Control and Tuning Methods in Switched Mode Power Converters
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Module - 01
Switched Mode Power Converters and Simulation
Lecture - 03
Switched Mode Power Converter (SMPC)

Welcome to lecture 3. Today, we are going to discuss basic Switch Mode Power Converter Topology.

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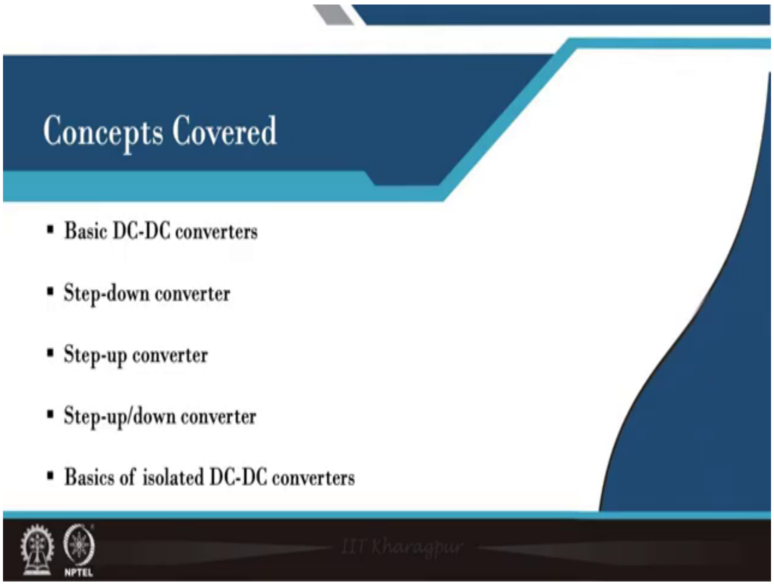

We want to cover primarily non-isolated switch mode power converters and a few isolated converters as well. In this class, only we want to limit our topological aspect because this course is primarily for control, modelling, and tuning approaches. So, we just want to re-investigate or just want to revisit the basic topology, switched-mode power converter topology.

So, here we will consider basic DC-DC converter then step down step-up converter and step-up down like buck-boost converter and a few isolated DC-DC converters.

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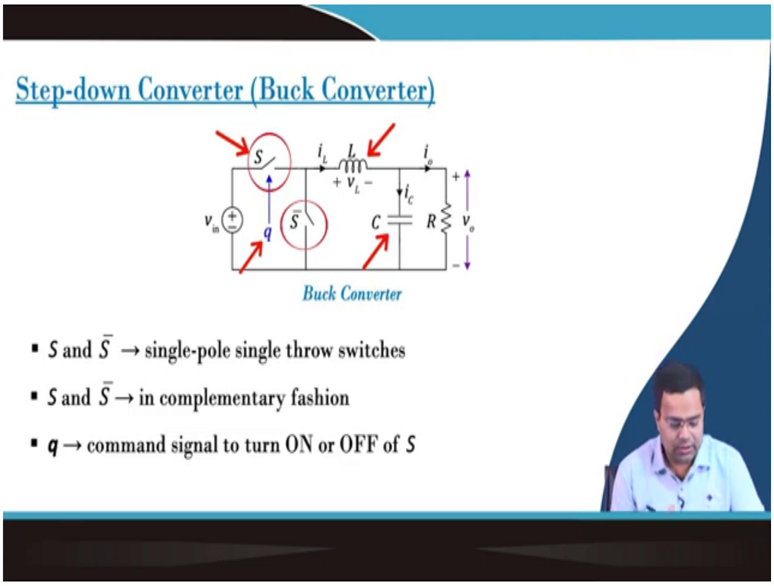

So, step-down converter switching converter, which we discuss in lecture number 2 at the end, and we talked about inductive DC-DC converter. So, in this converter, it is a well-known topology in which inductor and capacitors like this inductor and capacitor are used to yeah this inductor and capacitor are used for filter purpose and we use a switch this switch it is a single pole single-throw switch and this switch is complementary to S and this S switch is operated by this gate signal q.

And this S switch is like a single-pole single-throw switch and will turn ON and OFF by providing the gate pulse q. When the gate pulse is 1, the switch will be ON. When the gate pulse is 0, the switch will be OFF and the S bar will operate in a complementary fashion.

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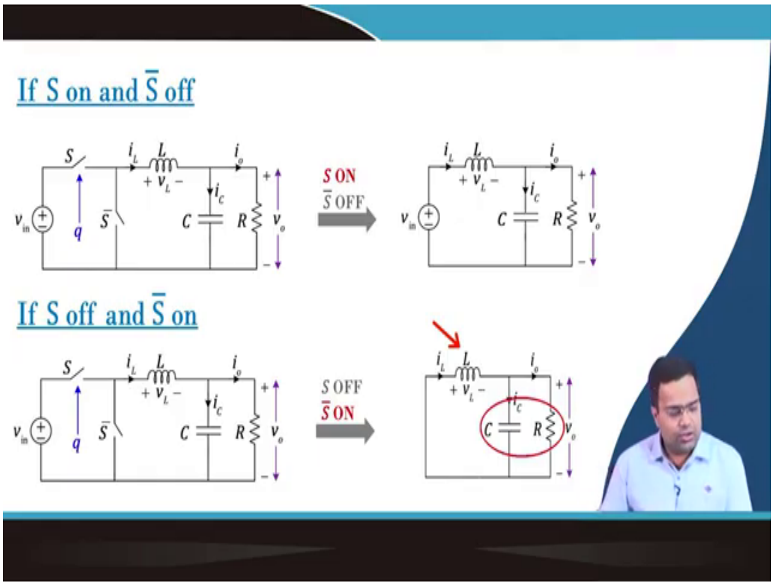

So, if we turn ON the switch q then the circuit looks like this. That means you have like a parallel RLC circuit that we have discussed in which input voltage like a DC input voltage and you have inductor, capacitor and load resistance. When the switch is OFF, that means S bar complementary switch is ON, then the overall circuit looks like this. So, this is the inductor, and this is the output capacitor and the load resistance.

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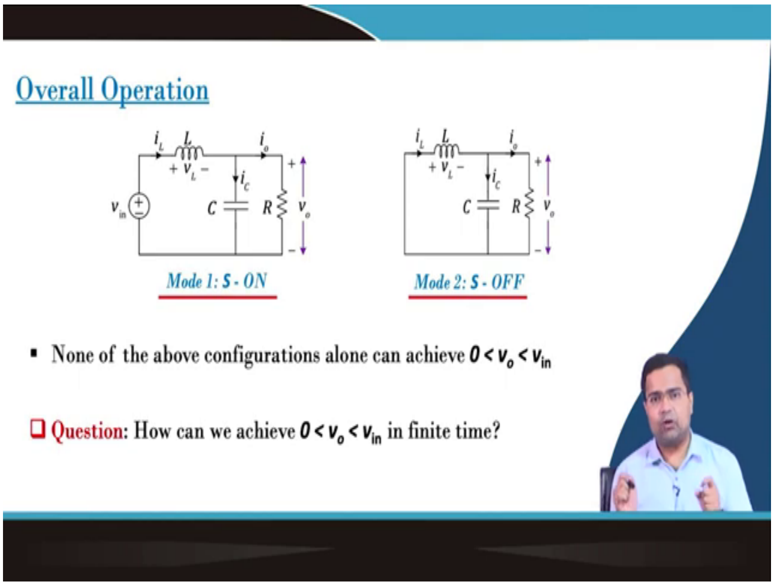

So, now if we look at the overall operation in during when the switch is ON we call it as a mode 1, when the switch is OFF we call it as mode 2. And here we are talking about asynchronous buck-converter which you know have two like a which has two MOSFETs like a high side and low side MOSFETs and the MOSFET can carry current in either direction.

So, in this case, this buck-converter will always operate in continuous conduction mode. So, that is why we are getting two configuration mode 1 and mode 2. But, none of this configuration like if we continue operating in mode 1 like a ON state or that means, during the ON state the output voltage will at steady-state will become input voltage.

Similarly, if you continue to operate in mode 2, the output voltage will equal to 0 like it will get completely, the capacitor completely get discharge. So that means, neither of these two configuration can achieve the output voltage which you want to achieve which should be higher than like which should be positive voltage greater than 0 and it should be smaller than input voltage because we want to achieve a step-down DC-DC converter.

So, we need to operate the switches in such a way so that we get the desired output voltage, which is smaller than input voltage. Now, the question is, how can we switch? Particularly, how should we generate the ON and OFF pulse of the main switch, which is the controllable switch that is S such that our desired output voltage is achieved; that means, output voltage can achieve? We can achieve the desired output voltage in finite time ok.

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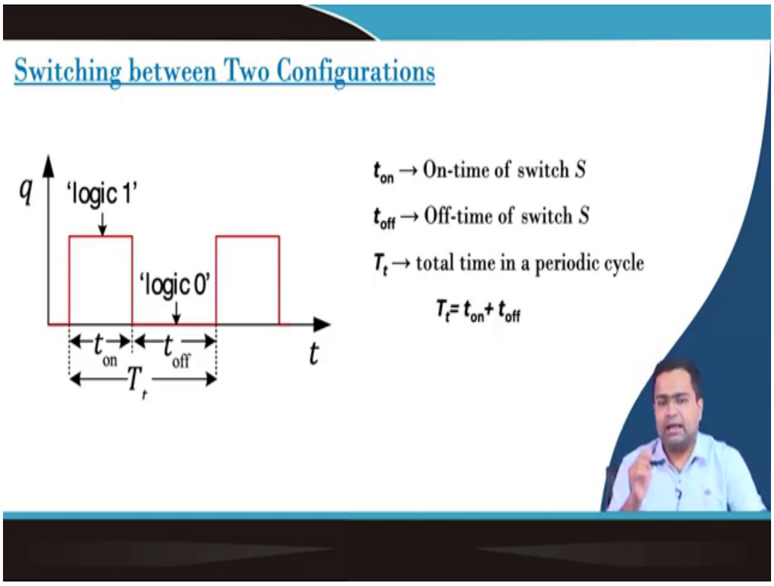

So that means the q can be set to logic 1 then the switch S will be on and when it is set to logic 0 the high side switch will be off and the complementary switch will be on. Here we are assigning time on time as t_on and the off time as t_off. It differs slightly from our conventional notation of d into t 1 minus d into t and the total time period is T_t small subscript small t.

Why we are writing separately t on and t off and the total time period? Because we are going to discuss in subsequent class, it is unnecessary that total time period has to be constant because there are different modulation technique in which you know in one case we can keep time period constant. When under that condition, like if you keep the time period constant, then we if you vary on time, then off time will be automatically adjusted from the total time.

The other possibility that we can change on time by keeping off time constant, we can change off time by keeping on time constant. In those two cases, the total time period can vary, perhaps the third possibility that we can vary both on and off time. In that case also the total time period can vary. So, these are the possibility by which we can switch the main switch like a S in order to achieve the output voltage to its desired value ok.

t on, on time of the switch S, off time of the switch S and then the total time in a periodic cycle, but at steady-state, they must operate in a periodic fashion. That means, at steady-state, the time period will be constant. But, if there is a change in an operating condition the steady-state condition can change then depending upon how we are generating the timing constant the time period can also change, but when it reach a steady-state, then that time the time period will be constant.

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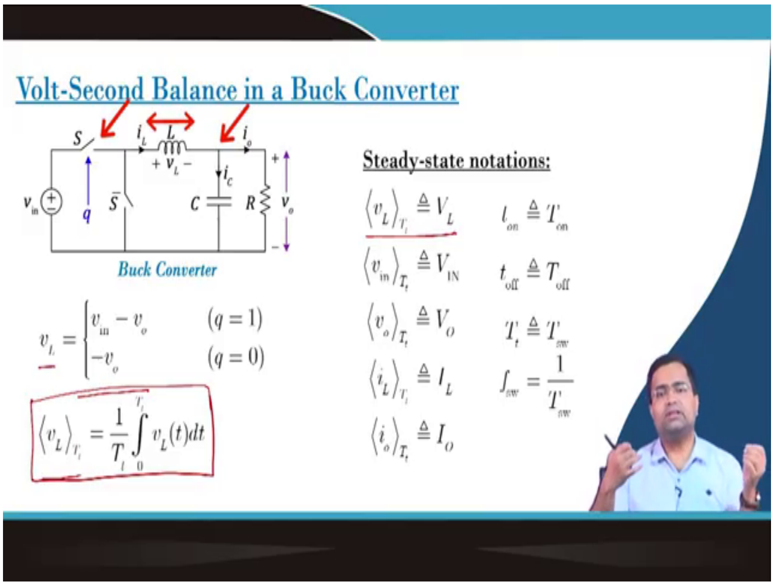

Now, this is well known, like a volt second balance in a buck-converter or any DC-DC converter. What is the volt second balance that we know, but just to revisit the concept. If we consider the voltage across the inductor, that means we are talking about this voltage.

The voltage across the inductor, this voltage changes its polarity when the switch status changes. For example, the V L for this buck-converter is equal to input minus output voltage. So, the input voltage is the voltage across this terminal and the output voltage is voltage across this terminal. So, we are talking about this terminal and this terminal. These two are the terminals.

So that means the voltage across the inductor is equal to input voltage minus V 0. You can see the right-hand side terminal is fixed, where the left-hand-side terminal the voltage can change. If S is on that can become input voltage, if S is off when the S bar is on then it will become 0 voltage and this is shown here. So, V L can be V in minus V 0 or minus V 0 depending upon whether q is on or 1 or q is 0.

Now in this scenario, we are talking about this average inductor voltage. That means, if we take the average of the inductor voltage over a periodic cycle t in this case T t, the subscript and we want to and this is well known that the average inductor voltage over a periodic cycle should be equal to 0. Why?

Because average the inductor voltage is nothing but it is proportional to the voltage across the inductor, which is the induced voltage is proportional to the rate of change of flux in the inductor. So, if we can ensure over a periodic cycle, the average inductor voltage is 0 that means the average flux change over a periodic cycle will be 0.

If we cannot ensure the average flux to be constant or the rate of change of average flux to be 0 that means the average flux to should remain constant, then what will happen? If any residual flux that keeps on building in every cycle, then it can saturate the core. So, it can saturate the core if we either keep or keep up building up or it can go down.

So, any way you know, depending upon the b-h curve of the magnetic curve, it can saturate in either direction. So, we want that average inductor voltage should be 0. Now, before we move forward, we just want to make sure that the steady-state notations are clear. So, capital all capital quantities represent the steady-state values like V_L, V_IN, V_0 then I_L, I_0 all are the steady-state quantity.

If we take the timing constant like a on time capital T_on, capital T_off then T_sw is the switching period at steady-state and then f_sw which is the switching frequency, is equal to 1 by time period.

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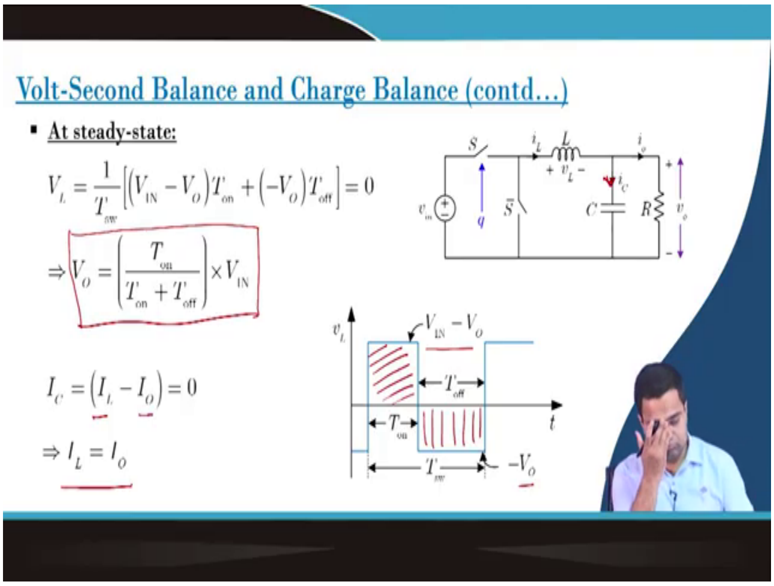

Now, we want to go next. We want to check that from volt second balance, what is the inductor voltage. We know we have already discussed that if you take the average in the average sense when the switch is on, the voltage across the inductor is V IN minus V 0 and when the switch is off, then the voltage across inductor is minus V 0.

That means, the voltage across inductor changes from V IN minus V 0 to minus V 0 and what is our interest that during on time this is the positive voltage. So, you want to show that this area under the curve during the on time period must be same as this area under this curve. That means their sum should be 0, so that the rate of change of flux should be 0 over its periodic cycle.

And if you do that the area under the curve that means, that V L which is the average voltage V IN minus V 0 then T on plus minus V 0 T off and whole thing divided by T_sw should be 0 and this gives us the output voltage expression of a of an ideal buck-converter in continuous conduction mode.

So, this expression of output voltage in terms of input voltage and the timing parameters differ somewhat from what we are familiar with that we look we always think of V 0 is equal to d into V IN and that is the case when the time period is constant then the T on by total time will be the duty ratio. But we want to take a variety of modulation technique where we need to know the individual timing parameters. So, that is why we kept in terms of T on, T off terms.

Similarly, if we take the capacitor current, if we look at this capacitor current, this capacitor current always it is always equal to inductor current minus load current. So, if you take the average over the periodic cycle, it will become the average of inductor current minus the average of load current.

And again, under steady-state, the average capacitor current must be 0 because the average the capacitor current is nothing, but it is nothing but dq/dt that means rate of change of charge in the capacitor. So, at steady-state, the rate of change of charge in the capacitor over its periodic cycle must be 0.

Otherwise, if there is any positive charge that keeps on building, then the capacitor voltage will keep on increasing and that is not permissible. So, that must be 0 and which leads to the average inductor current in this case is equal to average load current alright.

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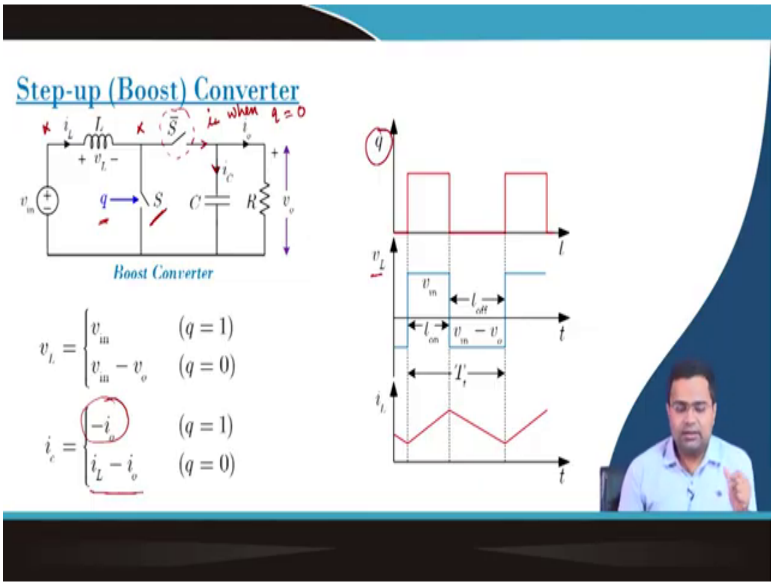

What happens to a boost converter? Again, these are the well-known fact, but we just want to revisit once. So, here also you can draw the waveform of this boost converter where this q is my gate signal that is the controllable switch for this S. Now, in this case this is our controllable switch and this is a low side switch and S bar which is the complementary switch high side.

So, this high side switch can be replaced by a diode in case of a conventional boost converter and this is called synchronous boost converter where we consider two MOSFET rather than diode and they operate in a complementary fashion. So, S is the controllable switch which we are going to control using the gate signal q and S bar operate in complement with S.

So, now, we can see the inductor voltage. Inductor voltage when the q is high or S is on then inductor voltage if we take this terminal and this terminal this exactly equal to the input voltage. When the switch is off, then the inductor voltage is equal to input voltage minus output voltage so, V in minus V 0.

Now, we can write that inductor voltage equations, which is at different switch state when q equal to 1 and q equal to 0 and accordingly we can write the capacitor current. But interestingly here if you look at the capacitor current when the switch S is on then this S bar switch is off; that means, the capacitor current is equal to minus load current because they are the direction of the currents are reversed.

I mean the capacitor current notation. It is the positive direction of the capacitor current and i_0 is going to the load that is the load current which is going out of the capacitor current. So, their sum should be 0. So, as a result, i c equal to minus i 0.

When the switch S is off, the S bar is on. In that case, we will see the inductor current here. That means this path will be inductor current when q equal to 0 ok. So, when q equal to 0 we will get capacitor current will be i l minus i 0 that is shown here alright.

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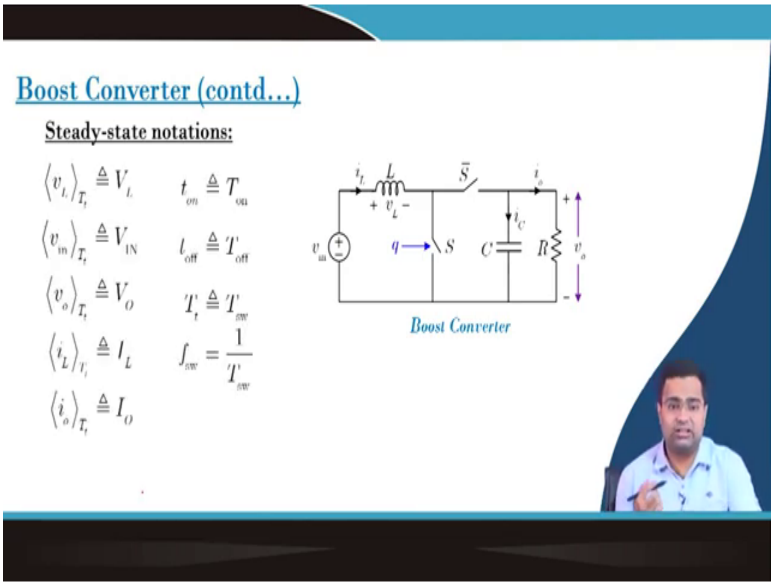

So, now we got the inductor voltage under two switch configuration configurations and again we can write the notation.

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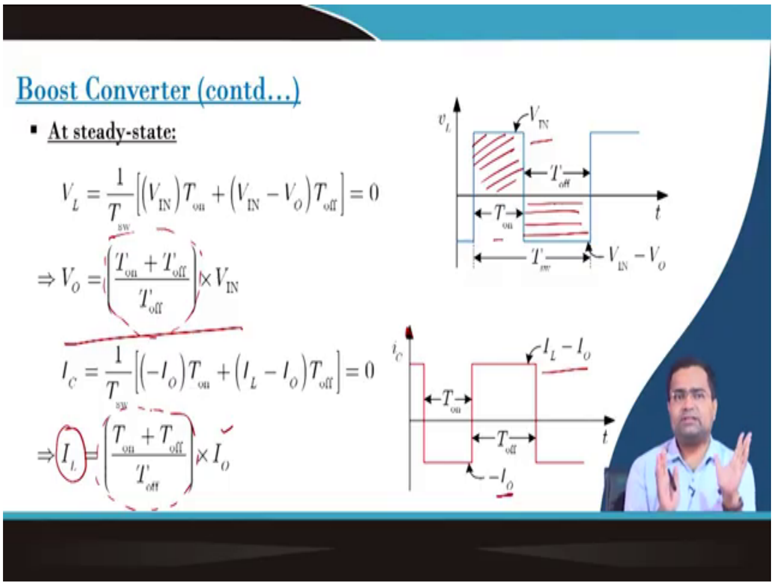

What happens under steady-state? At steady-state, our input voltage that means inductor voltage is equal to input voltage when the switch is on that we discussed and we assume that output voltage and input voltage are almost constant; that means the ripples are assumed to be negligible. So, you can write in terms of the DC quantity.

And then we can again write the steady-state on time and off repeatedly we want to show that the area under this curve should be equal to the area under this curve and if we can make sure these two areas are same the area under curve, then the average voltage across the inductor will be 0 and as a result the average change in flux over a periodic cycle will be 0.

So, that means the flux will remain constant over a cycle under steady-state and this gives us the output voltage and input voltage relationship. So, output voltage is equal to these are my timing parameters and input voltage alright. Next, we can now draw the capacitor current and we know that when the switch is on this capacitor current will be minus I 0 when the switch is off, it will be I L minus I 0.

Now, we can again write what is the average capacitor current over a cycle and that can be written simply from this graph say waveform and if we set it to 0 because we want the average capacitor current to be 0 then we can get the average inductor current is equal to average load current multiply by this timing constant ok.

Now, so, we can find out the current gain, we can find out voltage gain from this relationship, but remember we are still dealing with ideal DC-DC converter whether it is a buck or boost all are ideal. So, the relation is not so simple. In fact, it is not the right correct relationship when we consider the parasitic drop like a for a practical converter and that we will also discuss in subsequent lecture, but it is at least it is the basic point I mean these are the basic equation to start with.

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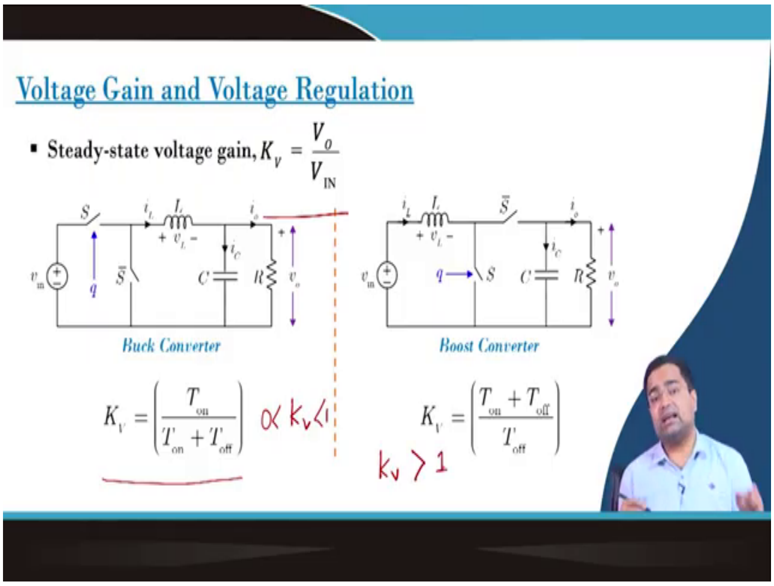

Now, if we want to write the voltage gain, the voltage gain of any converter we can write. Output voltage by input voltage for step-down it will be smaller than unity for step-up. It is greater than unity and we want this K V to be positive because we want output voltage to be positive. For a boost converter this voltage gain can be written like this and for buck sorry for buck-converter it can be written like this and K_V is greater than 0 and less than 1.

For boost converter we can see that the K_V the voltage gain is greater than 0, sorry for boost converter yeah this K V can be greater than 1; that means it is higher than unity. So, output voltage will be higher than the input voltage.

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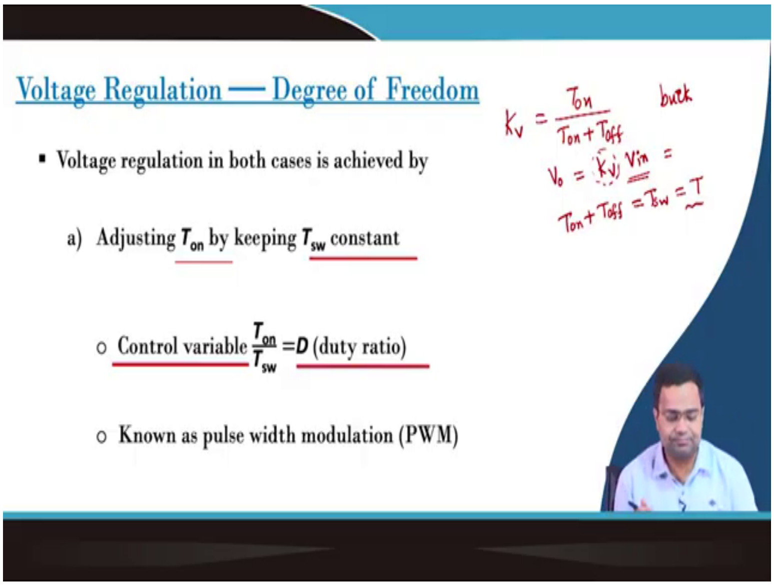

Now, we our ultimate aim is to regulate the voltage whether it is the step-down or step-up converter we want to regulate the voltage. In order to regulate the voltage, what can vary? As we have discussed in the previous slide that voltage gain K V is V 0 by V I. So, we want to keep output voltage constant; that means, output voltage we want to maintain and regulate when there can be a change in input voltage V IN.

There can be change in load current also, although this voltage gain expression does not include explicitly the load expression load current, but if we consider parasitic that load dependent term will also come. So, our ultimate aim is to regulate the output voltage. Then how can we regulate the output voltage? When there can be variation in input voltage or there can be variation in load current.

So, we can adjust T on by keeping T_sw constant. We know the relationship that voltage gain for a buck converter is T_on by T_on plus T_off. Here, that means, if we write V 0, it is simply K V by V in. And what we want? If there is any change in V_in we need to adjust this voltage gain such that the output voltage is regulated.

So, the first criteria we can set this T on plus T off which is nothing but switching period that we can keep constant and this if we keep this constant this is the condition I am showing then we can regulate the output voltage by adjusting the on time. So, then since the time period is constant, and the on time by total time is the duty ratio.

So, essentially, we are controlling the duty ratio that is my control variable. So, I have to control the duty ratio in order to regulate the output voltage whenever there is any change in input voltage or load current. So, this technique is known as pulse width modulation.

In fact, there are different variant of pulse width modulation like a trailing edge PWM, leading edge PWM, dual edge PWM, but in all cases the time period is constant and depending upon whether we want to control on time or off time that architecture differ. That the architectures differ whether you want to control the on time, off time or you know sometime we can vary both on and off subject to the constant the total time period is constant.

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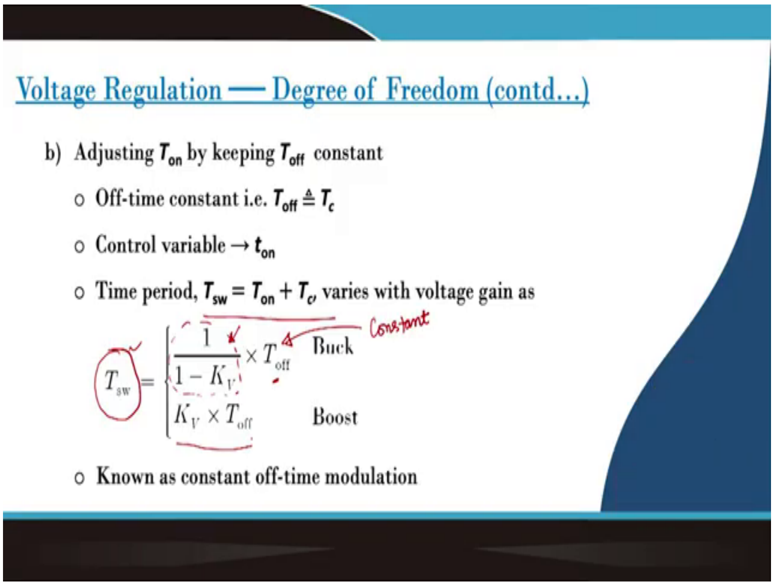

Now, another degree of freedom can be to adjust the on time that, which is same as earlier. Earlier also we adjusted on time by taking keeping total time period constant. Here we are adjusting on time, but keeping off time constant. That means this off time is equal to set to the constant value and the control variable is t on.

When we write small t on that means this is the instantaneous value and under steady-state, we can write capital T on. That means, the time period is equal to some of this on time and off time and if there is a variation in the voltage gain then, of course, there will be a variation in time period because we are keeping off time constant where on time can vary their summation can vary.

So, under this condition, if we write the time period expression, it will be a function of voltage gain. So, this is my voltage gain you know function and off time. So, this is something which is constant. This is constant. So, that means, if there is any variation in voltage gain because we want to regulate the output voltage. Suppose there is a change in input voltage, then K V were changing.

If K_V changes, this function changes, but their time off time is constant. So, the time period varies. That means any variation in K_v will also change the time period. The same thing is for boost converter only the expression is different ok. So, this technique is known as constant off-time control.

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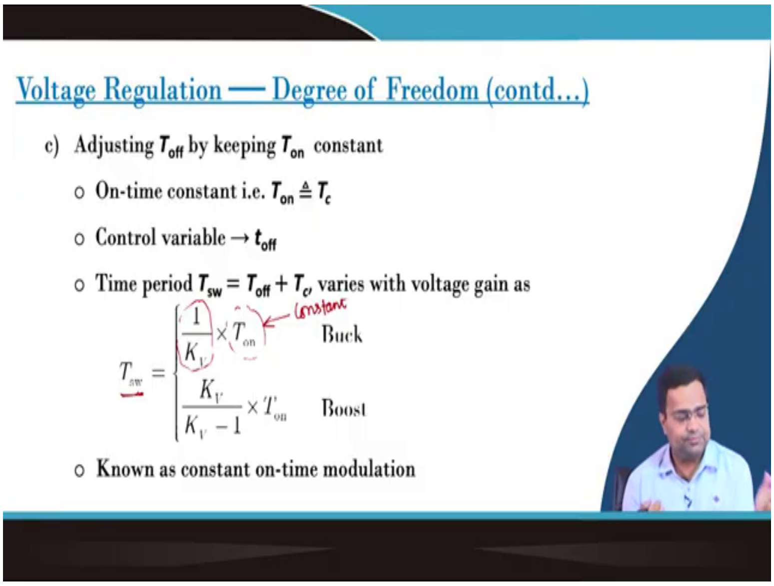

The third possibility that we can keep the on-time constant, and we are adjusting off-time. That means, T on is kept constant. Control variable is the off time, which is the instantaneous off time.

And again, in this case the time period will vary and we can get expression time period which is T_sw that is the switching period is a function of voltage gain multiplied by this on time and this quantity is constant. That means we can find out that this T_sw will vary when there is a variation in gain, ok. That means there is a variation in off-time.

This technique is known as constant on-time modulation and we will also discuss from case study like you know subsequent lecture. So, all these three technique has certain advantage and disadvantage and they also are very popular in their respective operating conditions or kind of control technique that we use.

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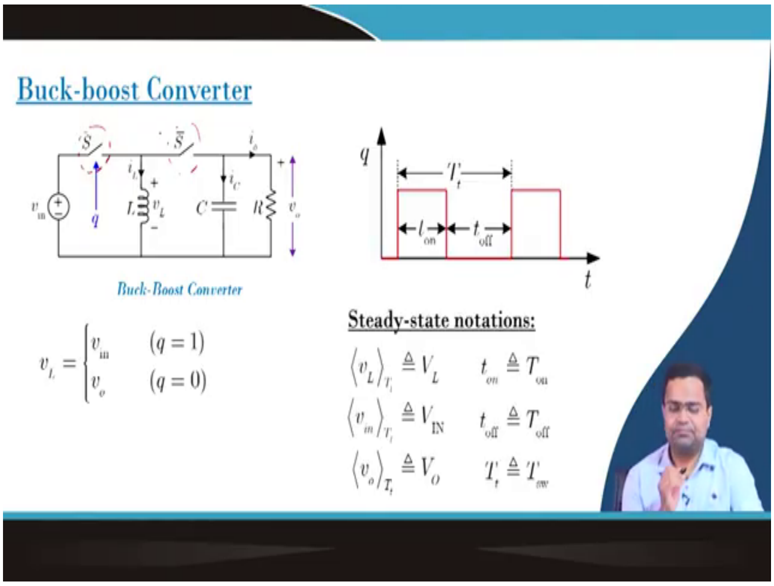

Now, the third converter which is left is the buck-boost converter which is well known, where again this switch is the controllable switch and the other switch is actually is used for as a complementary switch. And if we again draw the q; that means, the gate signal and if we write down the voltage across inductor then depending upon the q equal to 1 and q equal to 0; that means, whether S is on or S is off, we can write the inductor voltage and the steady-state equation.

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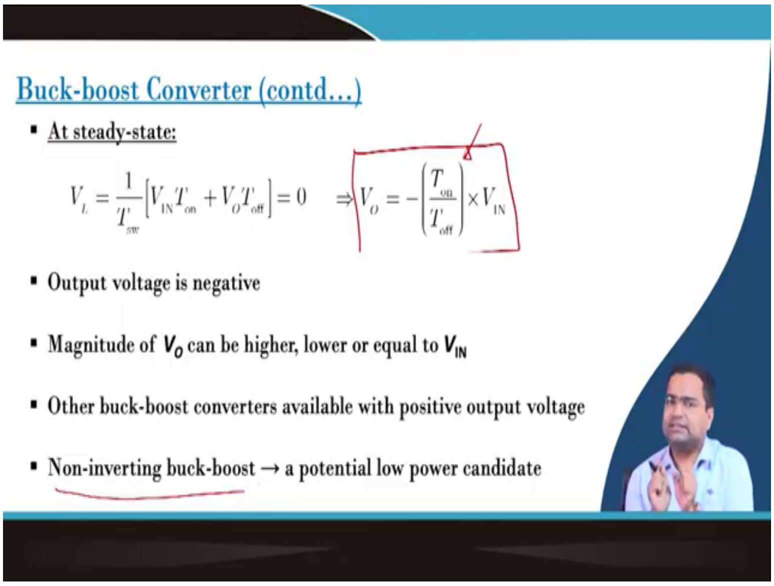

Then, if we carry out the volt second balance that we did earlier, we can find the output voltage is actually the negative of input voltage with a gain which depends on the on and off-time. That means, in this case we are getting output voltage negative, but if you take the magnitude of the output voltage, this magnitude of the output voltage can be higher than magnitude of the input voltage, it can be lower than the input voltage, but in this case it is negative.

Output voltage is negative, the magnitude can be higher or lower or even equal. So, this topology there are other topology related to buck-boost operation which can generate positive output voltage. And one of the topology is non-inverting buck-boost converter which is a potential candidate for low power application that mean, this candidate is used for low power.

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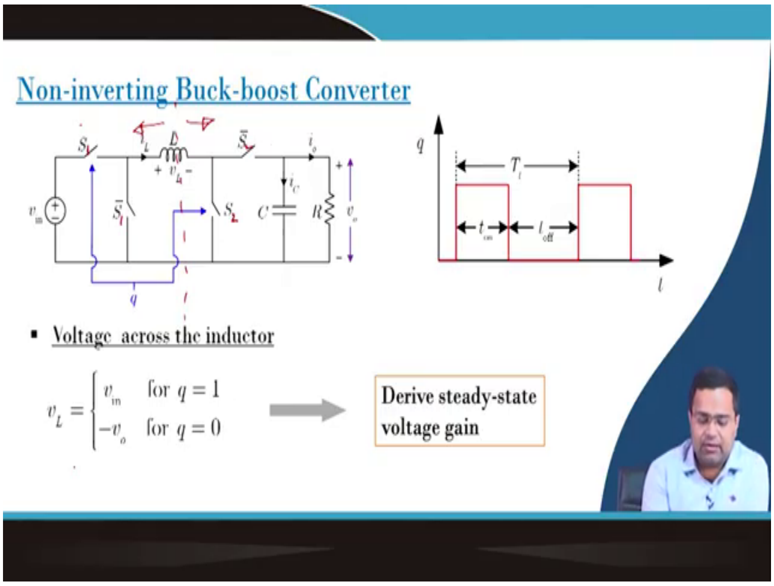

And if we take the circuit diagram of this low power non-inverting buck-boost converter, you can see there are four switches. So, the converter shows that if you break this converter into two parts, this side looks similar to the buck-converter and this side looks similar to the boost-converter. So, as if we are merging a buck and boost converter together and there are four switches.

This is the control switch S, and S bar. So, although I have used the same gate signal for S, but we can operate them independent; that means, S and this switch, this switch and this switch can be operated independently as well, depending upon the requirement. So, if we set q equal to 1, q equal to 0, then we can get the required you know buck-boost operation.

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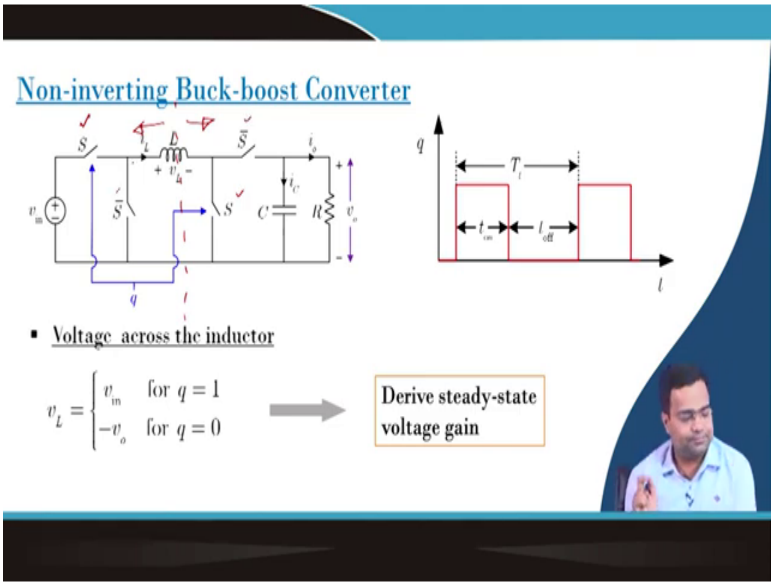

If we want to operate this converter like if we use independently then it is possible to operate purely in the buck mode, it is possible operate purely in the boost mode and the current configuration where I kept here if we keep this if we remove this buck; that means, if you operate these two switches identically, this switch and this switch and other switches are complementary to their respective switch, then this will operate like a buck-boost converter with positive output voltage.

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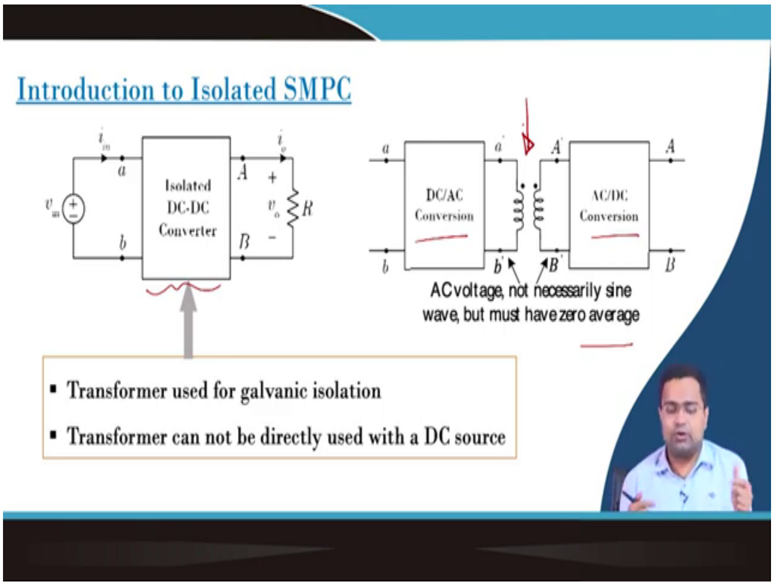

Now, we just want to introduce isolated switch mode power converter because in the subsequent lecture we also want to take a few case studies. So, that whatever we will do that is also equally applicable for isolated DC-DC converter. So, if we take the isolated DC-DC converter, this point is a, b, and this is the like isolated that means we are using a transformer as for galvanic isolation. But transformer cannot be used directly in the for a with the DC source; that means, if we use a DC source on either side of the transformer, the transformer core can get it will get saturated.

So that means we need to convert this DC to AC. We need to have a conversion like a signal DC voltage to AC and AC to DC, but it is not necessary. This AC to DC, DC to AC conversion the AC must it not it is not necessary the AC has to be a sine wave. It can be a square wave, it can be a quasi-square wave, but what we need that the average value of this AC signal which is going through this passing through this transformer that must be 0.

If there is any non-zero average value, then it will actually lead to transformer core saturation. So, you have to make sure that average value must be 0 at steady-state.

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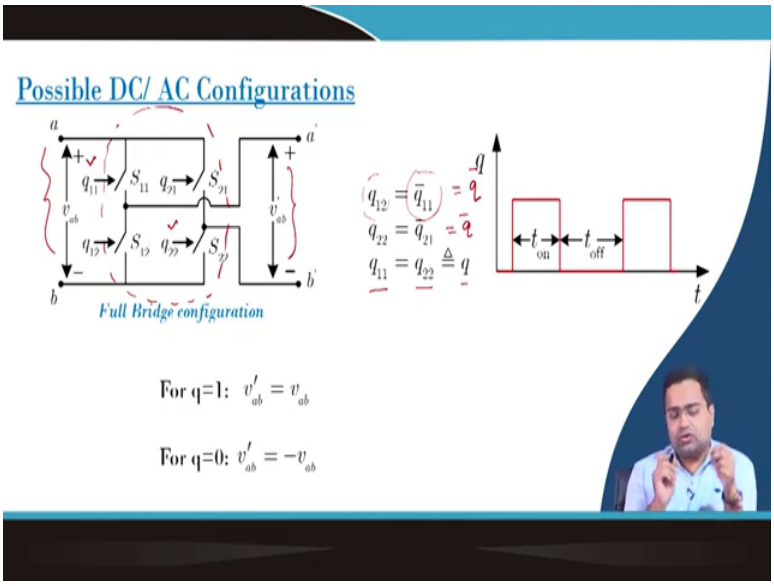

Now, the possible DC to AC configuration so, it is simply like you know it is like our full bridge configuration. We are using four switches and we can set the gate signal of the four switches accordingly like q 11, q 22 like this switch and this switch we set it using a controllable gate signal q whereas, the remaining switch S 12 and S 21 they are operated in a complementary fashion, like S 12 this gate signal is operated complementary to q; that means, this equal to q bar, this is also equal to q bar.

In this case, what will happen? Depending upon whether the switch is on and off, you will get V_ab, V_ab dash; that means the voltage across this terminal. If q equal to 1, it will see input voltage. If q equal to 0 it will see minus V a b; that means, this input voltage V ab and, if q equal to 0 it will say minus of V_ab.

It is not necessary that these two switches have to be operated using a same gate signal, but it is necessary that S 11 and S 12 they must be complimentary. So, we can operate them to generate a quasi-square wave also.

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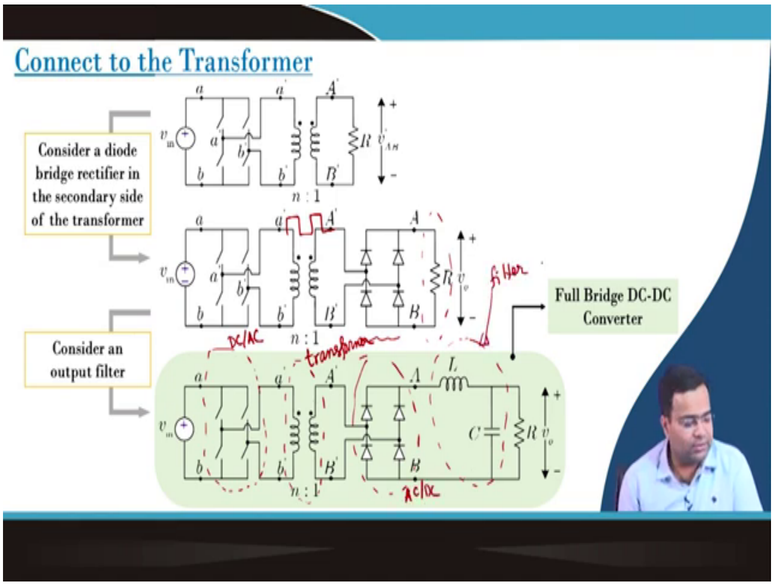

In this case we are taking about square wave, but even if we generate a square wave, this square wave will pass through this transformer, but the secondary side we have connected a resistive load. That means, resistive load will see a pulsating voltage, which a positive and negative polarity that is V ab dash.

So, we need to use a diode. So, if we use a diode based rectifier then we can convert this AC signal to DC. But since it is not a pure sine wave that means it is a square wave, so it will lead to harmonic. So, this resistance will not even it may not see the pure DC voltage because it may comprise some harmonics higher order harmonics.

So, in order to minimize the harmonic effect, we need to consider LC filter. So, this is my filter and this complete circuit is like a full bridge circuit, the full bridge circuit where in the first stage this is my inverter, which is my DC to AC conversion stage. This is my transformer stage, my transformer stage, this is my AC to DC stage, and this is my filter stage. The whole thing is a full bridge converter.

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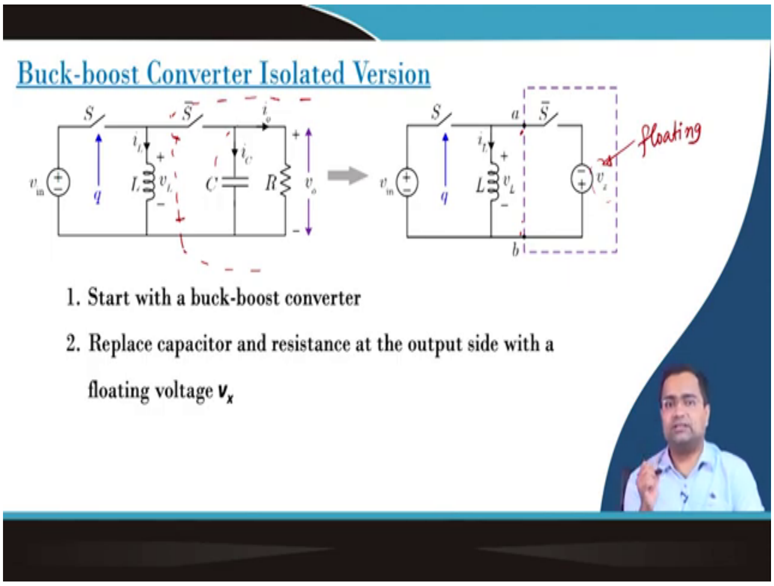

Now, if we want to generate if we want to get the isolated function of the buck-boost converter, we know that this side terminal is basically is a pulse setting voltage appears. Although this voltage is fixed, it is a negative voltage, but across this terminal V L, the right side voltage reflection of this right side will appear like a pulsating voltage, ok because it is the voltage across the inductor.

So that means we can replace this voltage V x now where we start with a buck-boost converter and this is the floating voltage. We will replace suitably what will be this floating voltage, we will take into that. But, across V ab this floating voltage will appear like a pulsating voltage depending upon the status of switch S bar. So, this can be replaced by floating voltage.

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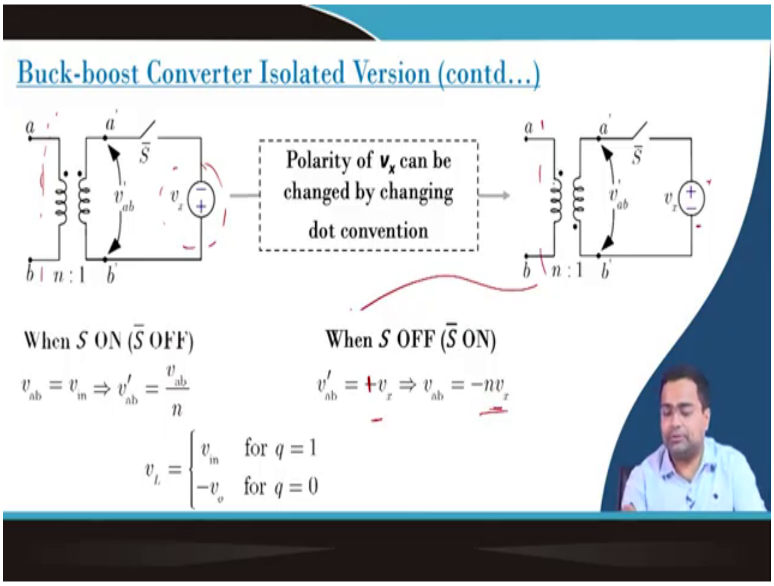

And if we take the floating voltage now, we have represented what we can do? We can change the polarity of this floating voltage. How? By changing the dot convention of the transformer, I mean, if we change the dot convention of this transformer, this polarity of the floating voltage can be reversed, provided the input side voltage polarity remains same. We have changed the dot convention of the transformer.

Now, if the switch is ON because this part is we are taking from after the inductor side of the buck-boost converter, the regular buck-boost converter and we have to use the transformer with a dot convention. Depending upon whether the switch is ON, then you will see the input voltage across this terminal where the inductor is connected to the left side. When the switch is OFF S when S bar is ON, then what voltage will be seen across V ab? V ab dash it will see V x minus V x like here.

Even though you are using a positive voltage because of the dot convention, it will appear as a minus V x and if we take the reflection of that voltage across V ab we will get minus n V x. And then actually this V ab it should not be minus it will be plus and if we take because we are talking about this circuit and if we take V ab then it will have a negative because of the dot convention.

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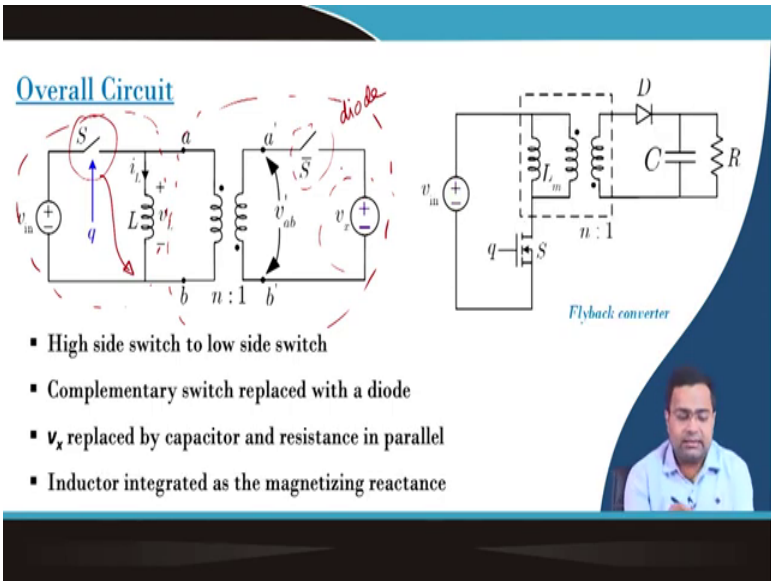

And that means, we can write the inductor voltage now. The overall circuit we can merge these two circuits. This part now we have merged in. Earlier there was inductor, and this is the part of the buck-boost converter. If we merge these two parts then, what we can do? The high side switch we can take this switch to the low side.

Complementary switch this can be replaced by a diode. And V x can be replaced by a capacitor resistance in parallel that means a resistance and a because the capacitor will act like a filter and the resistance is the load resistance.

So, now and this in this inductor can be realized as an integral part of the transformer, which is the magnetizing reactance so, this actually represent the flyback converter. So, by this you know variation starting from a non invert inverting buck-boost converter if we add the transformer and modify the circuit, then we came to the flyback converter. So, fly back converter is an isolated version of a non-inverting buck-boost converter with a positive output.

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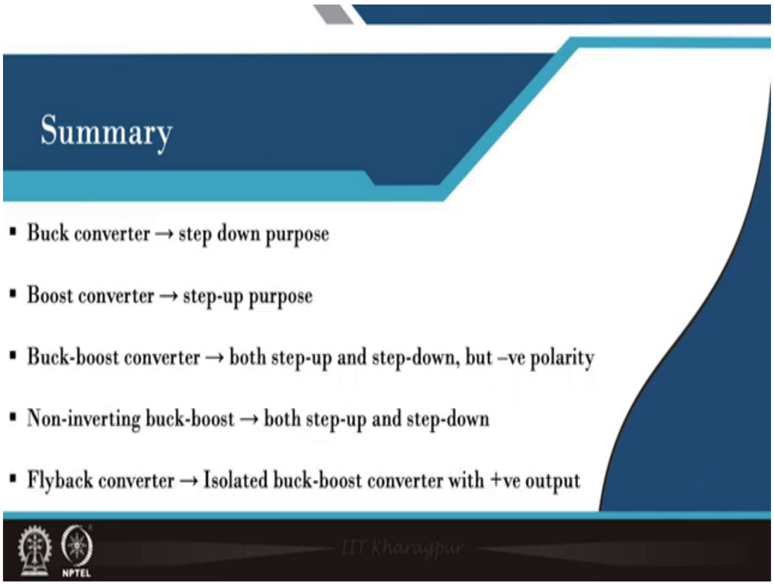

So, in summary, we have discussed buck-converter, step-down purpose, step-up purpose, we have discussed buck-boost converter both step-up and step-down purpose, but it was with negative polarity. We discussed non-inverting buck-boost converter and we have also discussed some basic isolated DC-DC converter architecture.

So, with this we will move to the other lecture like you know that modulation technique and you know the steady-state analysis. For today, this is sufficient.

Thank you very much.