about sinusoidal pulse width modulation and then full bridge and three phase circuits.

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Power Conversion



- We want to send power from source to load.
- We need to control the power flow.
- Resistive voltage divider circuits are useful to control the power flow, but they will cause losses in the system.

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So, the basic power conversion when we talk about power conversion; of course, we talk about a source of energy and sink of energy or we have a source and a load ok. So, we want to send the power from the source to the load. So, here you can see that we have a source here and we have a load here. We are assuming the load to be a resistive load here.

So, if we connect or if we analyze this circuit, this is a DC source and a load. We see that energy is flowing from the source to the load, but there is no control of the flow of energy ok. So, it is a fixed source and a fixed load and we cannot control the flow of power from the source to the load. So, how can we control the power flow? The easiest way of doing it is to add a potential divider or a resistive voltage divider as it is shown in the second figure, the resistive voltage divider here.

Now, if I add the resistive voltage divider and by varying this resistance on the variable resistance: I can control the flow of power into the load. However, although this system will function; however, this is not an efficient system because when we transfer the power through the voltage divider or through the potential divider or through this resistive voltage divider circuit, we lose a substantial amount of power.

In particular when we talk about high power levels is not at all suitable. This circuit is not at all suitable because it will cause a large amount of heat dissipation in this particular resistive voltage divider circuit and subsequently the efficiency of the system will go down. In all this high power conversion, efficiency is a very important factor and there are two reasons for that. The first reason why the efficiency is important is if you do not have the high efficiency you lose the energy. So, that is one important factor for any system that you want to whatever is the desirable power flow, you want to do it with the maximum efficiency.

So, that you get the maximum energy from the input, but there is another very important reason why efficiency should be very high because if efficiency is not high, then the losses in the system is very high. So, if the loss in the system is very high, then it appears as heat in the system which we need to dissipate. You must have seen power converters with heat sinks typically aluminum heat sinks is very frequently, we have seen. Heat sinks constitute a major component in all power converters because it occupies a substantial volume and also a weight of the converter.

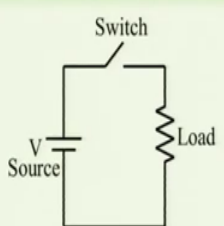
So, if the efficiency is low; that means, the losses in the system is high which in turn means that the high size of the heat sink should be bigger because we have to get the heat out of the system. So, let us take the example of power converter which is handling about 1 megawatt of power. Suppose there are two converters and the first converter runs at an efficiency of 99 percent and the second converter runs at an efficiency of 95 percent. Now in the first converter the losses in the system is 1 percent of 1 megawatt and which is equal to 10 kilowatt and for the second converter, the losses are 5 percent. So, the loss is equal to 50 kilowatt.

Now this means that all this loss is appearing as heat in the power converter and which must be totally dissipated into the ambient either through by natural cooling by air or by forced cooling through water or some kind of oil for example. So, the losses play a very vital role in the power conversion process and there is also one principle which is usually followed in the industry. It says this is the Arrhenius principle and it says that every 10 degree centigrade rise in the temperature of say a power device will reduce its lifetime by half. This is very important because if you operate a power device at an elevated temperature for prolonged duration of time, you are reducing the lifetime of the converter.

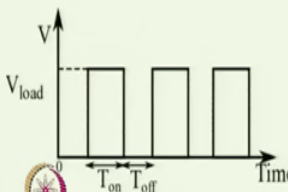
So, keeping the temperature under control in power devices or power converters is very important and there are lot of techniques to do that. Coming back to what we were discussing. So, here we see that we have a source and we have a load and the circuit although there is a potential divider or a resistive voltage divider, but unfortunately this is not a very efficient circuit because a lot of heat will be dissipated in the potential divider.

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Switch



- Power flow to the load can be controlled by operating the switch.

$$V_{load} = V_{source} \times \frac{T_{on}}{T_{on} + T_{off}}$$


- During T_{on} period, switch is on and during T_{off} period, switch is off.
- The net energy flow to the load is controlled by turning on and off the switch.
- So, we can use a switch to decrease the power loss and increase efficiency.

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So, we use; so, what is the solution for this? The solution for this is to use a switch which I have shown here, this is the switch here. Now when you connect the switch then suppose this is an ideal switch I mean it does not dissipate any heat. So, and it is a fully controllable switch which means I can turn it on and I can turn it off with control signals which is totally controlled by myself or by me. So, then we see that with this switch power flow to the load can be controlled by turning on and off this switch. If I turn on the switch if I turn on the switch, then the voltage of the source is impressed across the load.

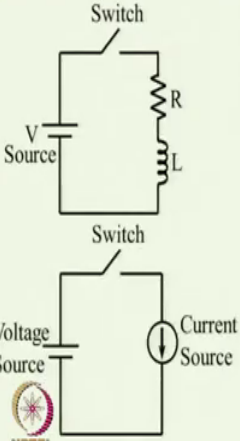
If I turn off the switch, no voltage comes across the load. So, the voltage on the load is a series of pulses which is shown in this diagram. So, when I turn on the switch that is this T_{on} period, then the load voltage is equal to the source voltage. When I turn off the switch the

load voltage is 0. So, by controlling so, therefore, there this V load which I have shown here the expression of V load is V source into T on divided by T on plus T off in an average sense.

So, therefore, we see that the load voltage can be changed by changing the duration of T on over this T on plus T off time; T on plus T off time is sometimes called the switching period. So, we can change the magnitude of the load voltage. So, we can use a switch to decrease the losses and increase the efficiency of power conversion from the source to the load.

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Inductive load



- Often loads are inductive in nature e.g. motors, transformers etc.
- Inductive loads are represented as current source.

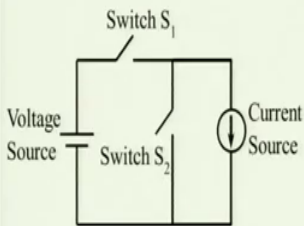
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Now, although this arrangement of load and source with the switch works well for resistive loads; unfortunately most of the power electronic converters have inductive loads that is R L loads, resistive inductive load or very pure purely inductive loads or highly inductive loads. So, often powered electronic converters feed to loads for example, motors transformers etcetera; they are inductive in nature.

Now once the load becomes inductive in nature, we face a challenge and that challenge is because of the property of inductive loads inductive loads are represented as current sources in the circuit ok. Now current source when you put into such a circuit along with a switch, then we face a challenge.

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Current source



The diagram shows a circuit with a Voltage Source on the left, a Current Source on the right, and two switches, S₁ and S₂, in the middle. Switch S₁ is connected in series with the Voltage Source, and Switch S₂ is connected in series with the Current Source. The Voltage Source and Current Source are connected in parallel with each other, and the switches are connected in parallel with each other.

- Current source and voltage source are dual in nature.
- Current sources can be shorted but they cannot be opened.
- Voltage sources can be opened but they cannot be shorted.
- Therefore we need two switches,
 - Switch S₁ opens the voltage source.
 - Switch S₂ shorts the current source.

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What is the challenge? The challenge comes from the property of current source. You know current source and voltage source they are dual in nature in terms of their properties. For example current sources can be shorted, but they cannot be opened. On the other hand voltage sources can be opened, but they cannot be shorted. For example, if you take a voltage source say a battery and then you can keep it open, you can take the volt battery in your hand and move round nothing will happen because you have opened the battery or the voltage source.

But if you short-circuit the terminals of the battery, then a very large current flows through the wire which is shorting the battery. If the voltage source is an ideal voltage source then the current which is flowing during this short circuit will be enormously high, it will be ideally infinite. Practically it will be very high. So, we cannot short-circuit a voltage source because the current will be enormously high or we do not know: what is the exact magnitude of the current only limited by the internal impedance of the voltage source.

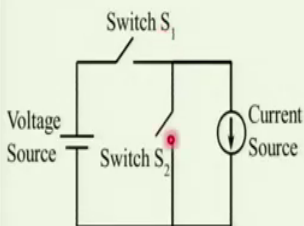
Similarly for a current source, we can readily short-circuit a current source, but we cannot open it because if we open a current source, then we do not know the voltage across the current source how much voltage will come across the current source, it will be very high. So, in this circuit, this current source here also we have to follow for this current source the same principle that it can be shorted, but it cannot be opened.

So now, therefore, in order to satisfy the property of both the voltage source and the current source, we need two switches ok, switch S 1 here and switch S 2 here. Basically we are transferring power from the voltage source to the current source using two switches here. So, what are the functions of these two switches?

Switch S 1 opens the voltage source and it isolates the voltage source from the circuit whereas, switch S 2 short circuits the current source ok. So, switch S 2 here short circuits the current source and switch S 1 here, opens the voltage source. So, we have achieved the first criteria of voltage source and current source.

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Current source



- These two switches can't be operated simultaneously, i.e. if at any time one switch will be ON, then other will be OFF.
- If they are ON at the same time, the voltage source will be shorted.

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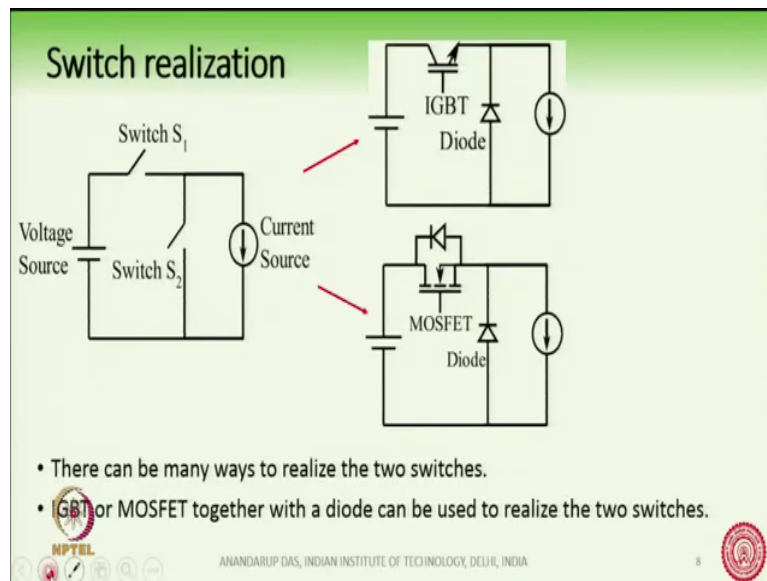
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Note that these two switches S_1 and S_2 cannot be operated together. For example, if I turn on both S_1 and S_2 together at the same time, then I am going to short circuit the voltage source which is not allowed. In a similar way, I cannot open both these switches together. At the same time in that case, I will open the current source which is again not allowed.

So, therefore, these two switches S_1 and S_2 must be operated in a complementary fashion like when S_1 is on, S_2 is off when S_2 is on, S_1 is off like that. So, they must be operated in the complementary fashion. So, how do we realize these switches in the real life circuit in a circuit real-life with real life power devices?

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There are many ways to realize these two switches ok. One way is to use for example, IGBTs or MOSFETs along with diodes. This is one of the simplest way of realizing these switches. For example, you can see on this one on this circuit we have realized using IGBT and diode. Switch S₁ here is replaced by an IGBT switch S₂ is replaced by the diode.

In this lower circuit, you can see switch S₁ is replaced by the MOSFET switch S₂ is replaced by the diode and we have the voltage source on the left and the current source on the right. This is one way of realizing this circuit using IGBT or MOSFET. We can also use other types of switches; for example, thyristors can be used.

However, in this course, we will not talk much about thyristors. The reason is many past decades thyristors have been quite popular. But seeing the future we see that in many of the applications thyristors are going to be replaced or have been replaced with IGBTs or

MOSFETs because one of the reasons is thyristors can be turned on, it is a semi controlled device. It can be turned on, but it cannot be turned off the circuit decides how to turn it off.

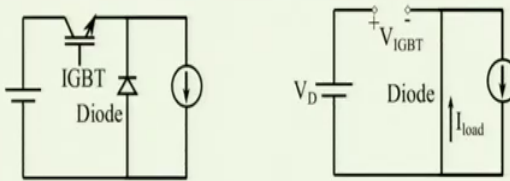
So, we see that thyristors are going to be replaced mostly with IGBTs at the medium voltage level and at the low voltage level MOSFETs will be predominant that is what we see in near future say for at least 10 to 15 years from now.

So, we are not going to talk about thyristors much in this course. Of course, thyristors will be used at very high power levels in LCC based HVDC for example. We will still continue to use thyristors, but they are very specific applications and in many new developments that is going to that is going on here now in the field of high-power high voltage HVDC for example, power electronics the thyristor newer developments are all happening with IGBT.

So, and in particular, we can also say that with wide band gap devices coming at least at the lower voltage levels huge presence of wide band gap devices are expected in near future. So, we will not talk much about thyristors in this course and mostly concentrate on IGBTs and the medium voltage level and sometimes MOSFET at the low voltage level.

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Switch rating



- Let us take the case of IGBT realization.
- The voltage rating of the switch is defined as the voltage across the switch when it is OFF. The current rating of the switch is the current flowing through the switch when it is ON.
- In this case, voltage rating of IGBT is equal to source voltage, $V_{IGBT} = V_D$. The current rating is equal to load current.

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So, let us take the case of this converter with an IGBT based realization which I have shown in this circuit here. We have a voltage source; we have the current source the IGBT and the diode here.

Now what is a switch rating? Switch rating is the rating of the switch that we are going to use. There are two there are many ratings of the switch which you can see from the datasheet of a switch, but there are two very important rating of a switch. One is the voltage rating and one is the current rating. What is a voltage rating of a switch? The voltage rating of the switch is defined as the voltage across the switch when it is off. So, when the switch is off how much voltage is impressed across the switch that determines the voltage rating of the switch.

What is the current rating of the switch? The current rating of the switch is the current flowing through the switch when it is turned on. There are many other ratings of the switch

for example, temperature rating of the switch and then there is also transient rating of the switch. Many other rating of the switch is present which if you open the datasheet of any device, you can see the different ratings of the switch. But these two rating are very important voltage and current rating of the switch.

. So, let us try to find out first what is the voltage and current rating of the IGBT and diode in this particular circuit. So, when we suppose we want to find out the voltage rating of IGBT. So, in order to find out the voltage rating of IGBT, we see or we try to find out what is the voltage across the IGBT when it is turned off. So, when it is turned off the circuit when the IGBT is turned off, the circuit looks like this. As I have told earlier that S 1 and S 2 are complementary in nature.

So, if the IGBT is turned off the diode is turned on so, I have put a short circuit here and through this short circuit the load current is flowing. Since the IGB the diode is short circuited therefore, the negative terminal of this source is connected here while the positive terminal is connected here. And so, we can see that the voltage across IGBT during this time is equal to the source voltage.

Now what is the current rating of the IGBT? The current rating of the IGBT will be equal to the load current. Because when the IGBT is conducting, the diode will be turned off because it will be reverse biased and so, the current of the load current is flowing through the IGBT and therefore, the current rating of the IGBT is equal to the load current. So, the voltage rating of the IGBT is equal to the source voltage and the current rating of the IGBT is equal to the load current. What about the diode?

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Switch rating

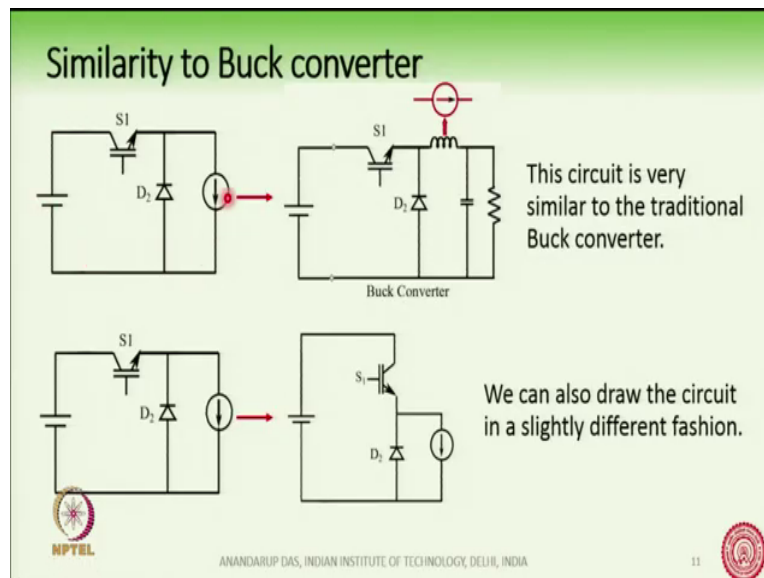
• The same rating is true for the diode.

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Again for the diode, we see that when the IGBT is turned on, then the diode is turned off. And since the diode is turned off and the IGBT is turned on so, this terminal positive terminal comes here and the negative terminal is here. So, the voltage across the diode is equal to the source voltage.

So, therefore, voltage rating of the diode is equal to the source voltage and what is the current rating of the diode? The current rating of the diode I have already shown it here is equal to the load current. So, therefore, the voltage and current rating of both the IGBT and the diode is are same; voltage rating is the source voltage and current rating is the load current.

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Now, the circuit which we have so far developed is this one with the switch diode and the voltage and current source. Those who are a little bit familiar with power electronics will immediately see a similarity of this circuit with a buck converter.

I have drawn a buck converter here and the buck converter also has a voltage source and then, there is a load, there are two switches here. There is an inductor and a capacitor. If we consider the current flowing through the inductor as a current source, then we see that the buck converter here has very much similarity with the circuit that we have developed so far. So, I can also redraw this circuit whatever I have drawn, I can draw it a little bit differently. The same circuit, but I have drawn it a slightly different as I am showing it here in this circuit.

So, I have placed the switch in a vertical position and the diode here at the bottom and the current source like this. This circuit is exactly similar to the left hand circuit. So, both these

circuits are same, I have just redrawn it. I will come I will come back to this circuit a little bit later.

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Reverse current

• Suppose the current direction is reversed from the previous circuit.

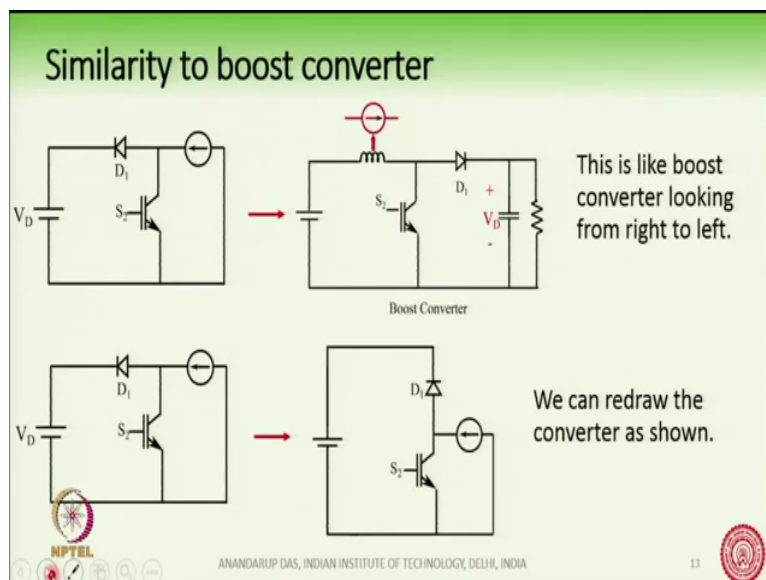
• One way to realize the circuit is shown.

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Now, suppose I have now changed the direction of the current. So, now, here let us assume that we have changed the current direction from right to left. Earlier it was from left to right, now I have changed the direction from right to left ok. What will happen now to the circuit? So, how can I realize the circuit now? So, what I can do? This is one way of realizing the circuit as you can see here, I have interchanged the positions of the diode and the transistor.

So, the IGBT has come down here and the diode has been moved here compared to the previous circuit. So, this is one way of realizing a circuit with the voltage source here and the current source here where the current source the current direction is from right to left.

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So, this circuit which is the current where the current direction of is from right to left is very similar to a boost converter, but you have to look from right to left. So, for example, this is a traditional boost converter and you have this is the voltage source and this is the load here. In a boost converter, we have an inductor at the front part of the circuit and then we have two switches here and then the capacitor which acts as a voltage source.

So, if we replace this inductor with a current source like this, then we see that looking from left to right looking from in this direction from left to right, we see that there is a current source and there is a switch controlled switch and there is a diode here and then there is a voltage source here; the capacitor is a voltage source here.

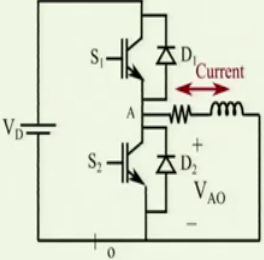
Similarly looking from on this circuit; if we look at in this circuit and see that there is a current source here, there is a switch here, there is a diode here and there is a voltage source

here. So, for this circuit looking from right to left and for this boost converter looking from left to right, we see that these two circuits are very very similar ok. Looking from left to right, there is a current source, switch, diode and voltage source; looking from right to left current source two switches and a voltage source here. So, they are very similar.

Again therefore, what I will do now I will again redraw this circuit in a slightly different fashion as I have shown it here. You can see the voltage source is here and the voltage source is here. The current source is here and the current source is here. The switch the transistor here S 2 has been now put down here and the diode there has been redrawn in a slightly different fashion here.

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Half bridge converter



- We can combine both the buck and boost converters.
- This converter is a half bridge converter.
- It can produce unidirectional voltage on the load.
- It can support bidirectional current through the load.
- All four switches are useful.

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So, we have now redrawn the circuit. Now, combining this circuit which was derived from the buck converter analogy and the circuit which was derived from the boost converter

analogy, we can combine these two circuits. And how does it look? It looks like this. This is the current source here is the current source present which is shown by an R L load here, there is the current source.

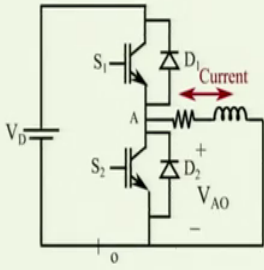
The current source is bi-directional in nature. So, it can be positive or negative. This is the voltage source here and then we have two transistors or two IGBTs here and two diodes here. So, we see that from the buck converter and boost converter topologies, the analogy from that analogy we can combine this buck and boost converter with a single circuit like this and this circuit is called the half bridge converter.

The half bridge converter is one of the basic topologies of our electronics. And also for this course half bridge converter is something which will be used frequently and derivations of half bridge. So, understanding the half bridge converter is very important for this course. So, we see that in this half bridge circuit, the voltage here at point A can be controlled by the switches S 1 and S 2. If we measure the voltage at point A with respect to point O at the bottom, then we see that the voltage at point A can be either 0 or V D. So, when the lower switch is on then the voltage is 0 between A and O and when the upper switch is on the voltage is V D.

So, the voltage between point A and O is unidirectional; however, the current which is flowing through the load can be bi-directional. So, it can be both the current can be both from left to right or from right to left that is both positive and negative current is possible. And depending on the voltage and the current situation at any instant of time, all four switches here that is the two IGBTs and the two diodes, they will be conducting depending upon the situation. So, let us see how this happens.

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Half bridge converter



V_{AO}	Operating Switches
V_D	S_1 or D_1
0	S_2 or D_2

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Say for example, if the voltage V_{AO} is equal to V_D , now if the switch is S_1 and D_1 either of them if the upper switch is on, then the voltage V is V_D . When the lower switch is on, the voltage is 0. When the upper switch is on either S_1 or D_1 will be conducting when the lower switch is on either S_2 or D_2 will be conducting.