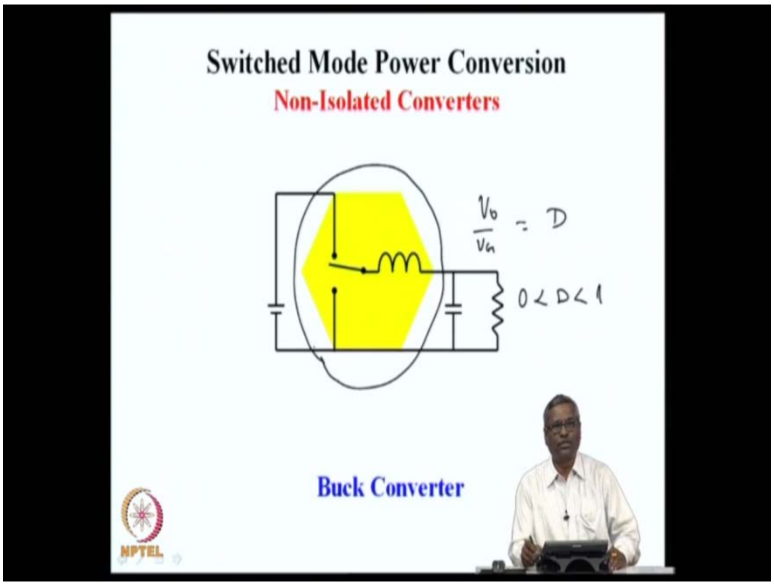
Switched Mode Power Conversion
Prof. Ramanarayanan. V
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 12
Non-Isolated converter – 1

(Refer Slide Time: 00:37)

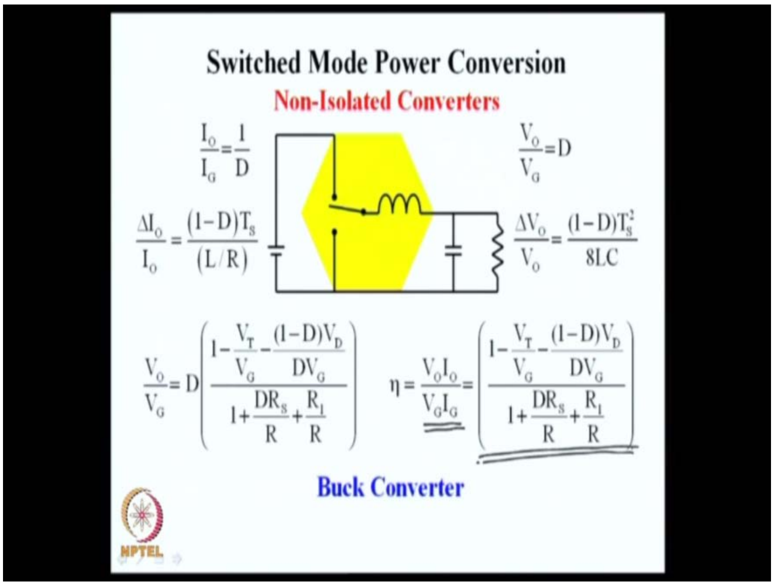
Good day to you all, in this session today, we will continue on what we had seen in the previous lecture on the topic of non isolated converters. In the previous lecture, we had gone through some of the rules that govern the connection off storage devices, which switches. And we came across as a very simple basic converter sell, which is what is shown here. This basic converter cell consists of 1 single pole double throw switch and 1 inductor. And we call this is the basic power converters cell and we had seen in the earlier lecture, how this power converter cell.

(Refer Slide Time: 01:08)



Is connected with a source and a load, a source consisting of a DC voltage and a load consisting of a resistive load, which is supported by a capacitor to filter out the switching frequency ripple current and ripple voltage. The single cell, which we had seen in the previous slide, which we called a basic converter cell can be connected with a source and a load as a buck converter. We had seen in the previous lecture, that this converter has a voltage conversion ratio V naught by V G, V naught by V G equal to D duty ratio and this duty ratio is always less than 1. And on account of this relationship, this type of converter is defined as the buck converter or step down converter, you can get an output voltage, which is less than the input voltage and that is the reason, why this is called a buck converter. The switching cell that we had defined is, what is in the middle, which consists of the switch plus the inductor and it is possible.

(Refer Slide Time: 02:36)



To convert this converter, this buck converter, which has a V naught by V G of D into a different type of power converter. So, before that to we will look at all the other relationships that we had seen in the step down converter or buck converter. It has voltage conversion ratio V naught by V G indicated by D. And it has a current conversion ratio that is the ratio of the output current I naught divided by the input current I G is 1 over D. And we also saw that the product of these 2 numbers V naught by V G and I naught by I G is the efficiency of the power converter V naught I naught by V G I G. And because the, these ratios are inverse of each other, the power conversion efficiency in the buck converter or the ideal power converter is unity. This also we had seen and the ideal purpose of a power converter is to convert a voltage V G to another voltage V naught.

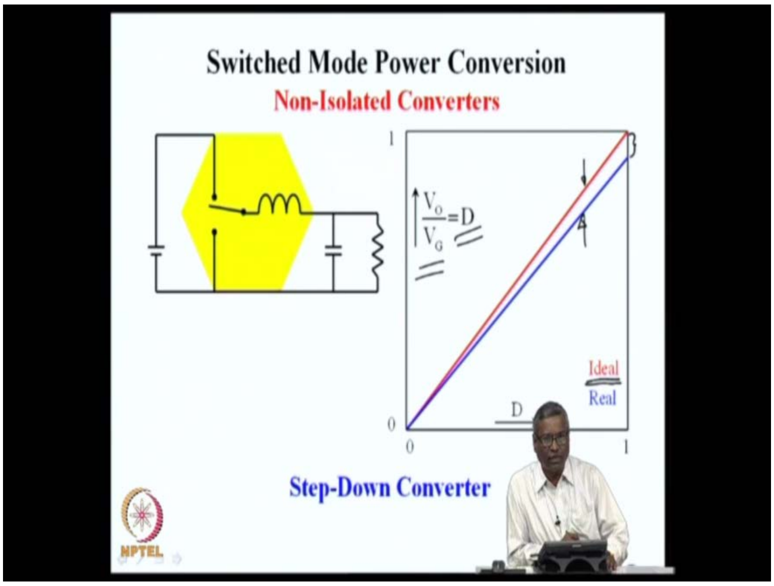
And in this converter V naught is less than V G and it draws power from the source and delivers it to the load. But this kind of converters also have several non ideal performance features, one of them is that the current that is supplied to the load is not perfectly constant D C. It has a ripple which is given here as delta I naught by I naught the ripple factor. In this factor, we had seen that is a function of the operating duty ratio D, 1 minus D and it is a function of the switching period T S. And it is also a function of the time constant of the converter L by R and this non ideal current ripple will be quite small. If the ratio of if the ratio of switching period to the L by R is much less than 1. This non ideality can be neglected another non ideality in the converter is the voltage ripple at the output. Ideally, we would like this power converter to provide an output voltage, which is constant, fixed and with no other disturbances.

But because the power is processed with a switch here, the converter provides an output voltage V naught which also has undesirable ripple delta V naught and this ratio delta V naught by V naught is a non-ideal property of the converter and we would like this delta V naught by V naught to be as small as possible. And that is possible, if we make the switching period of the converter T S very much less than the natural time on time constant of the converter, which is root of L by C. If T S square divided by L, L C is a small function, small fraction than the voltage ripple also, will be a small quantity and we saw that in these converters. The output voltage under ideal circumstances is D, but there are several non-idealities in that converter mainly, the switch voltage drop V T, the diode voltage drop V D and then the source resistance R S.

And then the resistance of the inductor R L and the non-idealities associated with every one of these elements. The switches, the source and the inductor results in the output voltage being different from the ideal value of D. And we saw that this correction factor on account of the non-idealities can be represented as a multiplying correction factor, which consists of in the numerator. An expression, which is dependent on the switch drops and the duty ratio and in the denominator, it depends on certain ratios of resistors and the duty ratio. And in a good converter, this correction factor must be as close to 1 as possible. And we also saw that on account of this voltage not being ideal the devices not being ideal, the power is not processed with 0 losses.

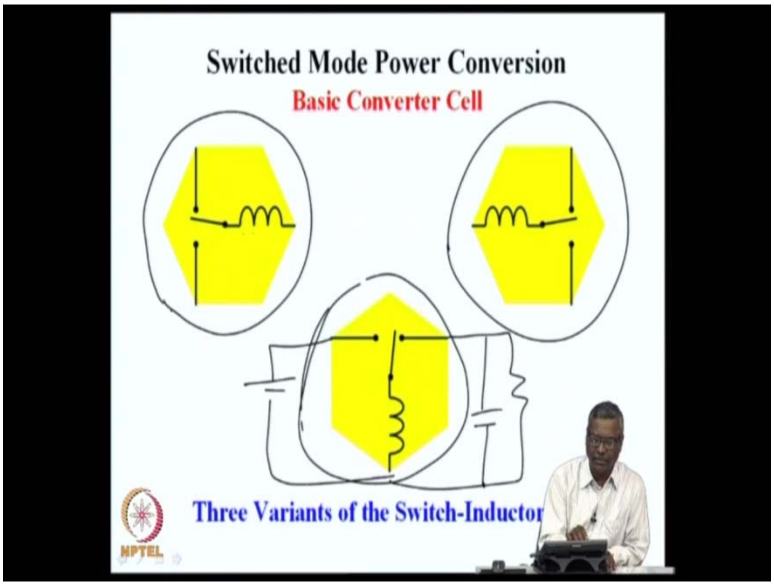
The output power by input power, which is defined by the efficiency of the converter, now has a number which is less than 1 to that extent. We lose some power in the converter and in the sense these where, we a steady state performance characteristics of the buck converter. We had spent quite some time in going through these processes. And finding out in operation, what are their non-idealities? How they are accounted for? And finally, how they are related through, the voltage gain, through the duty ratio for voltage gain current, gain current ripple, voltage ripple, voltage conversion factor, then efficiency and so on?

(Refer Slide Time: 08:01)



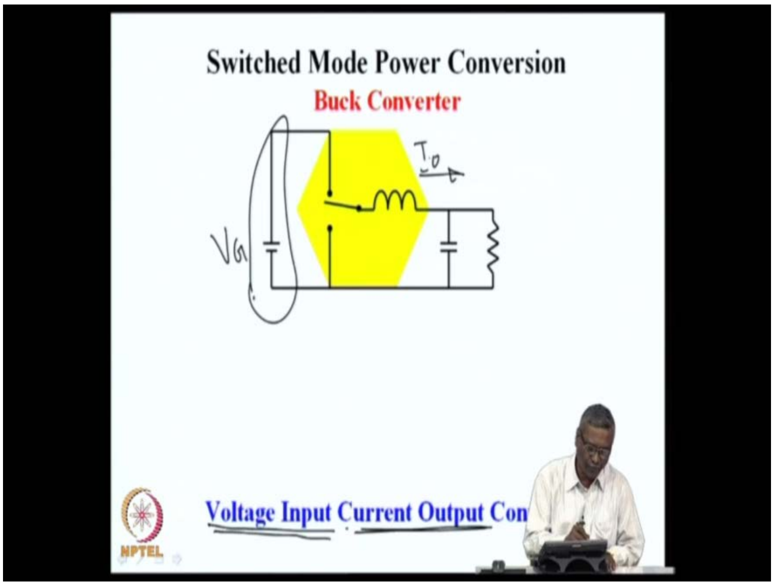
In this lecture, we would continue with some of the same methods. So, that many of the analysis methods, that we had learned in the first lecture. We will reinforce further by looking at the new type of converter. Again, this slide also is about the voltage conversion ratio of the step down converter. What you see in the red line is the ideal voltage conversion ratio, it is a function D. So, the voltage conversion ratio on the vertical axis is plotted as a function of the operating duty ratio. The red line is D, which is 45 degree line and duty ratio vary varies from 0 to 1, conversion ratio also, varies from 0 to 1. And we saw that because of several non-idealities there is a drop in the conversion factor and this also is the same as the efficiency of the power converter. So, in the non isolated buck converter we had seen many of these things.

(Refer Slide Time: 09:02)

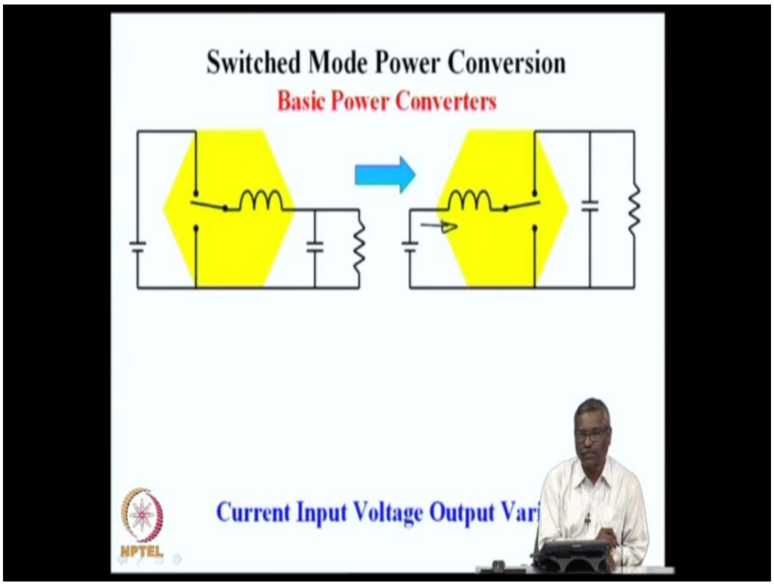


Now, we will try to see the other converter topologies, which are derived from the same switch cell. The cell that we had used in the first lecture was the buck converter, where the cell was used with the switch on the source side and the inductor on the load side in 2 other way is the cell can be used. Where the inductor can be on the source side and the switch can be on the, the load side. And we could also have a third method of connecting the switching cell to the source and the load, where one of the poles is connected to the source; the other pole is connected to the load. So, there are several variations of this switch cell, the one with the poles on the left hand side, the throws on the left hand side and in the inductor on the load side. The inductor on the source side and the throws of the switch on the load side and then the third one that I had shown here, these are the 3 variants.

(Refer Slide Time: 10:19)

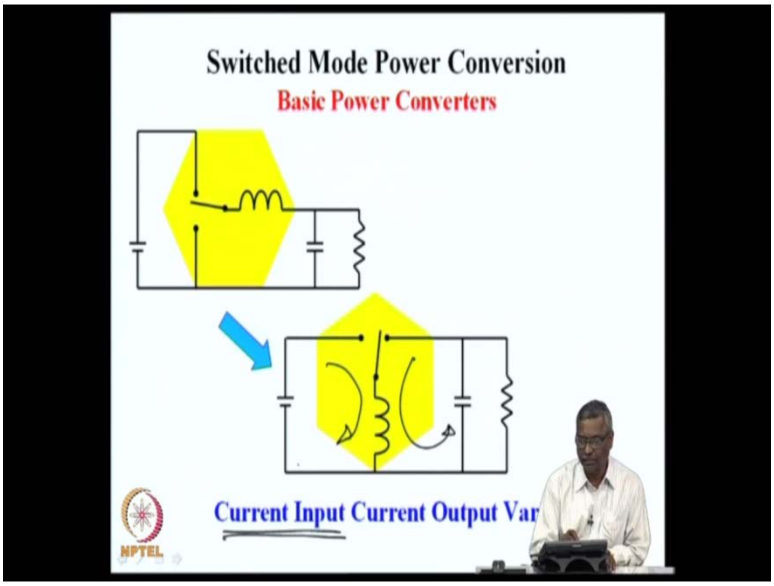


(Refer Slide Time: 10:43)



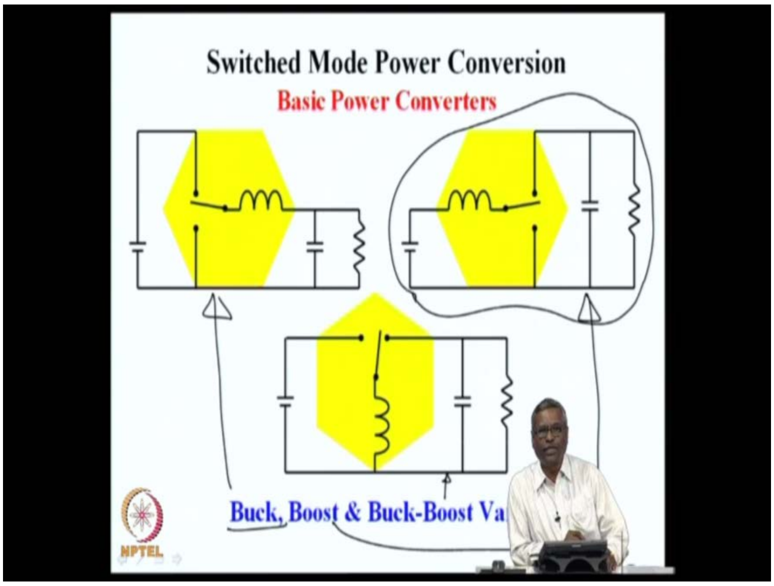
And the buck converter, the step down converter, we might define as a voltage input and current output converter. Because, on the input side, the voltage is constant, on the input side voltage V G is defined and on the output side, the current I naught is defined. So, this could be also defined as a voltage input current output converter. The second converter that we would like to see today is the current input voltage, output variant where the input side current is stiff from the source we draw a nearly constant current because of the presence of the inductor on the input side. And then on the output side, this current is being used to charge a capacitor so that the output side has the voltage to be stiff. So, we might define this converter as current input and voltage output variant.

(Refer Slide Time: 11:22)

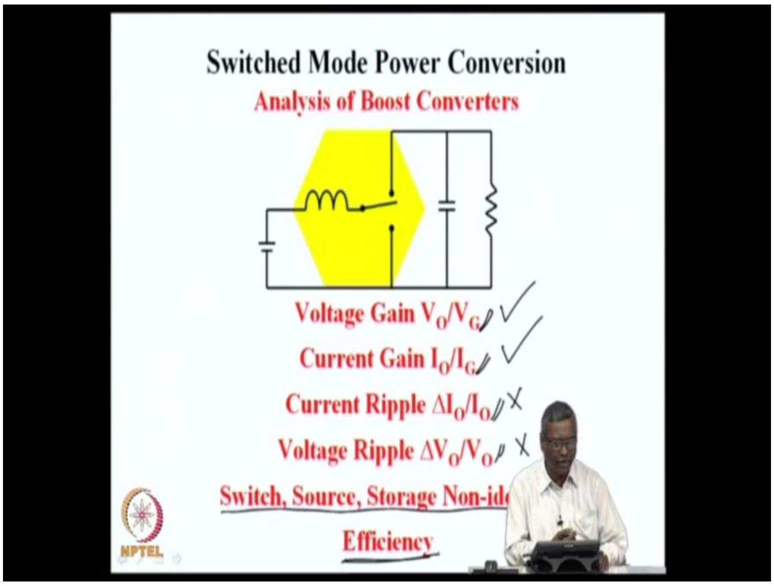


The third variant is shown here, where the input side current is also stiff. When the switch is connected to the source a nearly constant current is drawn, because of the inductors presence and when the switch is connected to the load side, merely constant current is supplied to the load side. So, you can say that the switch while is connected here draws the energy from the source and then dumps in to the load. And on both sides, the current is defined in, so this can be called a current input, current output variant.

(Refer Slide Time: 12:00)



(Refer Slide Time: 12:32)



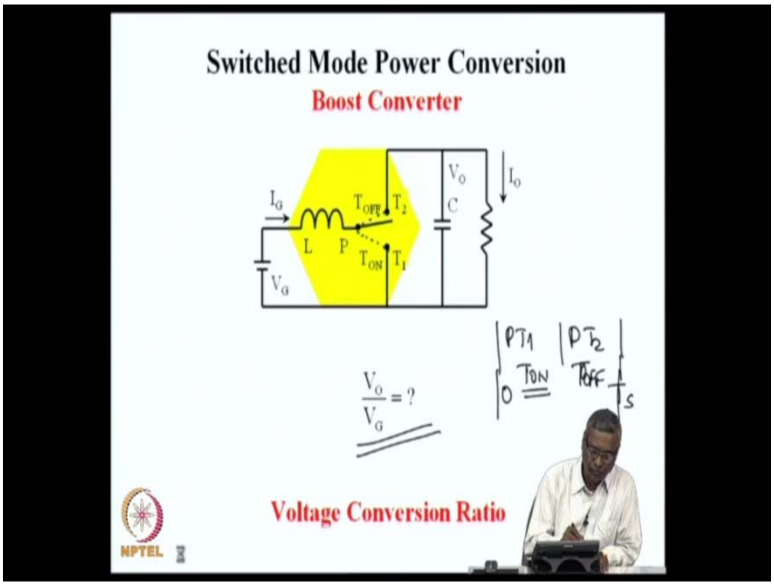
The 3 variants have these names as step down or the buck converter, which is this converter then the boost converter, which is the second variant, which we will see in detail today. And the third one is the buck boost converter or the current input current output converter. So, in today's lecture, we will spent a lot of time, trying to find out the various study state perform performance functions of the boost converter. This converter has the name boost converter and we will spend some time to find out, why it is called a boost converter? We will also go through the entire process of study state performance analysis of the converter.

We will follow the very similar pattern that we had do, we had done for the step down converter going through V naught by V G, I naught by I G and so on. The idea is to make sure that, we fully internalize, we fully absorb the analysis methods for the study state performance of any converter. The steps that we had gone, through earlier are the same as the steps that we will go through now. We would like to see what is the voltage gain V naught by V G that is output voltage expressed as a ratio of the input voltage V G. And similarly, the current gain in what way the output current I naught, the load current I naught is related to the source current I G through the switching duty ratio D and the ideal performance of the converter is to draw study power from the source.

And deliver steady power to the load, but because we are using switches in the converter power is being drawn intermittently, and it is delivered to the load intermittently and the purpose of the inductance and the capacitor is to smoothen the power flow. So on account of that we will get what we want namely steady state average output voltage and steady state average output current. But on all these quantities on the output voltage V naught as well as the current I naught, we will have a switching ripple the inductor current, which is supposed to be steady and constant will have a ripple which is delta inductor current or the ripple current in the inductor.

Similarly, the output voltage which is supposed to be steady and constant will have a switching ripple present on that. So, we would like to see again each one of these performance factors, these two are the desirable quantities and these two are the undesirable quantities. But we would like to know how much they are? And in the next step we would like to see, what are all the non-idealities present in the converter? The switch has certain non-idealities during conduction the voltage drop is not 0, the source has impedance, the storage components like inductors and capacitors have resistors parasitic resistors. What is the consequence of all these non-idealities and then finally, how does it affect the power conversion through the efficiency? This is something which we had done before in the case of buck converter, we will do it again so that we fully internalize the method of study state analysis.

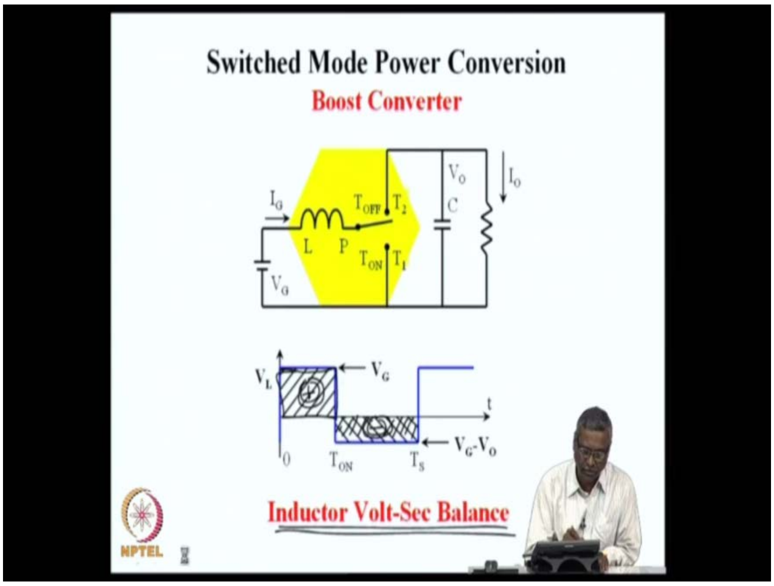
(Refer Slide Time: 15:29)



The first concerned is the voltage conversion ratio which is V naught by V G. The converter is now operated in pulse with modulation technique where, T S is our total switching period. In that, we have a duration called T ON and we have a duration called T OFF. So, during T ON the switch is connected between P and T 1 and during T OFF the switch is connected between P and T 2. So, if you see the switch cell here, during on time the switch is connected between P and T 1 and during off time the switch is connected between P and T 2.

And 1 switching period is T S 0 to T S is 1 switching period and within each switching period there is a duration called on time and a duration called off time, on time during on time energy is drawn from the source and during off time the energy is passed on to the load. And how this operation takes place, we had already seen in the case of buck converter, we will see again in this converter. And we would like to find out ideally, what is the voltage conversion ratio, what is the current conversion ratio and so on?

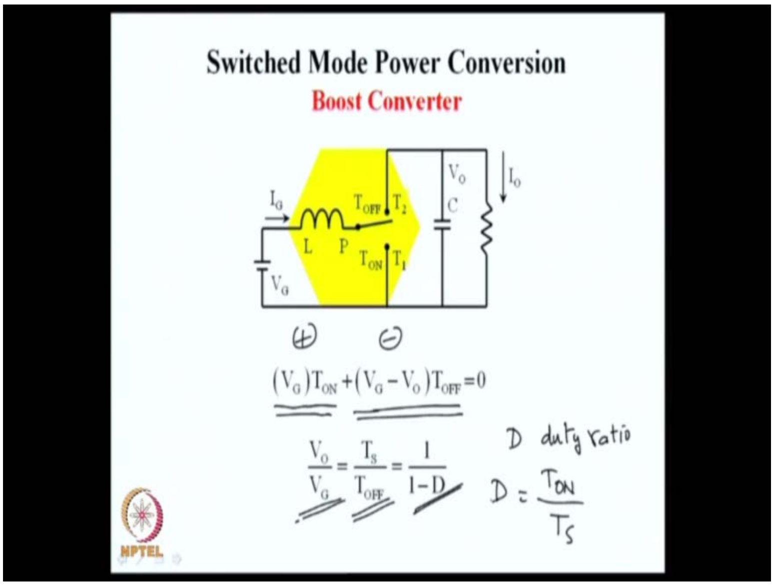
(Refer Slide Time: 16:52)



We had seen that the voltage conversion ratio of any power converter is always obtained by applying the principle of volts, second balance on the inductor. This is the first step in finding out the ideal voltage conversion ratio. So, in order to do that, we draw the voltage across the inductor for one cycle under steady state, we draw what is the voltage that is applied across the inductor in the converter for one cycle. We can see that during the on time P T 1, when the switch is on the voltage across the inductor is V G, what is shown here. And during the off time, when the switch P to T 2 is connected, the voltage across the inductor is negative and it is this V G minus V naught.

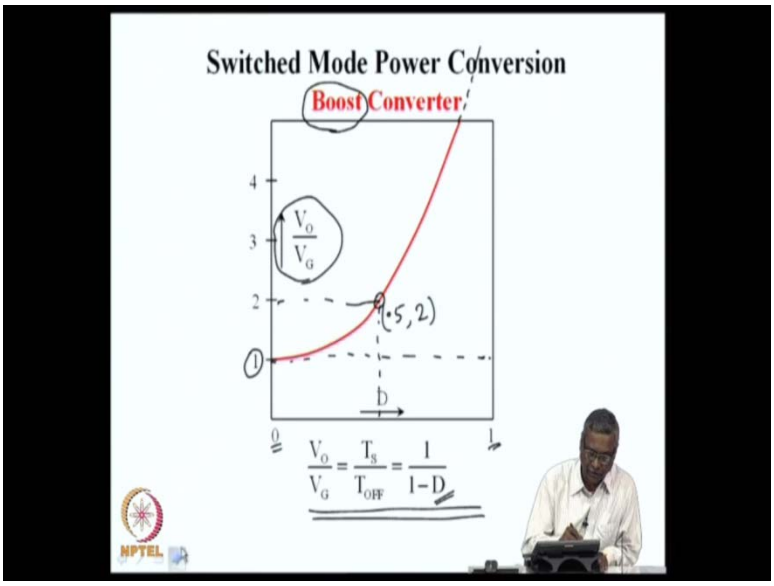
The volts second balance is in a sense indicating that the voltage across the inductor on an average has to be 0. In every cycle, the inductors net voltage and time applied is 0. So, this can be seen here as the hatched region. Whatever is the voltage time product applied to the inductor during one part of the cycle in one polarity is the same as the volt second, which is applied across the inductor during the other part of the cycle. So that over one cycle, this positive area what you see here and the negative area that you see here are same. The positive area is V G multiplied by T ON and the negative area is V G minus V, V naught multiplied by T S minus T naught and that is what in a sense means inductor volts second balance.

(Refer Slide Time: 18:39)



And this can be mathematically written as the volts second during on period and the volts second during off period, adds up to 0. In one cycle the net volts second has to be 0 or the positive volts second and the positive volts second, and the negative volts second have to balance each other. So, this if we expand, we will see that the ratio V naught by V G is the same as the ratio of T S by T F that is switching period divided by off period, which can be expressed as 1 by 1 minus D. Where D is the duty ratio of the switch and this duty ratio is T ON divided by T S. In the first converter that we had seen step down converter, this ratio was D duty ratio directly determine the ratio of output voltage to input voltage in the boost converter, this ratio is 1 by 1 minus D.

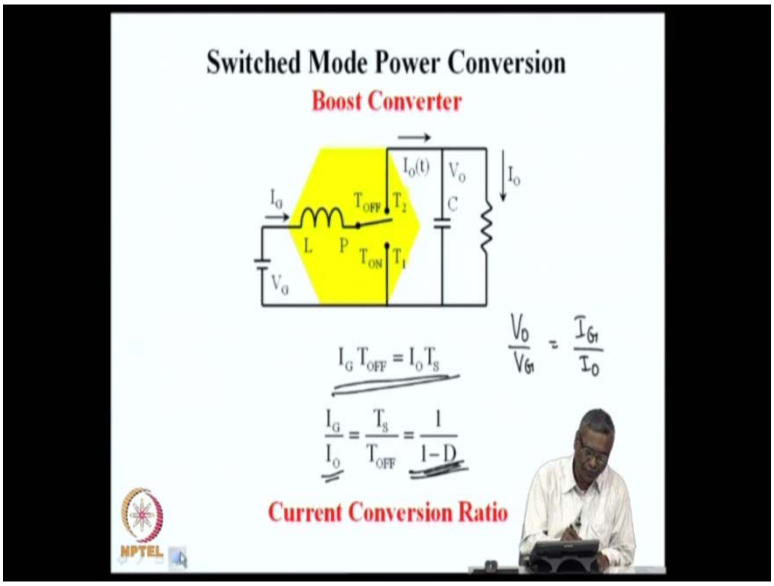
(Refer Slide Time: 19:43)



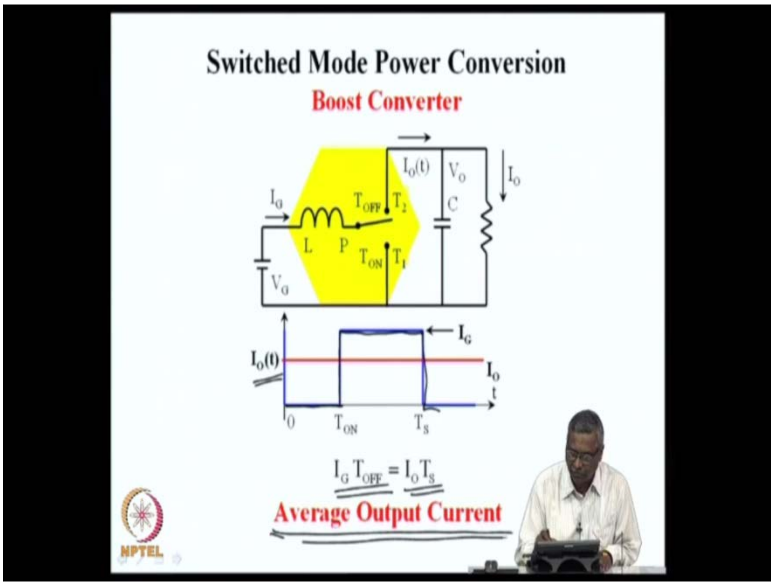
We can see it in the form of a graph, this relationship of V naught by V G here on the Y-axis as a function of D on the X-axis. D varies from 0 to 1 and when D varies from 0 to 1 V naught by V G. In the ideal case varies from 1 by or varies as 1 by 1 minus D or when D is equal to 0, the gain is 1 and when D is equal to 1, the gain is infinity very large. When D is equal to exactly 0.5, you will find that the gain will be to 1 by 1.5 is 2. So, when duty ratio is 0.5, the gain is 2, the duty ratio is 2 by 3 gain will be 3 and so on. This is the relationship, which determines what will be the voltage conversion ratio of the converter.

We see that it is all the time from 0 to 1 for all duty ratios the, the output voltage is more than the input voltage. V naught by V G is greater than 1 or V naught is always greater than V G in the entire range of the duty ratio 0 to 1 and that is the reason, why this converter is called a boost converter. It boost the input voltage to a value which is higher than the input voltage, and that is the reason for the name Boost, it is also called step up converter or a boost converter.

(Refer Slide Time: 21:18)



(Refer Slide Time: 21:39)

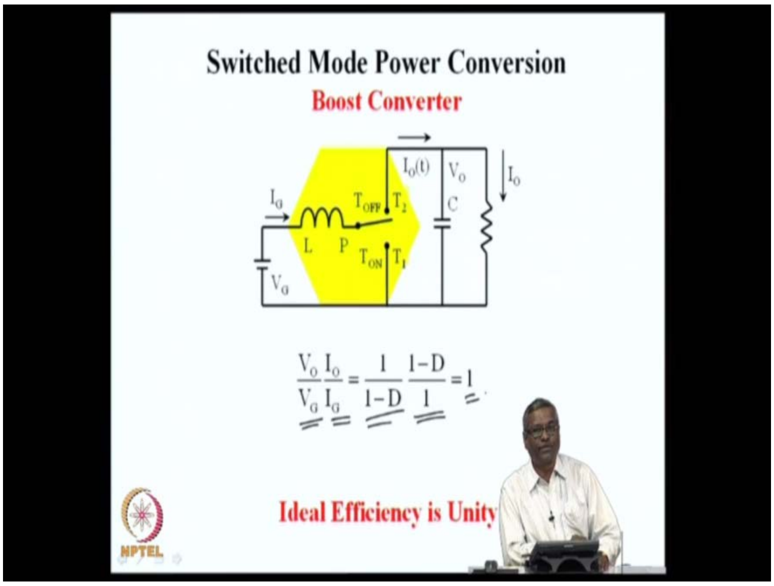


The second relationship that we would like to see is the ratio of I G to I naught and this is obtained as, we had seen before by finding out the current conversion ratio. How much of this current is transferred to the output side and how much of that is being delivered to the load? So, if you see this picture here, you can see that the inductor current if it is considered constant, during the off time it is delivered to the output circuit, during the on time the inductor is freewheeling on the source side. So I naught T can plotted as a function of time, during the on time, no current is being delivered to the load 0 current from here to here.

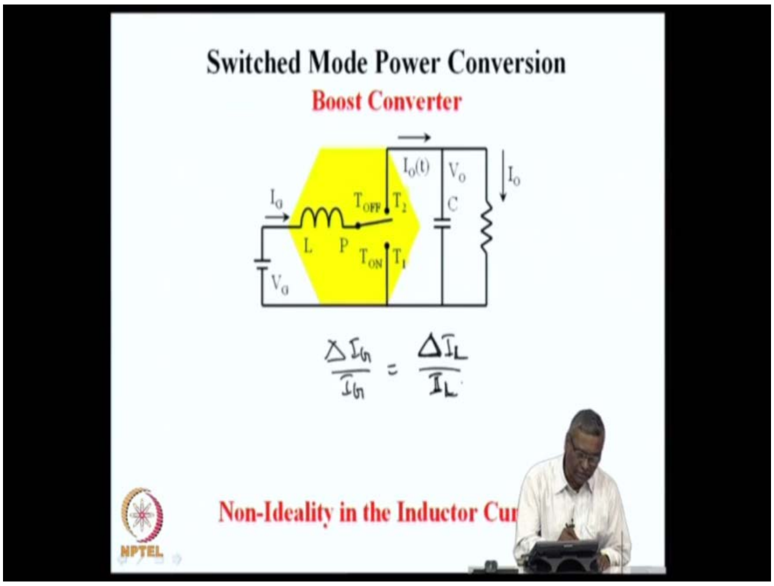
And during the off times T ON to T S, the full current of I G is delivered to the load. So, naturally, this I naught of T when you average it, it will be the same as the output current, because average current through a capacitor is 0 over one cycle. See if we apply that principle, you will find that I G into T of is a average of this quantity, which is same as I naught into T S. In this is obtained by finding out the average output current being delivered by the converter and this relationship can be reduced to get I G by I naught is 1 by 1 minus D.

This is again something which we had seen before the forward voltage converter, conversion ratio V naught by V G will be the same as the reverse current conversion ratio I G by I naught. This is because V naught I naught is equal to V G I G in an ideal converter, all the input power is the same as the output power. And because of that, we will find that the ratio of V naught by V G is the same as the ratio of I G by I naught which is what we have seen here is 1 by 1 minus D

(Refer Slide Time: 23:13)

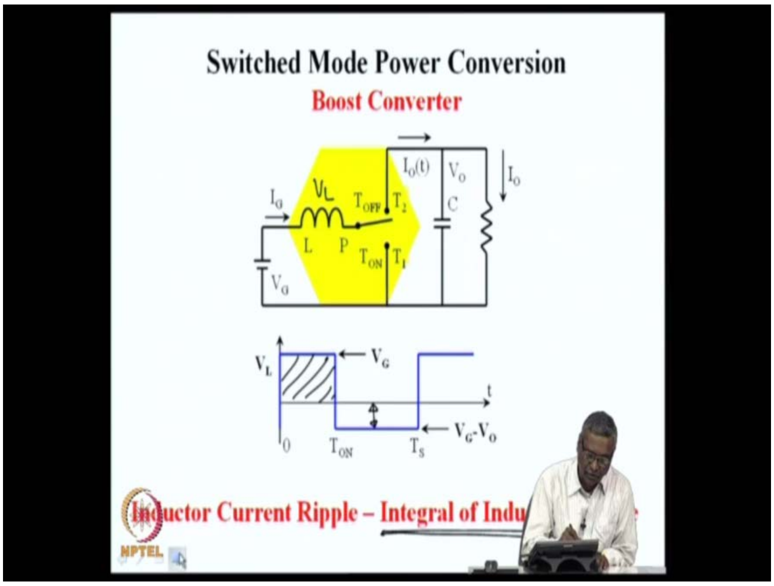


(Refer Slide Time: 23:34)

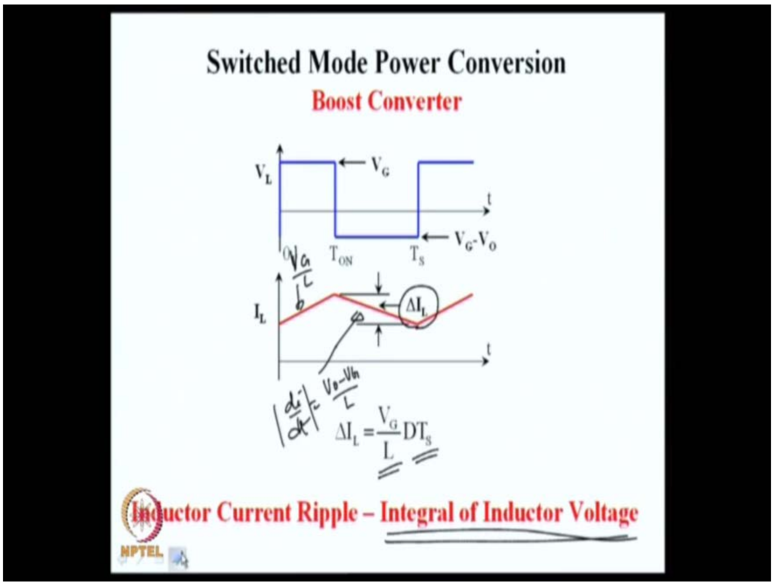


The efficiency, ideal efficiency of this converter as before can be seen it is a product of V naught by V G into I naught by I G. And these 2 functions are inverse of each other and you get the ideal efficiency to be unity, because there are no energy are dissipating elements inside the converter. There are several non-idealities in the converter, the non-ideality 2 non idealities, which we wanted to understand the in the sequence in which we are going or first the non-ideality in the inductor current delta I L by I L or in this particular case it is delta I G by I G. The inductor current ideally should be constant and steady, but because of the switching it will have a ripple and we defined that ripple current as delta I L and the ratio of delta I L by I L is a measure of this non ideality.

(Refer Slide Time: 24:17)



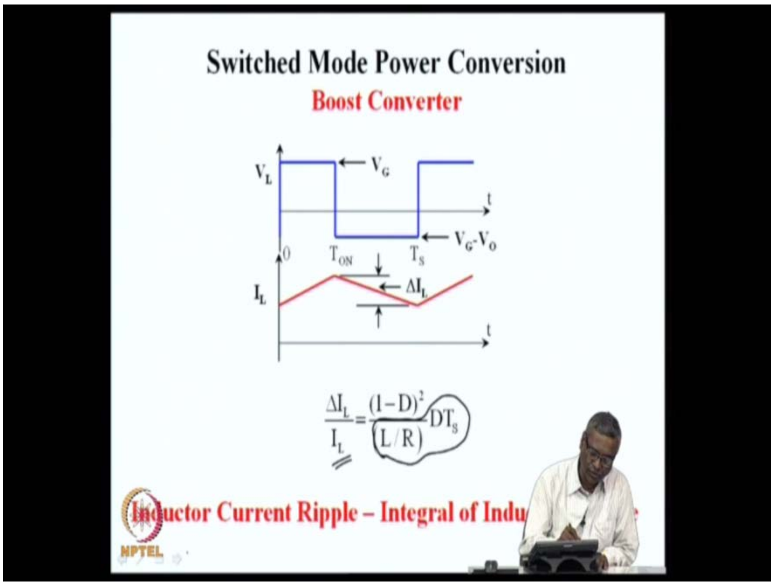
(Refer Slide Time: 24:57)



And this can be evaluated simply by integrating the inductor voltage, because L D I by D T is V is the relationship for any inductor. And if we know the voltage across the inductor V L integral of that will provide us the current through that. So, what I have done here is the voltage across the inductor, when the switch is on voltage across the inductor is same as V G during the on time. And when the switches connected to the off pole the voltage across the inductor is negative and it is V G minus V naught with a negative sign. And integrating this will give us the required inductor current and what you see is the integral of the inductor voltage waveform as expected. A steady voltage when integrated will result in a ramp.

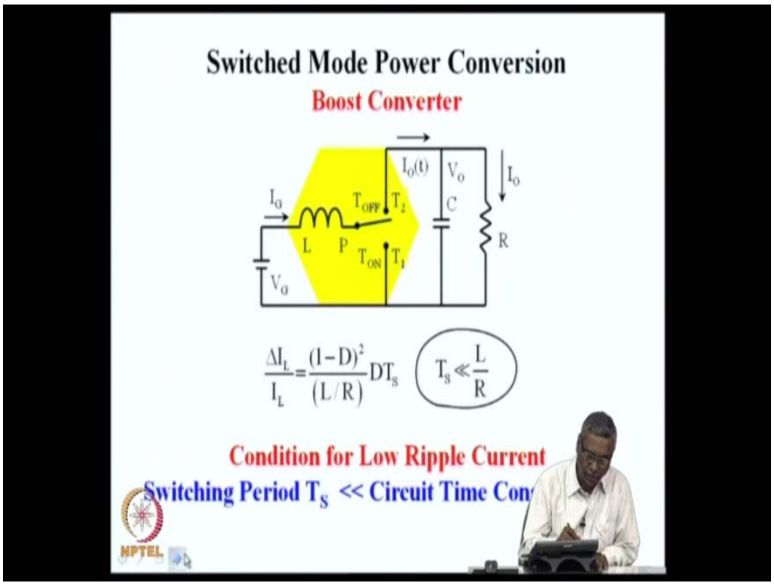
So, this would have a slope of V G by L, L D i by D T is V G in the first half and in this region the slope will be D I by D T is V naught minus V G divided by L and it is a negative slope, this is the magnitude of D I by D T. And for steady state the ripple in the positive half positive raising half is the same as the ripple in the falling half. So, we might find out this, this delta I L is nothing, but V G by L which is a slope multiplied by the on duration which is DTS. So, this inductor voltage inductor current ripple in all the inverters is found out by drawing the inductor voltage and integrating the same. And in all cases, because voltages are nearly constant, this integration will result in a simple ramp and algebraically, it is possible to find out what is delta I L.

(Refer Slide Time: 26:07)

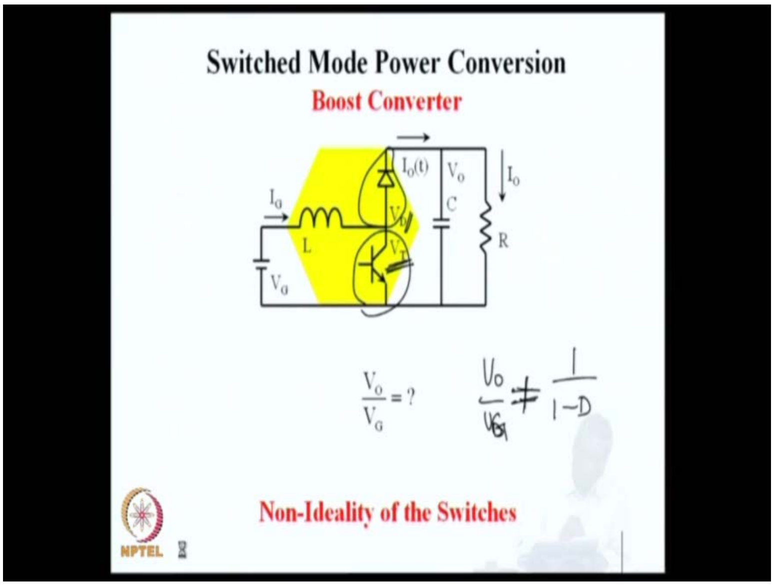


This delta I L is if you replace V G as V naught into a 1 minus D, this quantity in terms of V naught is V naught into 1 minus D divided by L into DTS. And the entire inductor current itself, we have seen the ratio that I L is I naught by 1 minus D I naught is V naught by load résistance. See, if you come by all these things together, the current ripple factor which is the ratio of the ripple current divided by the inductor current is now 1 minus D square multiplied by a ratio which is T S by L by R, T S is a switching period L by R is the time constant of the load, load and the inductor. Now, if this time if this ratio T S by L R is very small or if we switch at a high enough frequency it is possible to make this current ripple as small as possible. So, this non-ideality of inductor current ripple can be reduced arbitrarily to any small level by selecting a switching period, which is very small or selecting a switching frequency which is very high.

(Refer Slide Time: 27:22)

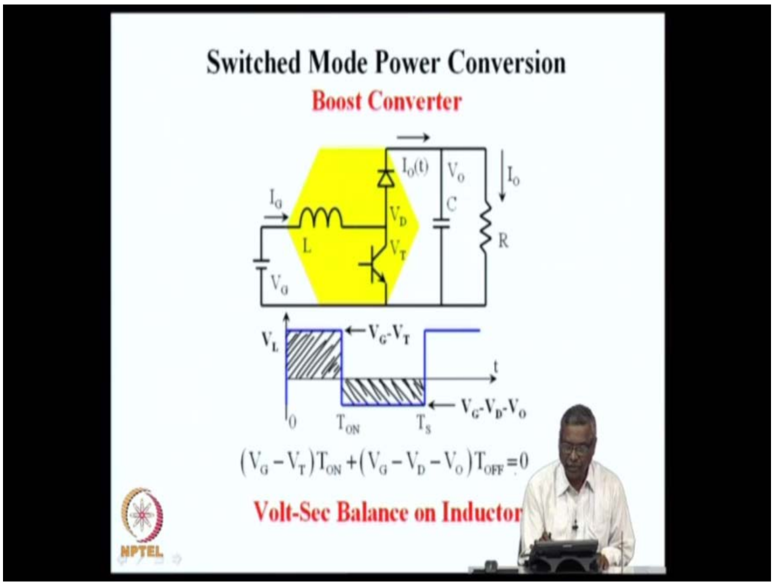


(Refer Slide Time: 27:43)



The condition for this low ripple current as I had said before is that the switching period has to be very small, compare to the time constant, the time constant of the inductor and the load L by R. This will ensure that our converter is working close to ideal conditions. The switches in the converter are not really ideal and they are realized by active switch transistor on this site and the passive switch, which is diode on that side. And these switches have a voltage drop during conduction, which is V T for the transistor and V D for the diode. Now, on account of that our V naught by V G is not going to be the same as, what we had found out ideally. Ideally, V naught by V G has to be 1 by 1 minus D, but because of the non-ideality in the switch V naught by V G, V G will be not equal to 1 minus 1 by 1 minus D.

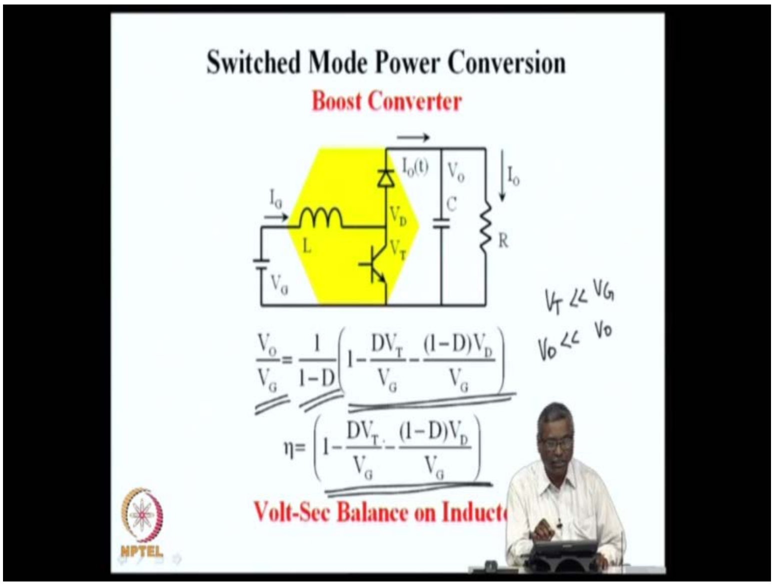
(Refer Slide Time: 28:31)



And, we would like to find out what is this effect to what extent, we will not get the ideal performance and by how much we will be away from the ideal performance. We now, take into account the switch drops, while calculating the volt second balance. The method is the same, but we have to make sure that we correctly account for the voltages across the inductor, when the switch was ideal this is only V G, but now it is V G minus V T. When the switch was ideal during the off time the voltage was just simply V G minus V naught, but now you have another term which is the diode drop.

See, if these are all taken into account the method of calculation is as simple as before the area of the volts second given to the inductor during the on time is a same as the area of the volts second taken from the inductor during off period. And this gives a relation V G minus V T into 1 time plus V G minus V D minus V naught in to off time and this total adds up to 0. And this is now the fresh volts second balance taking into account the non idealities of the switch and when that is done.

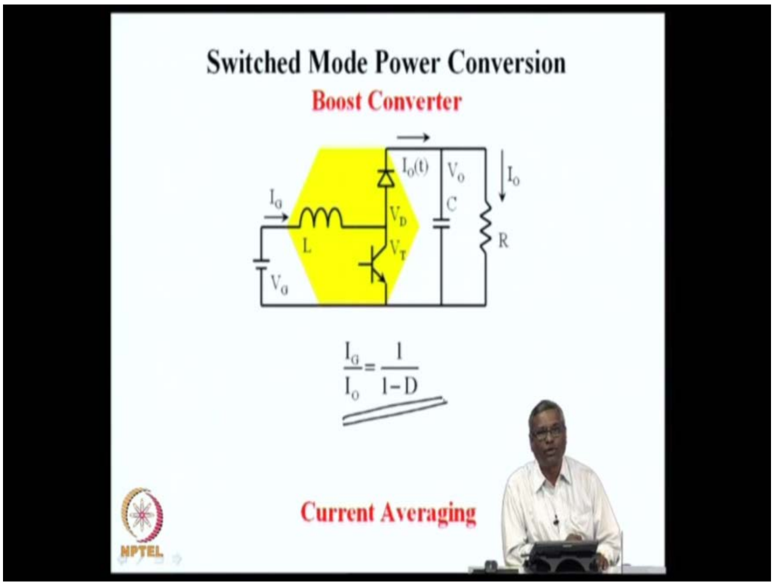
(Refer Slide Time: 29:45)



This expression results in V naught by V G is same as the ideal multiplied by a correction factor. And you can see that this correction factor is less than 1, because from 1 you have to subtract 2 ratios, 2 positive ratios V T by V G into D, V D by V G into 1 minus D. So, this ratio will be small if the switch drop is very much less compared to V G. This ratio will be very small if, V D is very much compared less compared to V naught is V G by 1 minus D is V naught. So, we can say that V T has to be less than very much less than V G, V D has to be very much less than V naught.

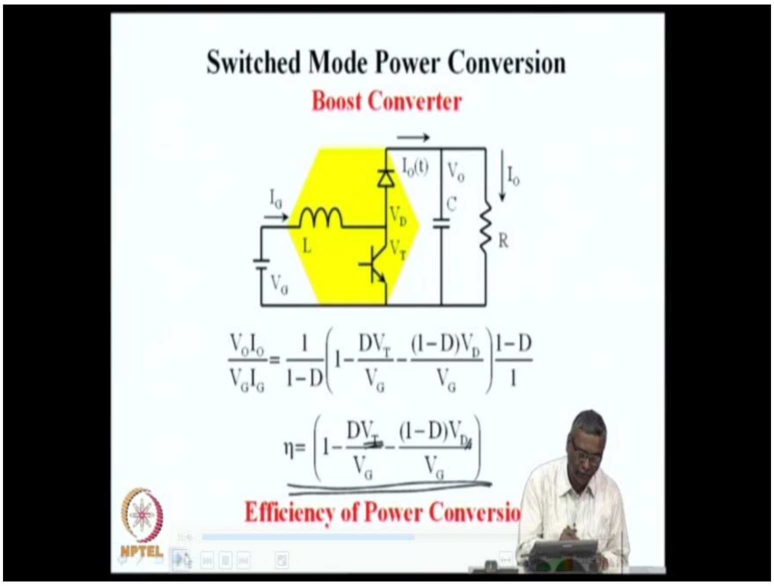
See, if this in equalities are true then the correction factor will be close to unity and this correction factor is although also, the efficiency of the converter and efficiency also will be close to unity and we will have a small factor by which it is different from one and that will contribute to the total losses. So, the method of calculating the voltage ratio has not changed, but the accounting is now more proper.

(Refer Slide Time: 30:57)

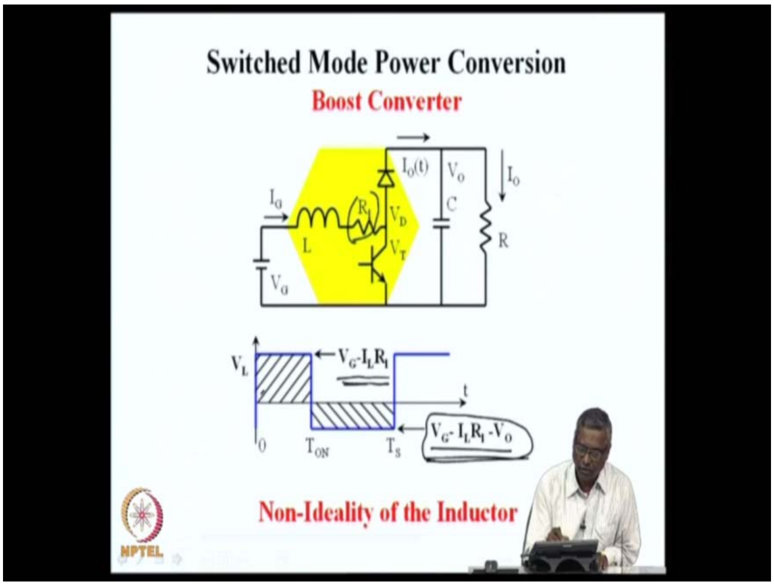


The switch drops also are taken into account. The current ratio does not change because of the switch drops, this also is a property which we have seen any non ideality which is coming in series in the converter, will not affect current ratios and so the ratio I G by I naught remains as before 1 by 1 minus D.

(Refer Slide Time: 31:18)

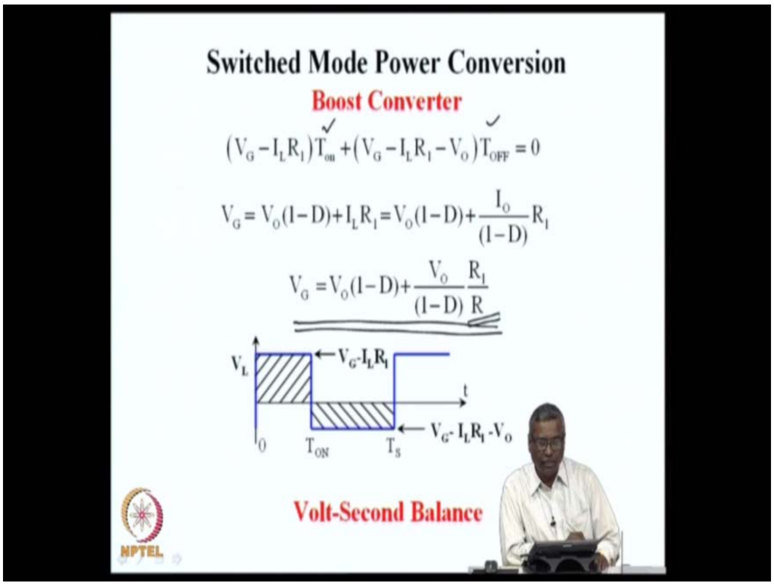


(Refer Slide Time: 31:49)



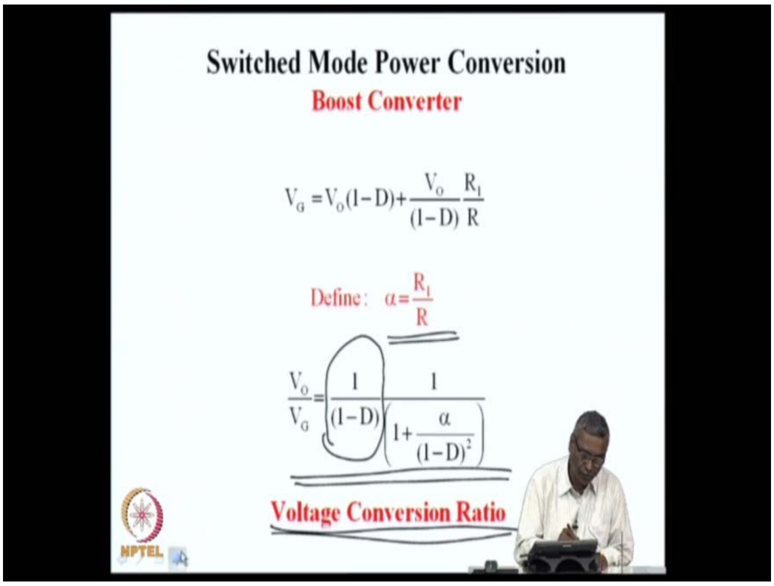
And as a result, the correction factor on voltage is also the same as the efficiency. So, what we see here is the efficiency of power conversion. The efficiency of power conversion has 2 reasons for being less than 1, 1 is because of the switch drop the active switch drop V T by V G and the other is, because of the passive switch drop V D by V naught. Now, we will take into account the non ideality of the inductor also, we will assume during this analysis that the switch are ideal, but we will find out only the non-ideality of the inductor and I have indicated in this picture R L, which is a resistance of the inductor winding. So, the method of finding out the voltage conversion ratio has not change, it is still based on the volts second balance. But now, we are accounting for the drop in the resistance of the inductor, V G minus I L R L during the on period and V G minus I L R L minus V naught during the off period.

(Refer Slide Time: 32:39)



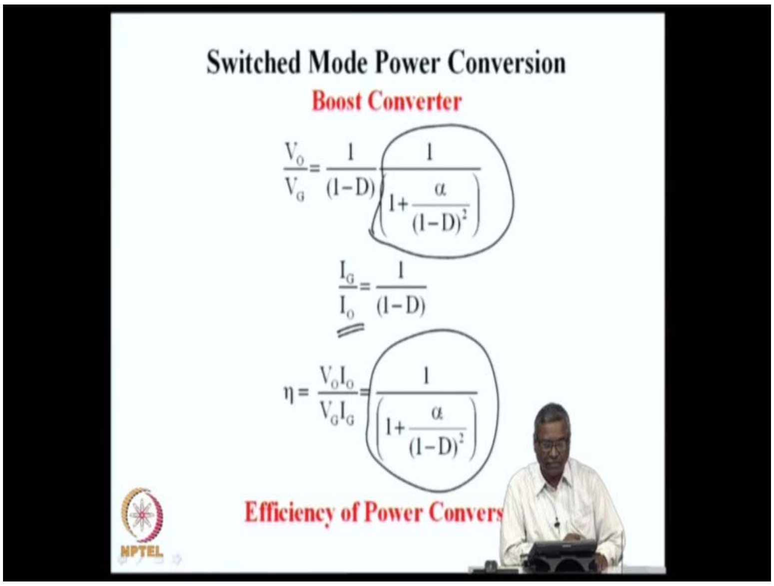
And if that is multiplied with the appropriate on time and off time and equate to 0. Then we have now finally, a relationship that the output voltage V G is V naught into 1 minus D plus V naught into R L by R divided by 1 minus D. Now, this volts second balance gives a result where, V G is now related through V naught D as well as R L by R. Now, the additional function element is a ratio of the parasitic resistance in inductor to the load résistance R.

(Refer Slide Time: 33:17)

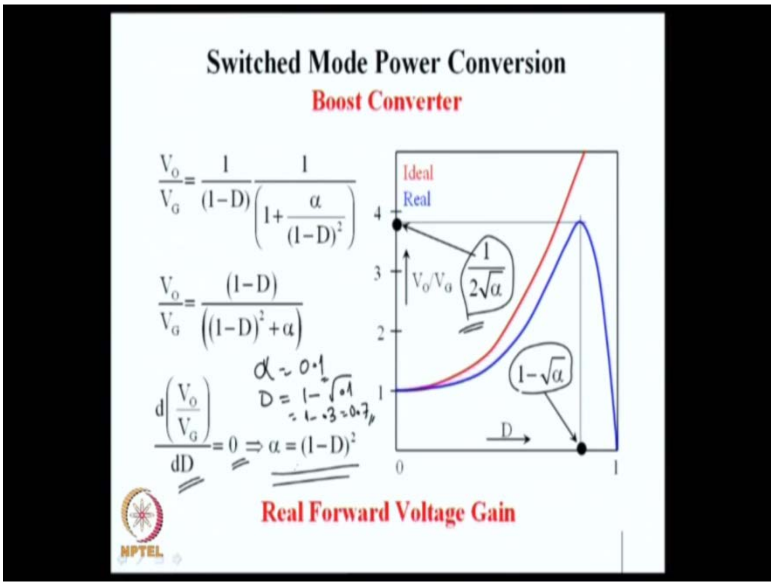


And if I define that quantity as alpha, then this relationship can be converted into the ideal result 1 by 1 minus D multiplied by a correction factor, which is 1 by 1 plus alpha into 1 minus D whole square. We see that the voltage conversion ratio, when the inductor has a resistance present is the same as the original ideal ratio multiplied by a correction factor. This correction factor you can see is 1 by 1 plus alpha by 1 minus D whole square. This correction factor will be less than 1 because what you see is 1 by a quantity in the denominator, denominator has 1 plus all positive quantities. So, this correction factor will always be less than 1.

(Refer Slide Time: 34:10)



(Refer Slide Time: 34:35)



The efficiency also is the same as the correction factor whatever is the correction in voltage will turn out to be the correction factor of efficiency. This is because these non-idealities do not affect the current transfer ratio. On account of that, we find that the efficiency also is the same correction factor 1 by 1 plus alpha by 1 minus D whole square. It is much better to look at this function graphically, because it will give us a lot more insight into the operation of the converter and preferred operating conditions. We had earlier seen that the ideal power conversion factor, which is shown here 1 by 1 minus D is a number which starts from 1 and goes to infinity as D goes to 1.

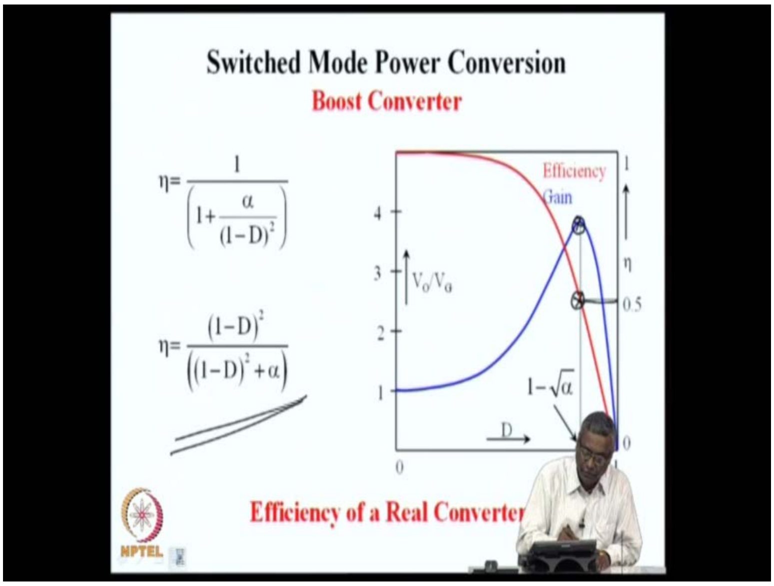
But on account of this correction factor, when D becomes 1 the correction factor is itself 0. So, when you multiply both of them the final result is 0 and this new function V naught by V G. Now, follows very close to the ideal function at lower values of D, but it diverges from the ideal function and eventually goes to 0. But it shows that we start from very close to 1 instead of going to infinity, it reaches a number which is 0. So, naturally something which starts from 1 and goes up and eventually reaches 0 will have a maximum at some point. So, these are all of points of interest to us, what is this maximum that is reached, what is the value of that maximum, when is this reached at D?

These are all something which we can find out, as I had shown, what is the duty ratio at which the maximum voltage, gain is obtained and what is that maximum gain or the questions that can be found out by just analyzing this function. The ideal gain does not hold good anymore because of the correction factor. The correction factor has change the nature of the gain and the nature of the gain is such that we start from very close to 1. But we end up at 0 gain and in between it reaches a peak and then falls down. So, let us try to find out what is the nature of this, this is very simple to do because this is a simple function in D and alpha and if you want to find out at what value of D it reaches the maximum.

This function has to be differentiated with respect to duty ratio and equate to 0 and back to 0 occurs, when alpha is equal to 1 minus D whole square. In this function, when the denominator terms are equal that is when the maximum gain is reached and that duty ratio is 1 minus root alpha, alpha is ratio of R L to R and the maximum gain occurs when the duty ratio is 1 minus root alpha and that maximum gain is 1 by 2 root alpha. This will be the maximum gain and it will not be infinity, it will be something which is less than 4 or 5 or something depending on what is 1 minus root alpha.

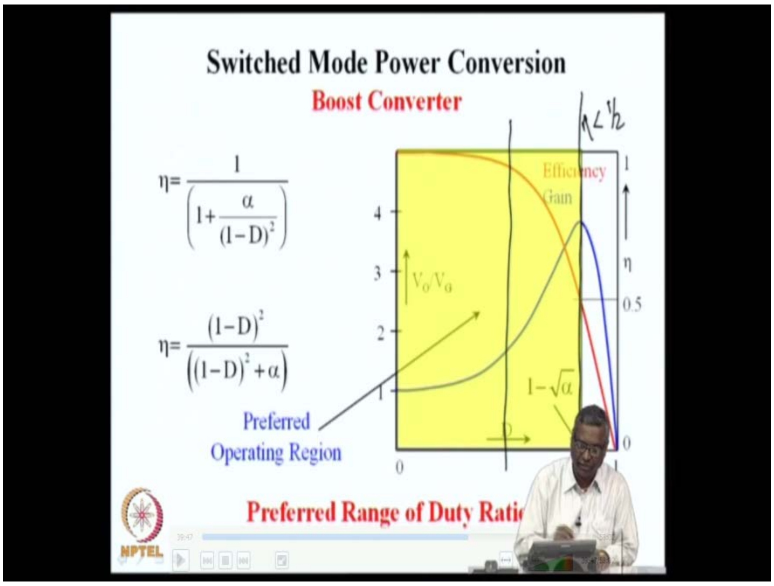
For example, in the same converter if, alpha is equal to 0.1 if, alpha is 0.1, then the duty ratio at which maximum gain occurs is 1 minus root of 0.1. So, that will be 1 minus probably root of 0.1 may be about 0.3 so that will be around 0.7. So, you will find that the maximum gain occurs at D equal to 0.7 and D equal to 0.7, if alpha is 0.1. We know that that maximum is 1 by 2 times root of alpha root of alpha is 0.3, 2 times 0.3 is 0.6, 1 by 0.6 will be about 1.7 or so the gain is quite small, if alpha is this number. Now, we can also try to plot the…

(Refer Slide Time: 38:32)

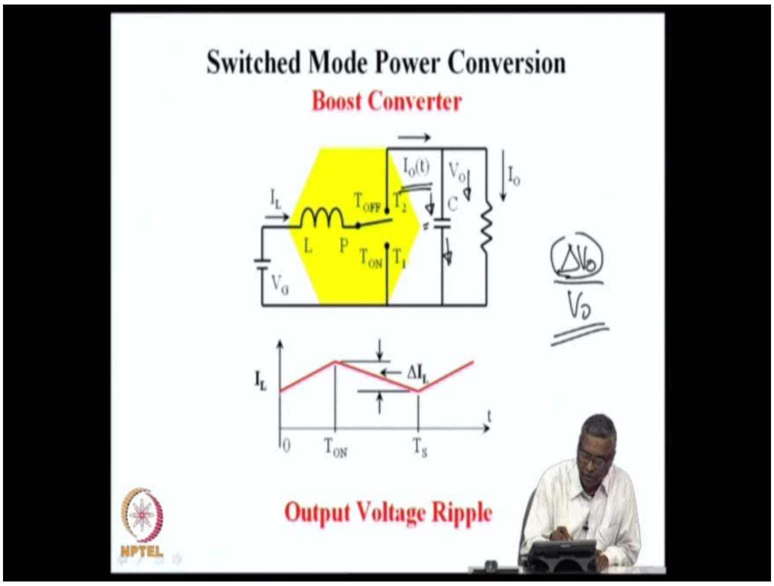


As we had drawn the corrected gain, we can also plot the efficiency of power conversion. Efficiency of power conversion is 1 by 1 plus alpha by 1 minus D whole square and we find that when maximum gain is achieved at that particular duty ratio, the efficiency is only 0.5. This has a very serious consequence because if efficiency 0.5, then the converter has more losses than what is being delivered. The power that is delivered is more than the power that is lost then it will not be a good power converter. So, we can even say that.

(Refer Slide Time: 39:13)



(Refer Slide Time: 39:51)

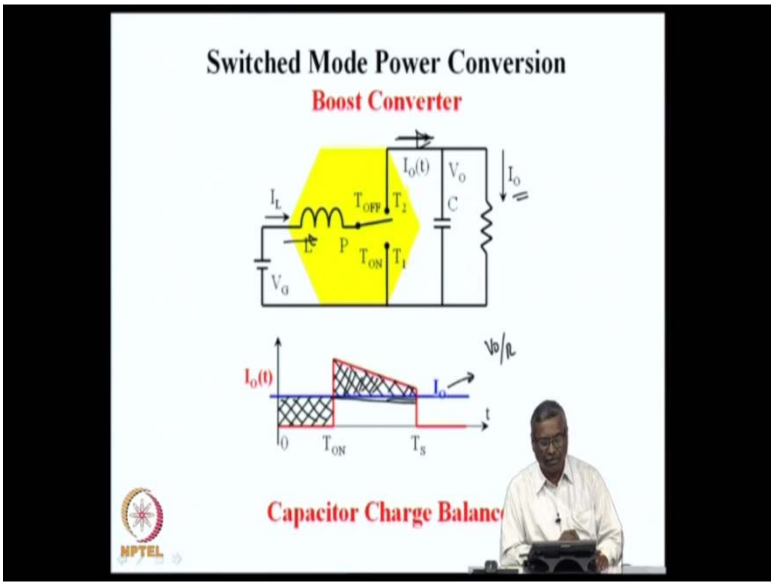


This region beyond, this peak where the duty ratio is such that the efficiency is less than 1 by 2 is not the preferred region of operation, what I had shown here is the yellow region here is before the peak of this gain and that is the preferred region where the duty ratio is more than 0.5. And in fact in many converters it will be better that it is somewhere close to 0.8 or so that the preferred operating region is not all the way to the peak, but something which is less than the peak. These are certain things which are different from the buck converter where we had no maximum, but in this converter there is a maximum gain, which is related to the non-ideality of the inductor.

The output voltage ripple is the next non ideality associated with that. In any converter, we like the output voltage to be steady and constant, but the switching performance, the switching nature of the converter makes it makes the output voltage to have a ripple switching ripple and naturally a performance measure, which can quantify, this is a ratio of switching ripple to the average output voltage.

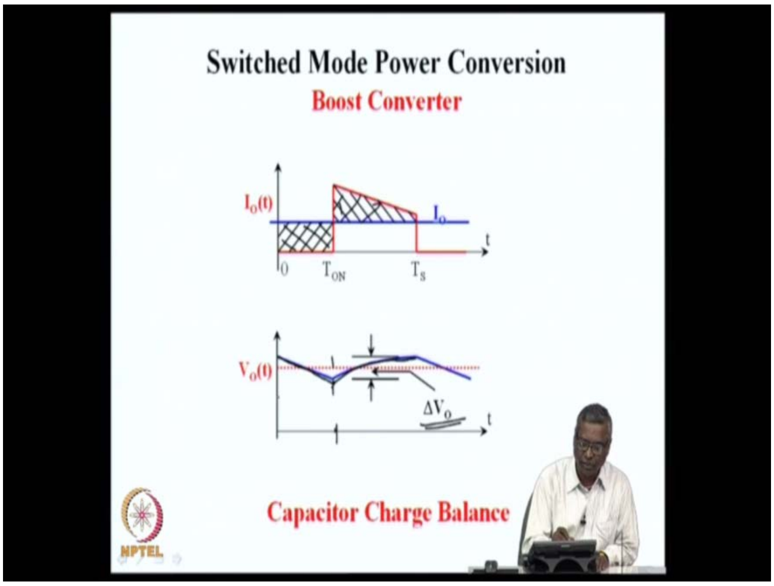
Now, that can be found out by how much of this current is being supplied to the capacitor and how much is coming to the load. The load part will be the average value of I naught the AC part of the current will go into the capacitor and that is the one, which will produce this delta V naught because in any capacitor if there is no current flowing throw that the voltage across that is constant. See if there is a switching ripple there will be switching current in the capacitor, if the switching current is known it is possible to find out the switching ripple. So, out of the inductor current the DC part, the part of the current, which is coming into I naught.

(Refer Slide Time: 41:17)

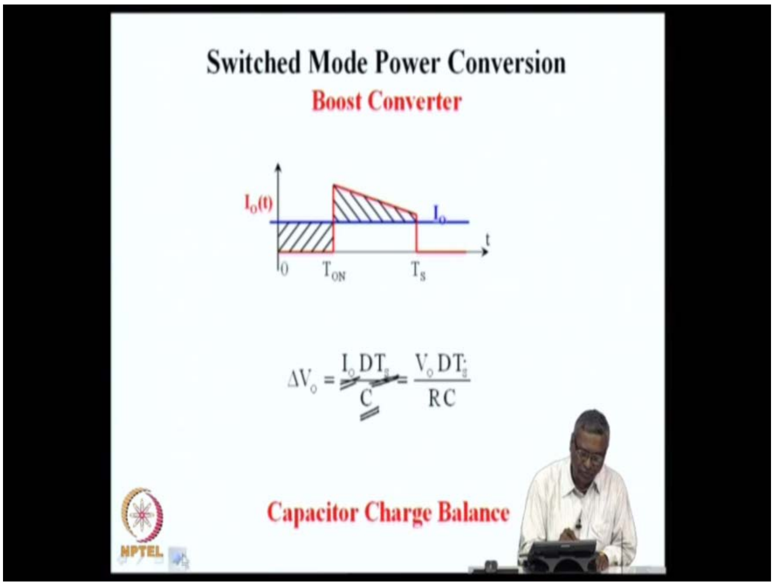


We know that the current coming in I naught is this portion and the average of that is the current going into the resistor average. This is going into the resistor and from I naught of T which is coming from inside the converter. If you subtract this I naught which is going into the resistor whatever is left with is the current that is going into the capacitor. So, as expected this has 2 components when the switch is on the capacitor is discharging into the resistor because no current is coming from the load and when the switch is off, the switch current which comes out supply the load and also charges the capacitor. So, the hatched region is the current in the capacitor.

(Refer Slide Time: 42:07)

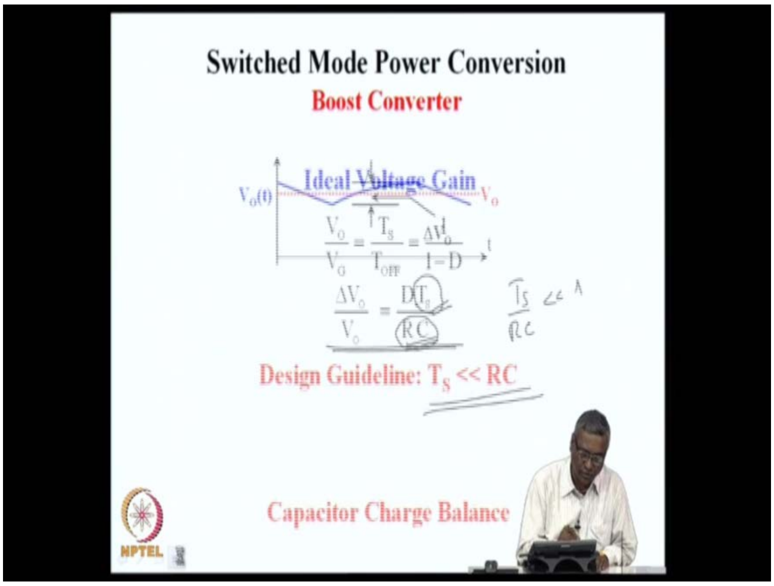


(Refer Slide Time: 42:49)



And if you integrate that that will give you the voltage across the capacitor, integral of we see the voltage across the capacitor is 1 by C integral ICDT. So you will find that the, the capacitor current which is here, if you integrate that. So, during the time capacity is discharging current will be dropping linearly and during the time capacity is charging current will be following this curve and then in one cycle during one half. During the on period capacitor is discharging and during the off period capacitor is charging and we might take anyone of this to find out this delta V naught. It is simpler to do it from the on time. So, during the on time the current that is supplied by the capacitor is I naught on time is DTS and it is supplied to C. So, total charge I into tie T divided by C is the delta V naught and I naught is V naught by R the other quantities or DTS by C.

(Refer Slide Time: 43:09)



(Refer Slide Time: 43:55)

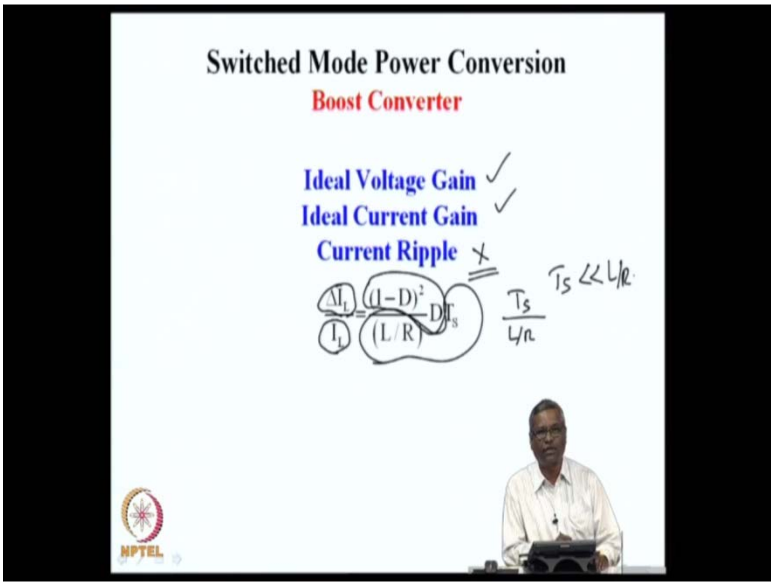
And if you transfer V naught to the left hand side, we get the voltage ripple is now a measure, which can be quantitatively expressed as duty ratio multiplied by T S by R C.

Again as seen before the voltage ripple appears as a ratio of a period time period of the switching and the natural period of the circuit, natural period of the circuit is R C switching period is T S and if this ratio T S by R C a small, if this is very much less than 1. Then we will find voltage ripple is also very small and that criteria, which is redesign guideline for making sure, that the boost converter has low output voltage ripple.

So, what we have seen is that the ideal voltage gain of the converter, see we have followed the same methods that we had done as before. In the boost buck converter also, we went through measuring several ideal quantities, several non ideal quantities than the non-idealities of the converter itself, the non-idealities of the inductors, the switches and so on. So, the first a quantity that we found out is the ideal voltage gain and this was done by finding out the volts second balance on the inductor, from volts second balance we found that V naught by V G is 1 by 1 minus D, which is a good thing. We are able to convert power deliver voltage, which is more than the input voltage and that is the reason for this converter to be named as boost converter.

As a next thing that we found was that the ratio of the currents ratio of input current to the output current is also a function of D and this also has the same ratio as the forward voltage converter. This is true in all the power converters where no loss is taking place. The forward voltage gain and the reverse current gain will be the same. In this follows either, this follows the fact that in an ideal converter there are no losses or because there are no losses you can say that one ratio is the inverse of the other ratio. I G by I naught is same as V naught by V G or V naught by V G and I naught by I G or inverse of each other.

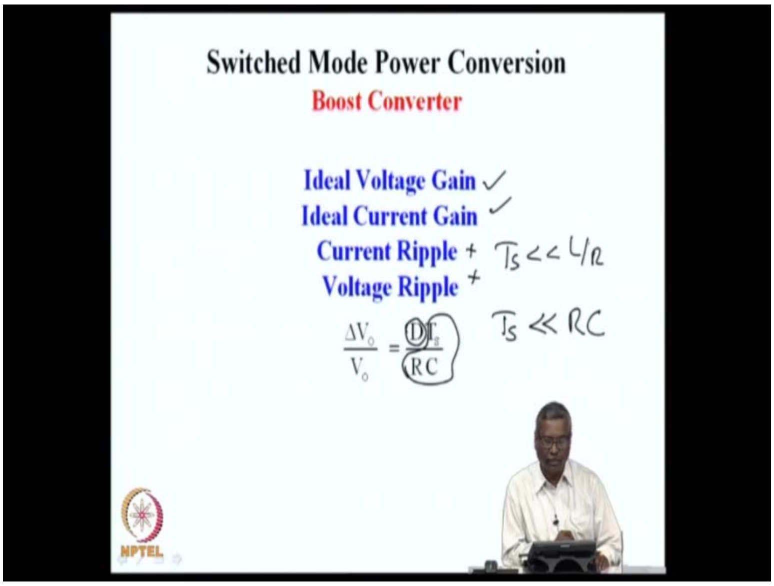
(Refer Slide Time: 45:36)



The next thing that, we found out these were the positive things power is converter at certain voltage and there is a ratio of current drawn from the output to the input. The third quantity is the non ideal property a standard linear converter will not have current ripple, will not have voltage ripple. It will draw current steadily and supply power steadily, there will be voltage gain there will be current gain, but there will be no current ripple or voltage ripple. But in a switching converter there will be current ripple and voltage ripple, because the process of power conversion involves switching. And the switching itself produces discontinuities in voltages and discontinuities in currents and this reflects as ripple current in all the storage elements, storage inductors and a ripple voltage on all the storage capacitors.

And we found that using the integral of the voltage across the inductor. It is possible to find out what is this delta I L and express it is a ratio of I L and this ratio delta I L to I L is a normalized current ripple called ripple factor and this ripple factor is a function of the duty ratio, 1 minus D square and D. And it is also a function of the ratio of the 2 times in the converters and these times are T S and L by R. The switching period divided by the L by R time constant of the converter and if we want this current ripple to be very small, we have to make T S to be very much less compare to L by R. This also is something, which we had seen in the previous converter and we see that appearing again in this converter also.

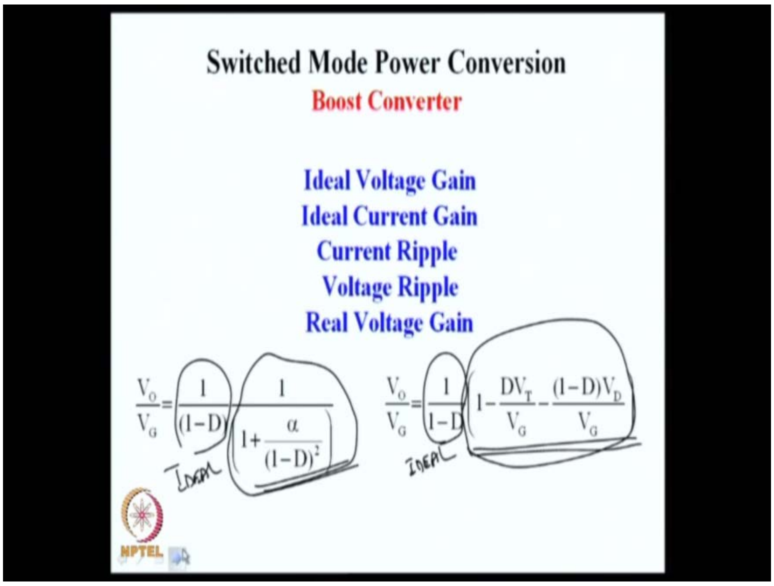
(Refer Slide Time: 47:23)



The next thing that we see is that the output voltage also has a ripple, it is not a constant steady output voltage, because of the power processing being discontinuous. We have delta V naught by V naught, which is a measure of the non ideal voltage present at the output and that also turns out to be a function of D and the ratio of 2 times switching period. If it is very much less than the output time constant output RC time constant then this voltage ripple will be quite small.

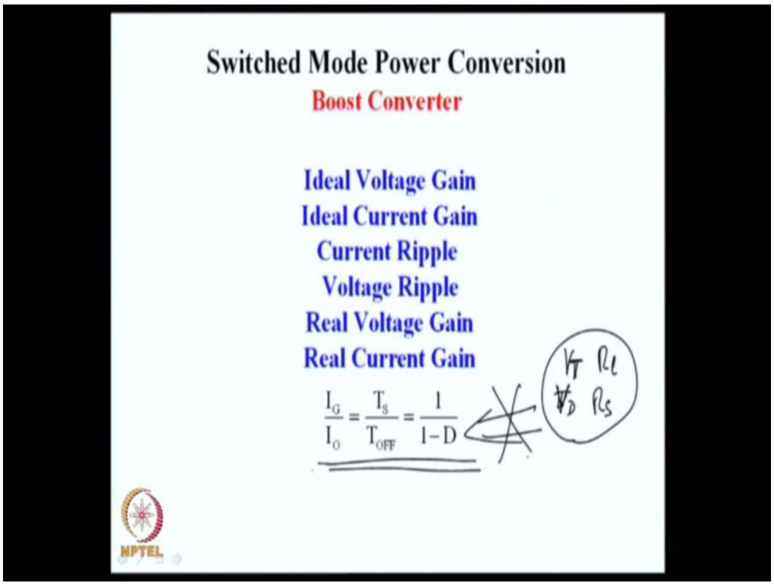
So, we had seen that this converter boosts the voltage with a ratio 1 by 1 minus D and the current gain is also 1 by 1 minus D. The current has undesirable ripple, voltage has undesirable ripple current in the inductor. The voltage across the capacitor, these undesirability ripple can be made as small as possible if we make the inductor time constant. And the capacitor time constant with the load to be very small, compare to the or the switching period very small compare to the L by R and R by C time constants of the converter.

(Refer Slide Time: 48:45)



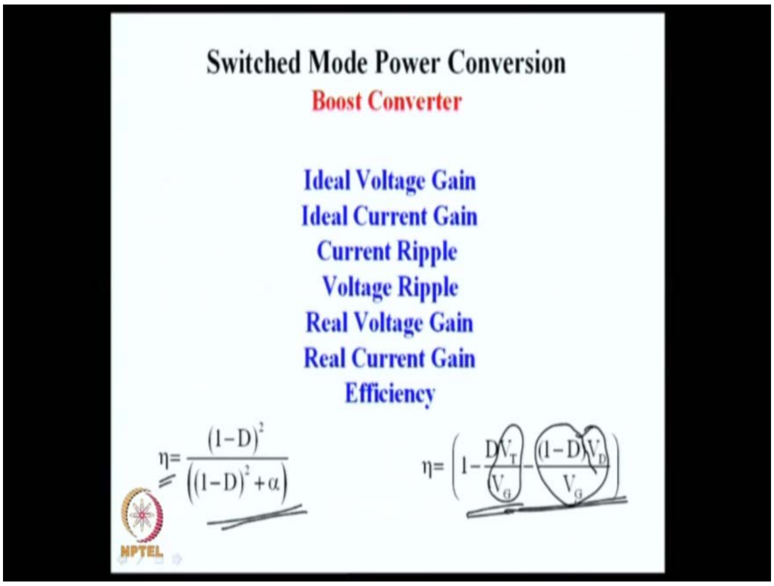
So, then we saw that the real voltage gain in the converter is not the same as ideal voltage gain, it has 2 non idealities, one of them is a non ideality, because of the conduction drops in the switches, another is the non-ideality because of the resistance in the conducting path. This can be in the source inductor and so on and both these non idealities or modifying the voltage gain from the ideal value. This part is the ideal value, this part is ideal value of voltage gain; this ideal value is now modified by a correction factor. In both the cases so in the case of inductor resistance it is modified by 1 by 1 plus alpha by 1 minus b square. In the case of switch drops a similar modification a correction factor exists and it is possible to find out these factors applying the same principles of volts second balance on the inductor.

(Refer Slide Time: 49:54)



The real current gain is not affected by any of the non idealities because all the non ideality are associated as series non-idealities. Series non-idealities do not affect the current gain, we can see that the current gain for the real converter as well as the ideal converter or the same. The reason is whether it is a switch drop or diode drop V D V T or R L R S, all of them are series non idealities. They are present in as a series element in the circuit and they do not affect the current gain, they do not affect the current gain of the circuit.

(Refer Slide Time: 50:38)

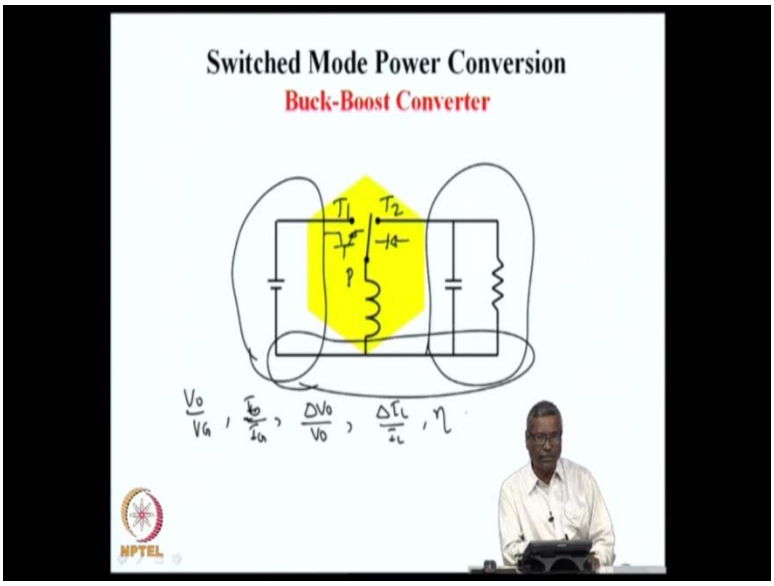


And the next measure is the efficiency of power conversion. The efficiency of power conversion again, is consisting of 2 parts. When the inductor has a résistance or the conducting path has a resistance, that contributes to some losses and those losses can be quantified. And efficiency can be calculated as the ratio of 1 minus D whole square divided by 1 minus D whole square plus alpha. And the conduction drop of the switches are also contributing to losses and on account of these losses again, there is a loss in power and that loss in power is quantified by the efficiency term that is here. So, as per this you will see that V T by V G is a critical quantity and V D by this quantity V G by 1 minus D is a critical quantity. V T has to be very much less than V G, diode drop has to be very much less than V naught, if that is true

(Refer Slide Time: 51:41)

Then, the efficiency will be better than the last point that we saw was the preferred operating range. We saw that the efficiency goes below efficiency goes below 0.5, when duty ratio is more than 1 minus root of alpha. So, when you are in the range beyond this the efficiency is less than 0.5, which is not a good operating condition so that the preferred operating range is limited to less than 1 minus root alpha are in a real case, it leave one limited much less than this quantity may be 1 half of this. And this is because of the losses in the converter and efficiency dropping drastically as you reach the maximum gain. So, what we had seen up to now are the performance factors of the boost converter is boost converter, we had seen is a variation, a variant of the same switch cell to switches to a single pole double throw switch one number and then an inductor. So, these 2 elements were combined together to get our boost converter.

(Refer Slide Time: 53:05)



Now, the, the another way of connecting the same switch cell consisting of the throws T 1, T 2 and P is to connect the source on one of the poles and the load on the other pole. And then make the, the inductor and the pole of the switch to the third end and such a converter is called the buck boost converter. And this converter has a similar set of performance switchers as we had seen before the voltage conversion ratio, current conversion ratio, inductor current ripple, capacitor or the output voltage ripple. Then the correction factors on the output voltage on account of non-idealities present the non-idealities could be the switch non-ideality. The diode drop and the switch drop all these factors of V naught by V G, I naught by I G then delta V naught by V naught, then delta I L by I L efficiency.

So, these are the study state performance quantities. So, what we will see in the following lecture will be to follow a gain the same kind of methods, the volt second balance for finding out the voltage conversion ratio, current averaging for finding out the current conversion ratio? The balance, the integral of the inductor voltage, to find out the inductor current ripple, integration of the capacitor current to find out the voltage ripple then again modified volts second are fully accounted volts second balance on the inductor on account of the switching drops, on account of the resistances in the various parts of the circuit. So, all these contribute towards losses in the converter to what extent these losses affect the voltage conversion ratio to what extent these losses appear in the efficiency of the converter?

So, in effect, we will repeat the same exercise again in the next lecture for the buck boost converter. So, that we fully understand the analytical method, the analytical method is very simple only, there are 5 steps. What are the 5 steps? The first step is the volts second balance on the inductor; this will give us what is the ratio of the output voltage to the input voltage. The second step is the averaging the current in the inductor, this will give us the ratio of the output current to the input current. The third step is integrating the voltage across the inductor; this will give us the ripple current in the inductor. The next or the fourth step is integrating the current through the capacitor, which will give us the voltage ripple on the capacitor.

So, these are all the ideal and the non ideal converter where there are no losses percent, very every element is ideal. Because of the switching, you have the non ideal, it is of switching current ripple and switching voltage ripple. After these are accounted for we analyze for the non-idealities of the switches. These are the conduction drop of active switches conduction drop of passive switches V T for the transistor V D for the diode. They also affect the output voltage they do not affect the current ratios, because there are series non idealities. And once we account for these things, we will get again the ratio of voltage V naught to V G. We will see that I naught to I G is not affected in the same correction factor that we see on V naught by V G will also be accounted as efficiency of the converter. So, to that extent there are losses in the converter. So, we will go through the same 6 steps in the next lecture, with a few method so far with a few examples. And once that is done, we are fully thorough with the steady state analysis of a any converter. We might take a few examples after that and continue with more advanced converters, which will be isolated converters.

Thank you very much.