Switched Mode Power Conversion
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Lecture - 11
Primitive Converter

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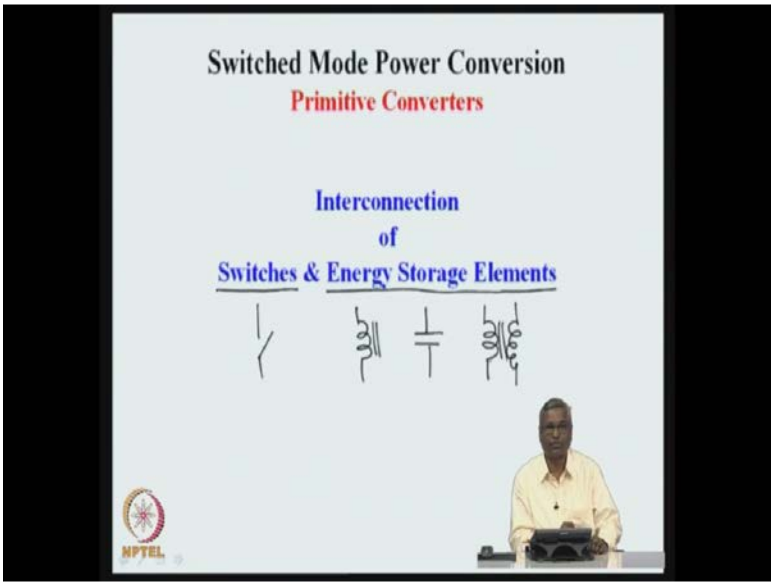

Good day to all of you. In the previous several sessions, we had spent adequate time on the components that are going into the power converters and these were namely switches followed by energy storage elements in these energy storage elements were inductors capacitors and transformers. So, we had spent enough time on understanding the characteristics of switches, operation of the switches then, the energy storage elements inductors, capacitors and transformers for transforming the power.

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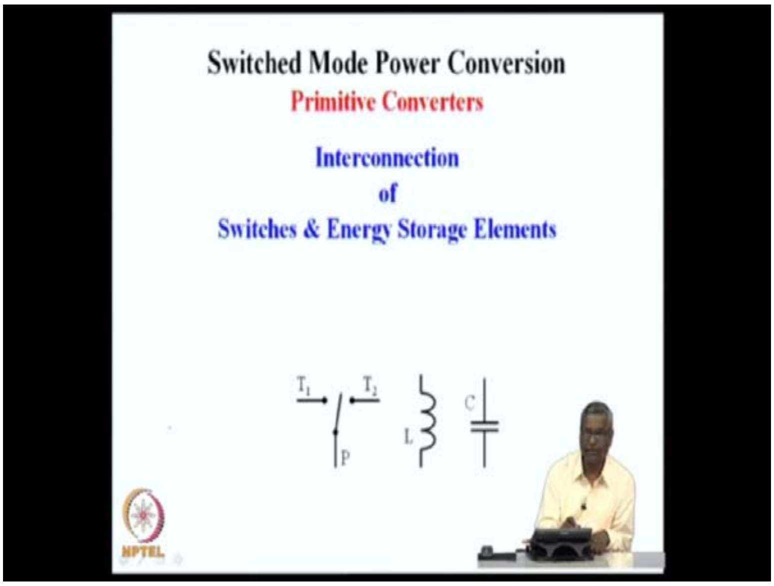

In all these cases, we had spent adequate time to understand their basic characteristics. What we are going to do in this lecture is to spend adequate time when the interconnection of these various elements. These elements will be interconnected in such a way that we carry out the power conversion functions satisfactorily. The switch that we had looked at it was an on off switch. But, for the purpose of interconnecting them in a circuit, we try to understand this circuit or understand a particular form of switch which is a single pole double throw switch and then, an energy storage element inductor and an energy storage element capacitor. This particular configuration of a switch is called a single pole and double throw switch. There are 2 throws in this switch T 1 and T 2 and there is a single pole in the switch which is denoted by P. A very simple power converter will consists of one switch and at least one energy storage element. So, we might put together for the purpose of our simple understanding a primitive converter.

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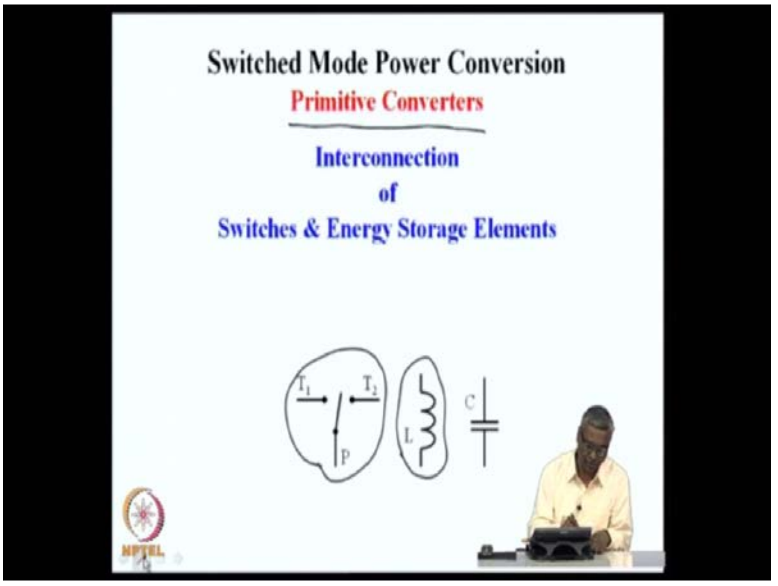

What we are going to study now in this session is about a primitive converter and this converter will consists of a single switch and one inductor. How we connect them together, following certain principles on circuit theory in order to carry out the power conversion function efficiently is what we are going to do in this lecture.

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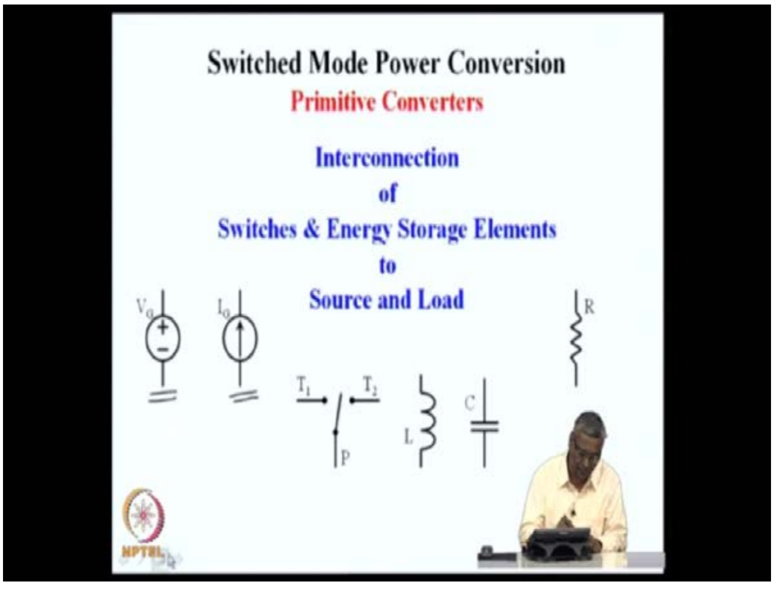

The switch and the storage elements are going to be connected as part of a power converter in order to transfer power from a source. A source could be a voltage source or the source could be a current source. So, from the source we are going to draw this power draw the power through switches and storage elements and transfer it to the load which is a resistive load in this particular case. So, while interconnecting the sources to the switch and the energy storage element. And eventually, to transfer the power to the resistive load there are certain conditions which have to be honored, there are certain circuit principles which have to be followed and those are the things that which will be we will see first.

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The interconnection rules are as follows: If you have a source, a current source or a voltage source, they may not be overloaded; this is one of the first principles that we have to honor. The voltage source or the current source may not be overloaded inturn this will translate into voltage sources are not to be short circuited in which case infinite current will be drawn out of that which can damage the voltage source. In the same way a current source is not to be open circuited in which case the voltage across the current source will go to infinity and this will result in overloading of the current source. So, from the point of view of the sources there are 2 conditions that we have to ensure and these conditions are the voltage sources are not to be short circuited and the current sources are not to be open circuited. Then, we have conservation of energy which is the bedrock of all engineering discipline and the conservation of energy states that, energy is to be conserved and energy continuously varies, energy cannot be interrupted.

The consequence of this conservation of energy is that, if a current is flowing in an inductive circuit, if we have current flowing in an inductive circuit that cannot be interrupted instantaneously. Such an interruption of inductor current will give rise to collapsing the energy to 0 and this is not to be done, this will give rise to over voltages in the system. And the dual of this is that, the voltage across a capacitor is an energy variable. The capacitor has energy, stored energy of half C V square and if the capacitor voltage is interrupted or short circuited instantaneously, the capacitor energy is also killed instantaneously and these are not to be done. So, the 2 interconnection rules are here that the source may not be overloaded which can be translated into no short-circuiting of voltage sources, no open circuit of the current sources and then, the energy has to be conserved which indicates that the inductor current may not be interrupted and the capacitor voltage should not be shorted.

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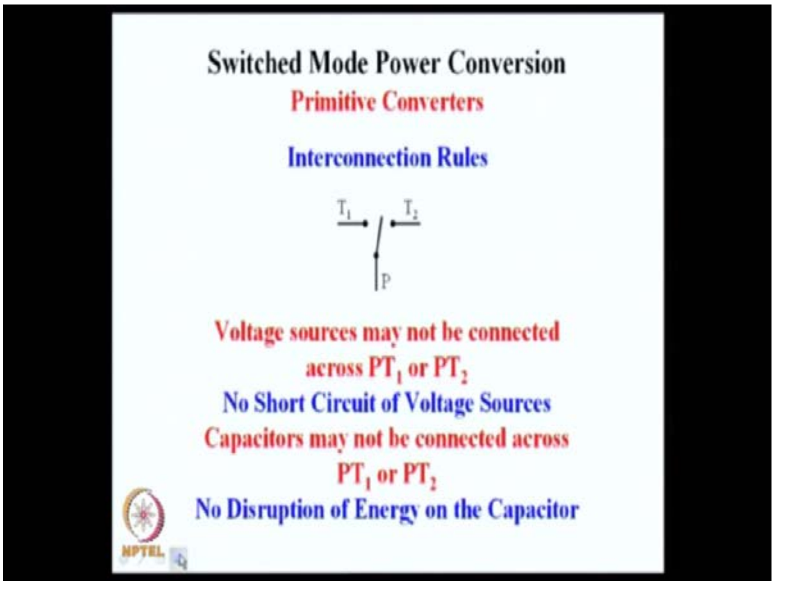

If we follow these rules then, it is possible to possible to translate these rules into certain simpler conditions for the switches and the energy storage elements that we are following, we are using. The switch is such that, the pole may be connected to T 1 for some time or the pole may be connected to T 2 for some time. So, the consequence is that the potential at point T 1 and potential at point P may be the same. So, if a switch has to be used along with a voltage source, it is very clear that we cannot connect the voltage source between T 1 and P. Voltage sources may not be connected across PT 1 or across PT 2 because in such a case, when P is connected to T 1or when P is connected to

P 2 the voltage source will be short circuited and that is not to be done. In the same way this should be current sources here, what you see here. Yeah, no short-circuit of voltage sources. Yeah, in the same way capacitors may not be connected across PT 1 and PT 2, the same argument holds if P is connected to T 1 and we have a capacitor between P and T 1 the capacitor voltage is short circuited and the same is true for P and T 2. So, these are the two rules as far as the voltage source or capacitors are connected. Voltage sources cannot be connected between P and T 1, voltage sources cannot be connected between P and T 2 and so also capacitor connect cannot be connected between T 1 and P, capacitor cannot be connected between T 2 and P. This is the first interconnection rule.

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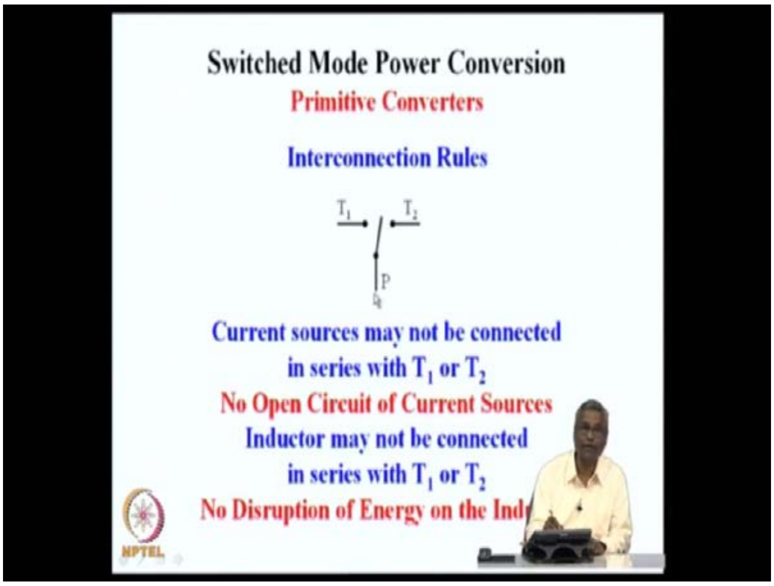

The second one is a dual of this; current sources may not be connected in series with T 1 or T 2. If we have an inductor in series with T 1, when the switch is thrown from PT 1 to PT 2, the current in the inductor is interrupted and that will give rise to the inductor energy being disrupted. So, we would say that current source may not be connected in series with T 1 and or T 2. And there is a similar condition that, current sources may not be open circuited. In the same way, if we have a current source it cannot be connected in series with T 1 or in series with T 2. And the interconnection rules as far as inductor or current source is concerned is that they may be not be connected in series with T 1 or in series with T 2, but they may be connected in the main path because whenever the switch is connected from switch from PT 1 to PT 2 we may have one circuit carrying current before the transfer of the switch and the current will transfer to some other circuit after the switch is shifted from T 1 to T 2 and that is acceptable. And so, any current source may be connected in series with P. So, these are the interconnection rules and if we follow these rules.

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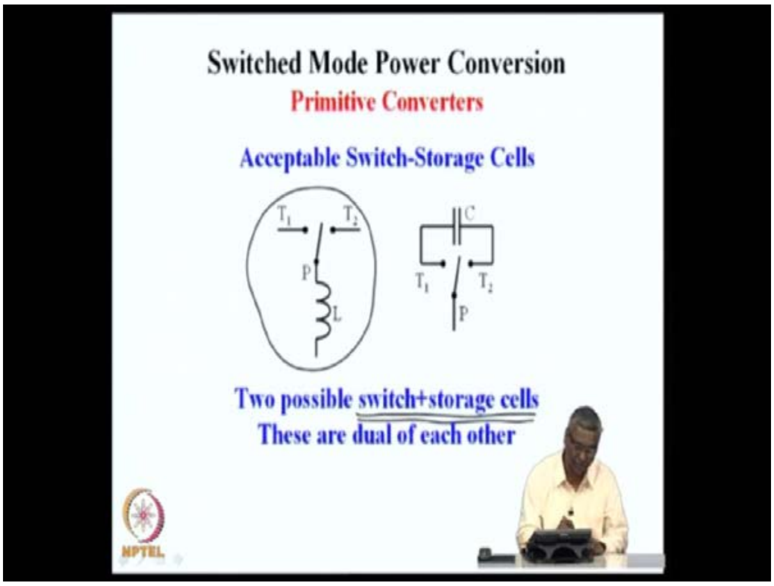

There are two possible storage switch storage cell configurations. What you see here a switch plus storage cell can be achieved in two different ways. We might use an inductor in series with the pole of the switch or we might use a capacitor across T 1 and T 2 and this condition ensures that the current in the inductor is never interrupted, it is always in the main circuit and the voltage across the capacitor is never shorted because the switch will be either at T 1 or T 2 but, never connected between T 1 and T 2. So, these two circuit configurations are acceptable switch storage cells and one is the dual of the other. And in this particular lecture, what we will notice or what we will follow will be application of this storage cell. And then, later on we will see that a dual to what we are studying exists and a similar kind of analysis and operation can be followed for the other switch plus energy storage combination as well.

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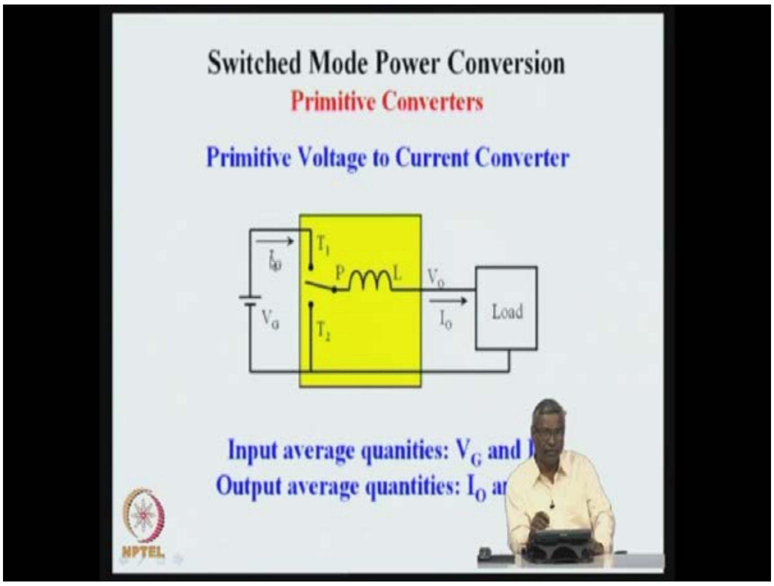

This converter, a primitive power converter, we might call this as a primitive voltage to current converter is the starting point of all our power converter circuit topologies. The switch cell plus switch plus the inductor cell that we had seen just before is now connected between a source, a voltage source on the left-hand side, what you see here a voltage source on the left-hand side and the load on the right-hand side. This being a DC power to DC power converter, the load invariably will consists of resistive load. We have a switch which has a single pole and the pole has an inductor connected in series with that, the other end of the inductor is connected to one end of the load, the return wire of the load is connected back to T 2 and then back to the source voltage V G and the positive pole of the V G is connected to the pole T 1 of the switch and the switch is capable of being connected either to T 1 between P and T 1 or between P and T 2.

These are the two possible switch positions .And we might say that the power converter is taking power from the source V G and delivering at to the load at this end at a voltage of V naught. The load current may be defined as I naught and the source average current may be defined as I G. So, this is the very primitive converter and it is possible to understand many operations of the power converters, many analysis methods of the power converters and many results that are very crucial in the study of power converters, from this primitive converter and a later on expand on the same. We will also define certain average quantities at the input side and certain average quantities on the output side. The source end is V G from where the power is taken and the load end is V naught at the load end power is delivered. The power is taken from a voltage source V G through a current of I G and delivered to a load at a voltage of V naught, at a current of I naught. These average quantities can be defined V G and I G at the source end and I naught and V naught at the load end.

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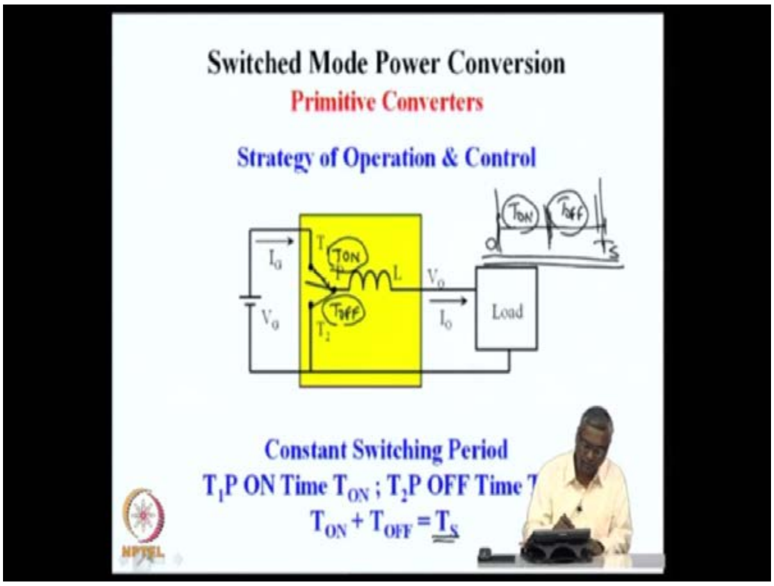

The operation of the switch and the converter is as follows: We consider one switching period as duration of T S. What we see here, a switching period may consists of a time duration of T S. And in this T S, we will have two intervals, one called T ON and the other called T OFF. So, every switching interval consists of a sub period of T ON and a period of T OFF. During the ON sub period, during the interval T ON, the switch is connected between PT 1. What you see here, the switch is connected between P and T 1. And during that time T OFF or it is known as the OFF interval, the switch is connected between P and T 2. So, we might say that this end is T ON and this end is T OFF. The switch has two positions and in one switching period of T S0 to T S, the switch is ON for duration of T ON connected between PT 1 and it is OFF for duration of P OFF, where the switch is connected between P and T 2. This is the operation of the switch and on account of that this converter will transfer energy from V G to load at V naught and let us look at some of the operating conditions and operating performance in this.

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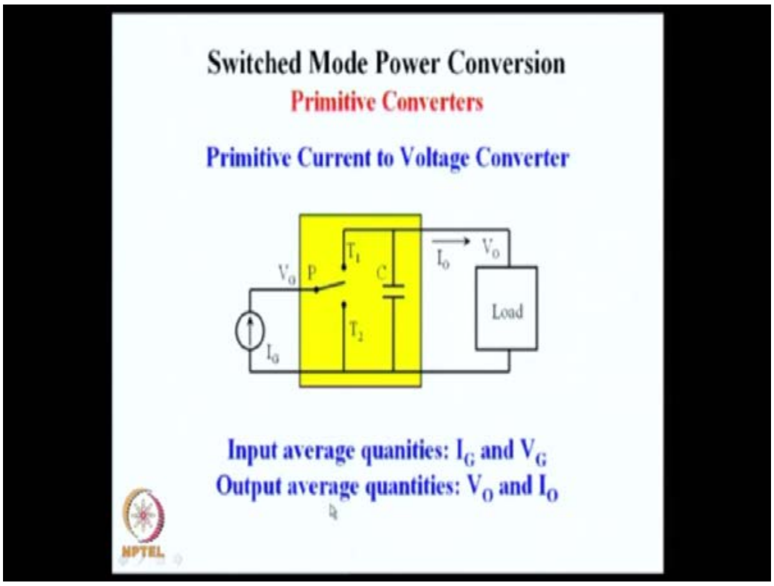

The dual to that is a single switch plus a capacitor configuration taking power from a current source I G and delivering power to a load at voltage of V naught and at a current of I naught and the elements used in the converter are the same single pole double throw switch, but with a capacitive energy storage element. Now, such a switch plus a capacitor cell is capable of taking energy from a current source and through the converter it can deliver to the load which will also be resistive in this case. Here also, it is possible to define average quantities at the input which is I G and V G and average quantities at the output which are I naught and V naught.

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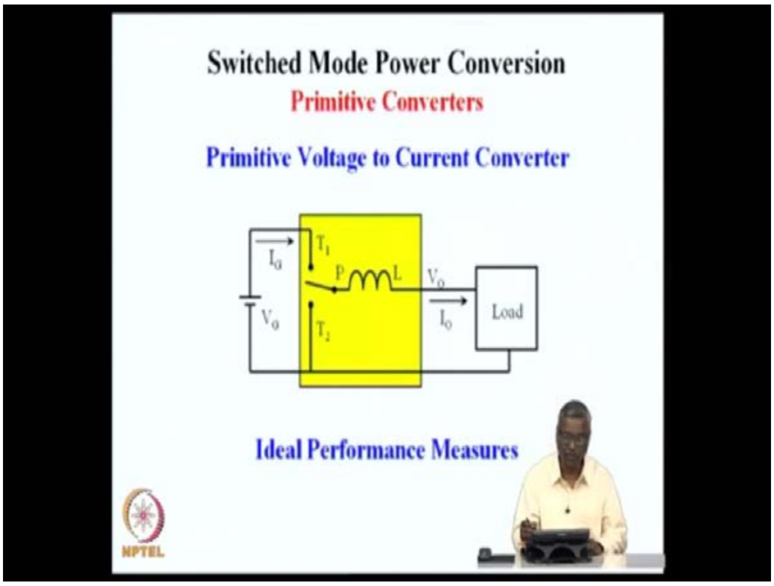

So, let us look at how the performance measures for this converter are going to be specified and how this performance measures are going to be evaluated. The ideal performance measure is what we are interested in. So, during the ideal performance measure we will consider every element in the converter to be ideal. All the switches when they are ON will have 0 voltage drop across them and when they are OFF will have no current flowing through them and the inductor will be a pure inductance with no resistance associated with that. So, we have only two elements in the power converter switch and an inductor. The inductor is an ideal inductor, the switches are all ideal and the operation of the switch is also following the ideal measures; it is the time taken for the switch to shift from on state to off state is 0 and the power losses associated with conduction as well as switching are all 0.

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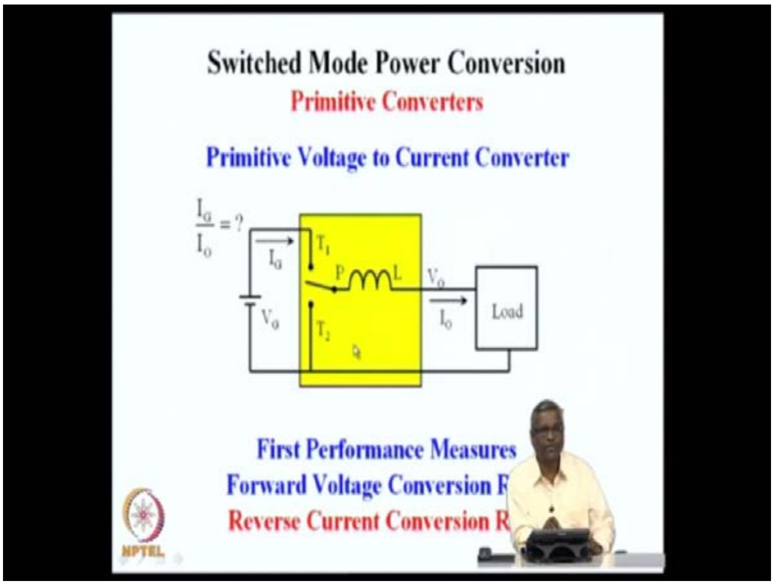

In such a situation, the performance measures are the following: if we have a power converter which is drawing power from V G, what will be the output voltage or what is the ratio V naught by V G, when the converter is operating under certain operating conditions? The first performance measure is the forward voltage conversion ratio. The forward voltage conversion ratio is the output voltage V naught divided by the input voltage V G. How do we evaluate that? The next performance measure is the reverse current conversion ratio, this is a ratio of the average input current I G divided by the average output current I naught. So, this ratio also can be calculated if we understand the operation of the converter properly.

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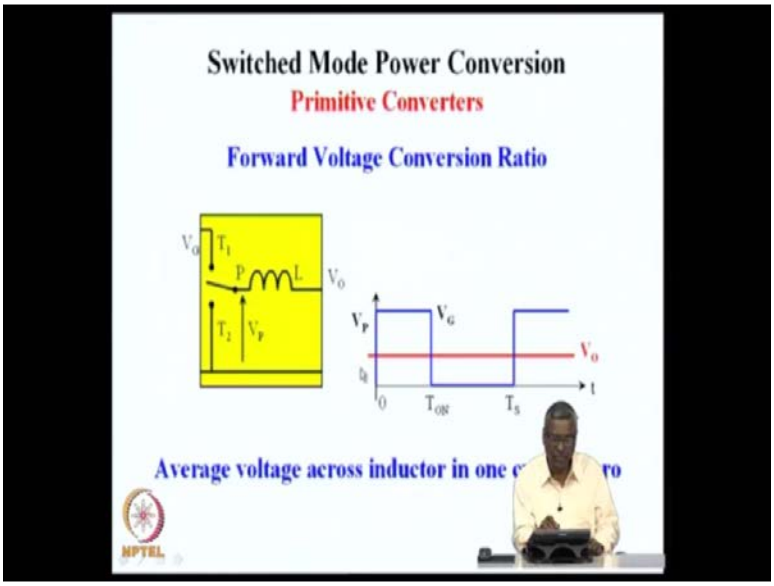

The forward voltage conversion ratio is evaluated based on the principle that, the average voltage across an inductor in one cycle is 0. What I have written here, the average voltage across the inductor L here over one cycle is 0. This statement is the same as saying that there is no DC voltage drop across an inductor. All of us know that the impedance of an inductor for DC is 0 so, whatever current is flowing across the inductor if it is a DC current the voltage drop across the inductor will be 0. The average voltage on one end of the inverter will be the same as average voltage at the other end of the inductor, on an average inductor does not support any voltage. All these are equivalent statements as the average voltage across an inductor in one cycle is 0. So, what we see here is that, the switch is operating with a duty ratio of with a switching period of 0 to T S and in that from 0 to T ON during the ON state of the switch, the switch is connected from P to T 1 and on account of that the voltage V P this is the pole voltage is the same as the source voltage V G. So, during the ON time the pole voltage here is the same as the source voltage V G. And during the second interval from T ON instant to T S, this duration is the OFF duration. During this entire OFF duration, the switch P is connected to T 2 as a result of which the pole voltage V P will be 0 because this is connected to ground. And what we see here is that, in one cycle during the ON period the voltage across the inductor is V G on one end and V naught on the other end and during the OFF period of the converter, the voltage across the inductor is 0 on one end and V naught at the other end. The right-hand side voltage on the inductor is always V naught shown by the red color line here.

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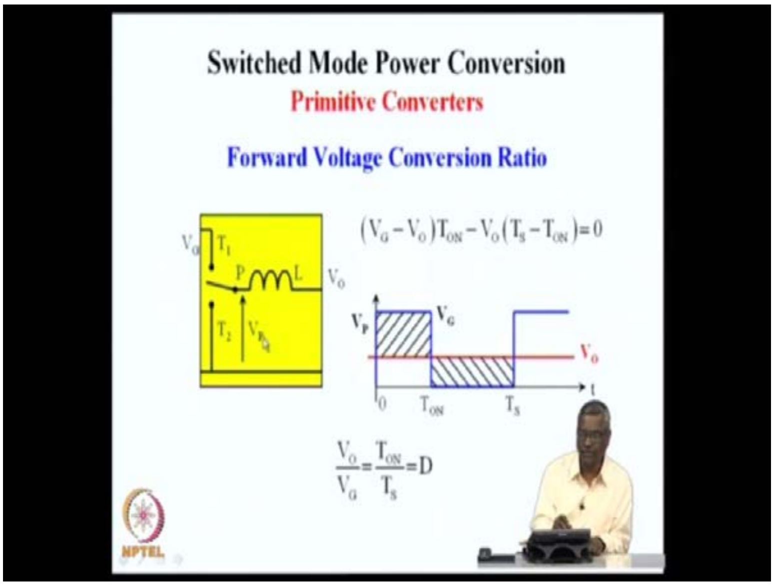

So, from this waveform of the voltage across the inductor, it is possible for us to find out the forward voltage conversion ratio. From this, we can see that the inductor voltage is the same as V P minus V naught. So, from the pole voltage if I subtract V naught, the difference between them is the voltage across the inductor. So, during the ON time the voltage across the inductor is V G minus V naught and during the OFF time, the voltage across the inductor is 0 minus V naught and the duration of OFF time is T S minus T ON and the ON time duration is T ON. So, if I find out the average voltage across the inductor, it is V G minus V naught into T ON, the first half of the first sub period of the switching period and then, the second period is minus V naught into T S minus T ON and this average voltage has to be 0 for an inductor. And if we expand this, this gives rise to the relationship of forward voltage conversion ratio V naught by V G is the same as T ON by T S and we give a name to that called Duty ratio. D is the duty ratio and it is a ratio of ON duration 0 to T ON divided by the total duration T S. So, this is the first performance measure of any power converter. The first performance measure is the ratio of output voltage to input voltage under ideal condition for this primitive converter this is the same as the switch duty ratio.

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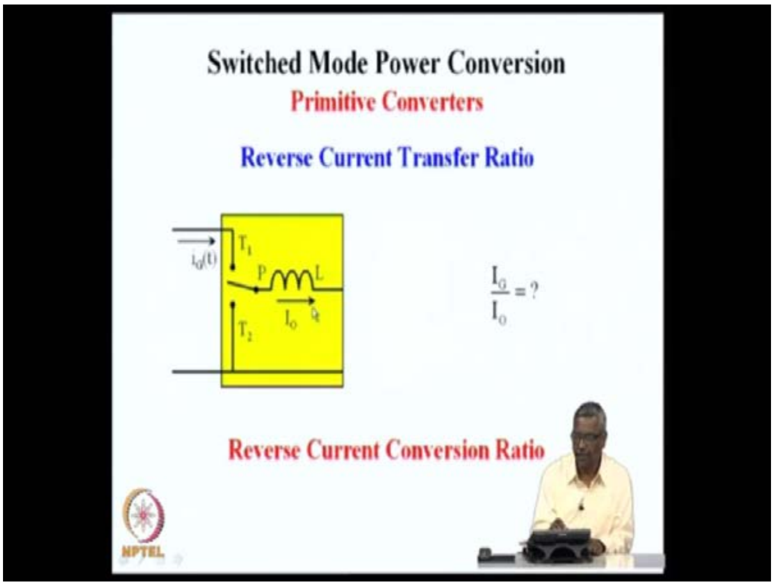

The second performance measure in any converter is the ratio of the average input current in relation to the average output current. The reverse current conversion ratio is the ratio of the average value of this I G of t divided by the output current I naught. This ratio is called the reverse current conversion ratio.

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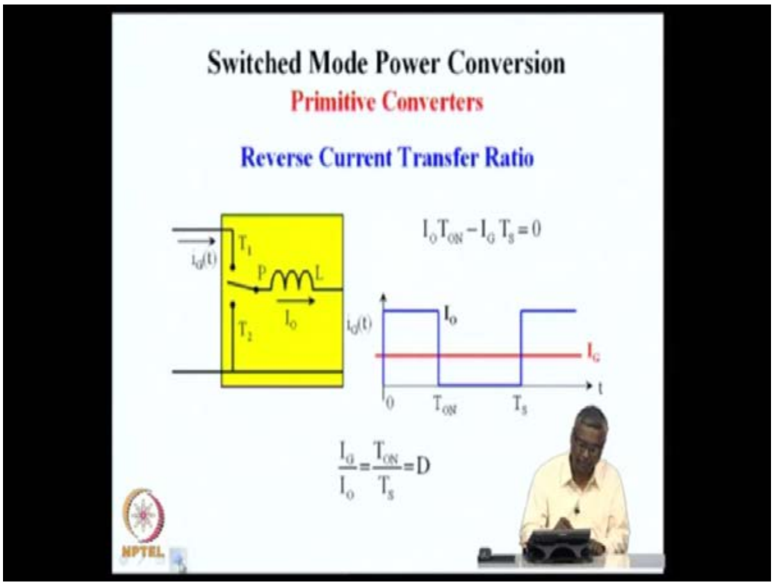

And this can be obtained by simply averaging in the current way form i G of t. What I have shown here for one cycle, the average current of i G of t is given by the red line I G. This i G of t when the switch is ON, it is the same as I naught the current is flowing through the switch and when the switch is OFF, the inductor current is freewheeling through P T 2, i G of t is 0 during this interval. So, if we average this section I naught into T ON is the same as I G into T S on averaging this and we get the ratio of I G divided by I naught is T ON by T S which is also the same as a duty ratio. The forward voltage conversion ratio V naught by V G was D, this is the reverse current transfer ratio I G by I naught; this also happens to be D. This is obtained by simple geometrical averaging.

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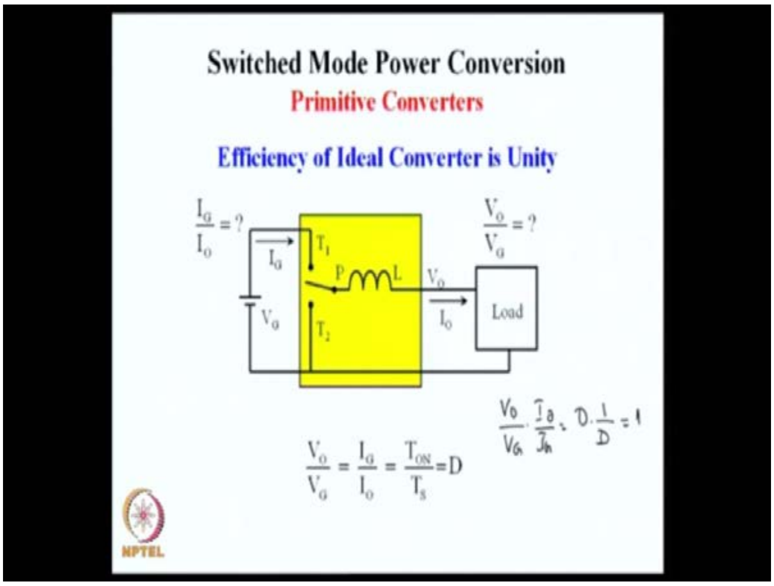

We find that the ratio of V naught by V G and I G by I naught both of them are D, the duty ratio of the converter T ON by T S. If you invert this I G by I naught as I naught by I G and multiplied by V naught by V G what we will get will be the total output power of the converter in relation to the input power of the converter V naught by V G multiplied by I naught by I G is same as D into 1 by D equal to 1. So, what we notice is that, the forward reverse forward voltage ratio and forward reverse current ratio being same when you multiply V naught I naught and then, find the ratio of V naught I naught to V G I G it is D into 1 by D which is 1. This signifies that ideally the efficiency of a converter is unity, all the power that is drawn from the source is completely delivered to the load and there are no losses in the switch or in the inductor. This is what we expected because all the components that are used in the converter have no losses and naturally therefore, all the power that comes out of the source has to be delivered to the load with no losses in the converter and this is what we see as the efficiency of the ideal converter being unity.

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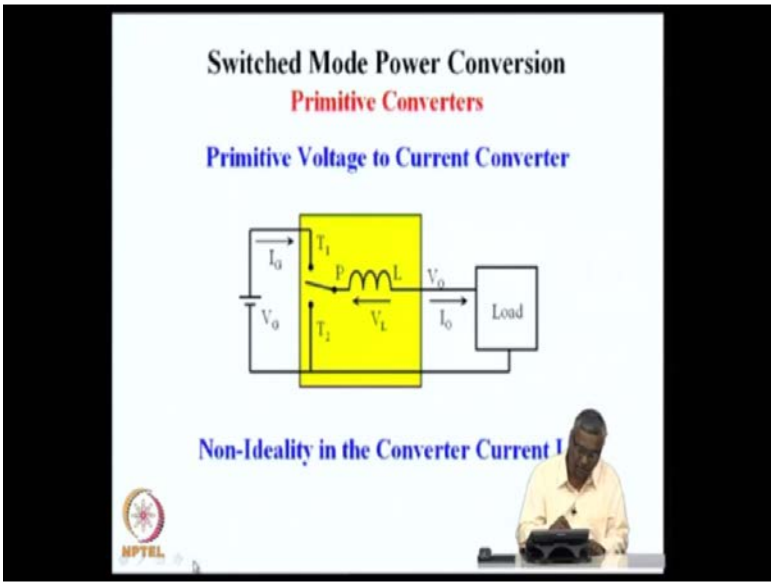

But, there are several non-idealities in the converter, we had assumed that this converter has a current which is perfectly constant and an output voltage which is perfectly constant and this I G has an average value of capital I G and current power is drawn from the source V G. But, in a real converter these ideal conditions of I naught being continuous constant and V naught being continues and constant are not really true, they are different. And what we are going to in the next a few sections is, How to find out this non-ideality? To what extent the converter current is not perfectly constant? To what extent it is different from the ideal condition? This is the first non-idealities in the converter.

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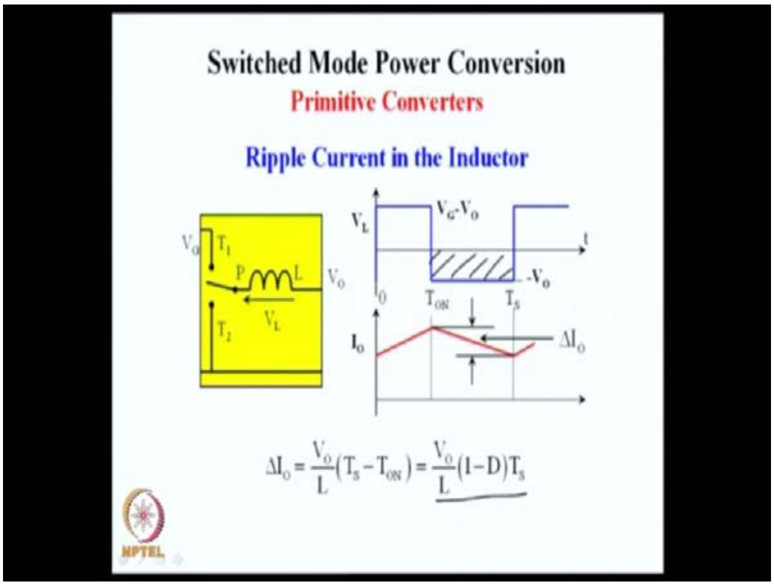

And this can be very easily found out by understanding that the current in an inductor is nothing but the integral of the voltage across the inductor. The inductor voltage is V G minus V naught during the ON period and minus V naught during the OFF period. This we already seen when we evaluated the average voltage across the inductor being 0. So, this voltage is what is applied across the inductor as V L. And so, the current through the inductor will be the integral of this voltage waveform. So, during the ON period current will keep increasing at a rate which is decided by V G minus V naught divided by the value of inductance because L di by dt is voltage and so, the current during this interval the integral of the voltage across the inductor divided by L. Similarly, during the OFF period, negative voltage is applied across the inductor and so, the inductor current drops. The integral of this negative voltage is a ramp falling downwards and under steady state condition the rise in current will be the same as the fall in current and so, this current ripple during the ON time current ripple delta I naught and the current ripple delta I naught during the OFF time both will be equal E and this can be found out either from this end or from the OFF interval. And that is, the change in current is the integral of this voltage which is nothing, but the area under this curve which is V naught into T S minus T ON divided by L, that will be delta I naught and that is given here as V naught by L multiplied by 1 minus D into T S. The integral of the voltage across the inductor is used in order to evaluate delta I naught.

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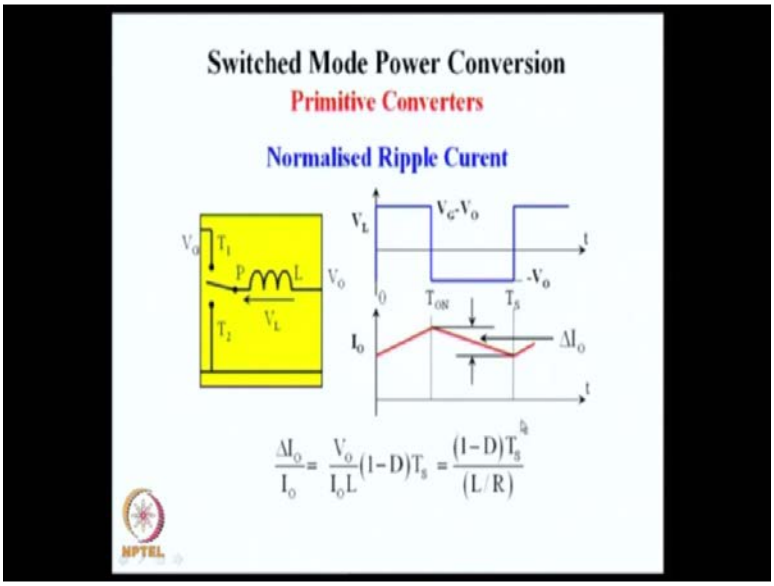

Now, this can be put in a normalized form because delta I naught by itself may not be of great use to us but, we might try to change or get a ratio delta I naught as a function of I naught. What is the ratio of the peak to peak ripple in relation to the average current can be found out from here. The ratio of delta I naught in relation to the average current delta I naught by I naught, this is the same result as before divided by I naught. And V naught by I naught is nothing but the load résistance R. So, we replace this quantity by R and write it in a form which is 1 minus D T S divided by l by R. This is the ratio of switching period divided by the time constant of the output circuit, L and R time constant multiplied by 1 minus D.

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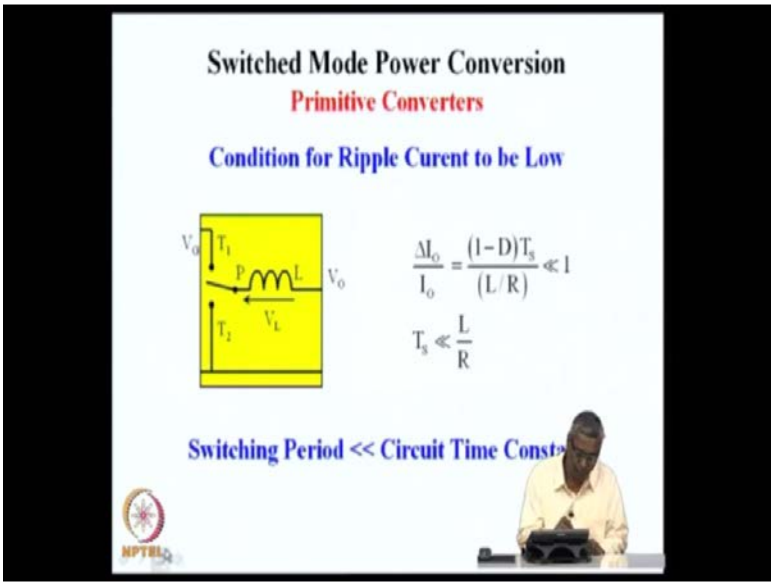

So, if the non-ideal condition of ripple current has to be very low then, we can say that this non-ideality which is delta I naught by I naught which is 1 minus D T S by L by R has to be very much less than 1 or we can alternately say that the switching period T S has to be very much less compared to the circuit time constant L by R. This is one of the conditions for the non-ideality to be negligible or for the converter to perform as close to the ideal as possible.

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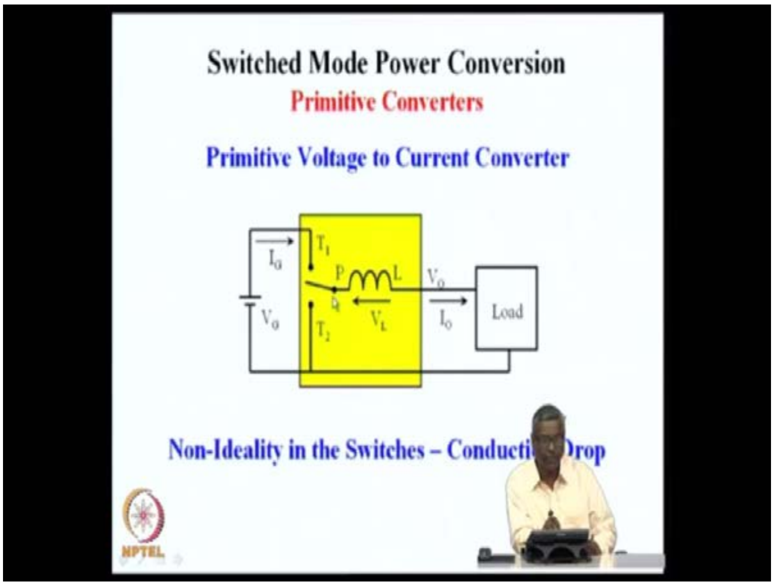

The other non-ideality in the converter is that the switch T 1 P and T 2 P do not have 0 voltage across them. When current is flowing through the switch T 1 to P, there is a small voltage drop across the switch and similarly, when the current is flowing from T 2 to P there is a voltage drop across the switch. This depends on the type of switch that we use.

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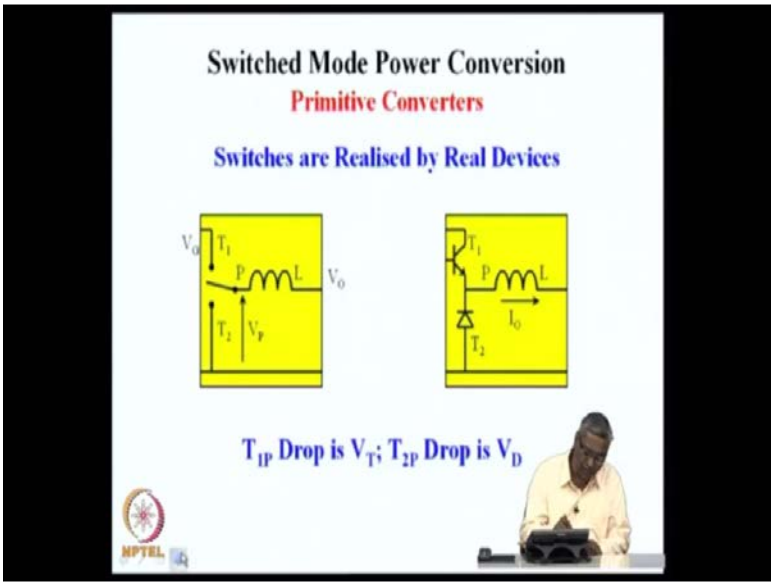

In a real converter these switches T 1 P and T 2 P are realized by a transistor switch or a MOSFET switch what you see here and a diode. The T 1 P is realized by an active switch which can be a bipolar junction transistor or a MOSFET or an IGBT. And the switch T 2 P is a passive switch, it can be a diode for this direction of current I naught. Now, while current is flowing through the transistor there could be a voltage drop of V T, we call the voltage drop in the transistor while it is ON as V T and similarly, the voltage drop across the diode when the diode is conducting is defined by V D.

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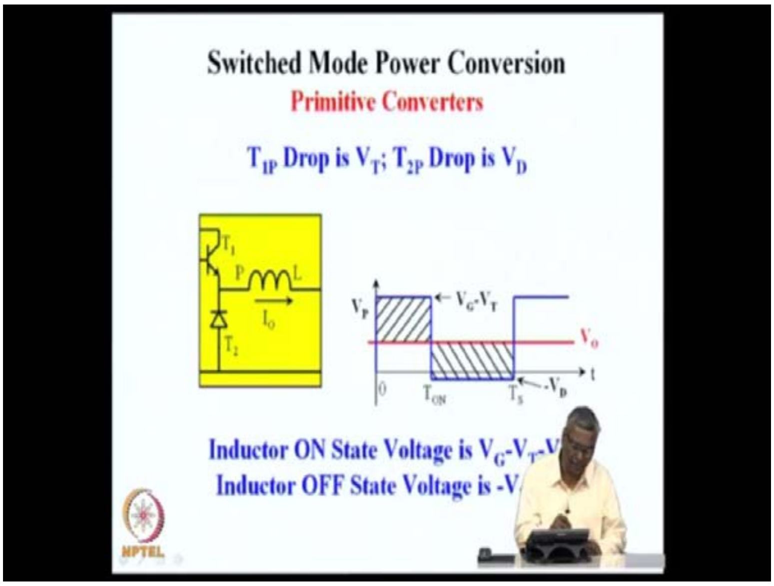

So, with these definitions it is possible to find out how the voltage conversion ratio is going to be different when these non-idealities are introduced. The switch voltage is V T the diode voltage is V D. So, in the voltage across the inductor now we will find that during the ON period the inductor voltage is V G minus V T minus V naught V naught is the average output voltage and on the freewheeling side the voltage is diode drop minus V naught diode drop is in the negative direction. So, effectively the inductor ON state voltage is V G minus V T minus V naught, OFF state voltage is minus V D minus V naught and with this we can recalculate the volts second balance on the inductor.

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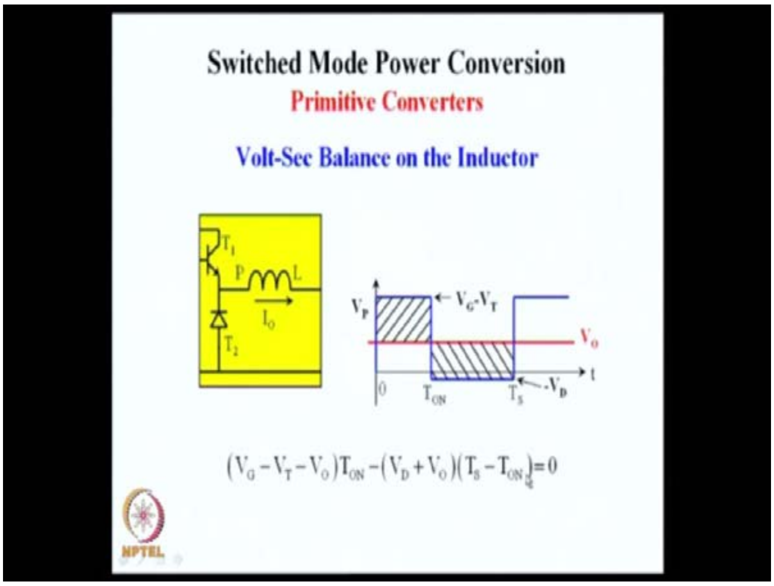

This volt second balance is nothing but the average voltage across the inductor in one cycle. That is also referred to as volts second balance and when it is evaluated it is V G minus V T minus V naught which is this area of this hatched region this multiplied by T ON. Similarly, this during the OFF period minus V D minus V naught multiplied by the OFF period.

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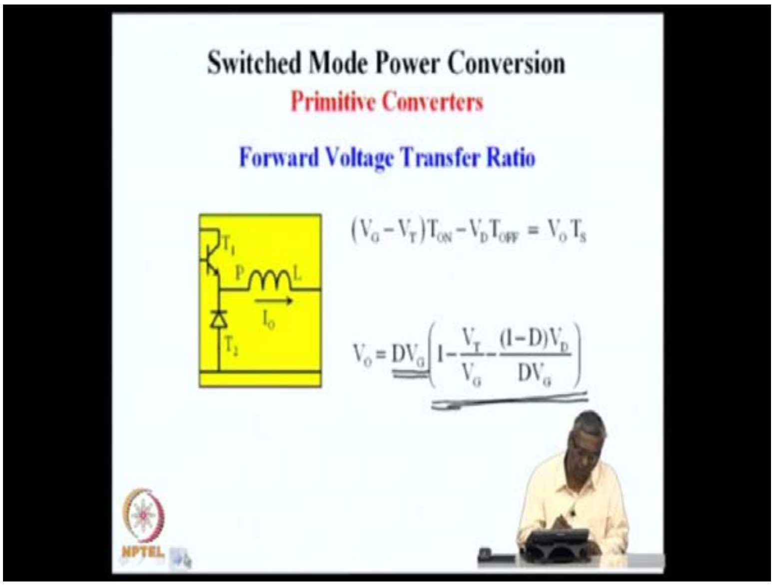

And if the total volt second is equated to 0 and we get a ratio of this output voltage as D times V G which is the same as the original ideal condition. Ideally, when the switches were not dropping any voltage, output voltage was D times V G. But, in addition now we have a correction factor, this correction factors as you can see is less than one. It is less than one by two ratio: One ratio is the transistor voltage divided by the source voltage and another ratio is 1 minus D times the diode voltage divided by V ideal output voltage D times. V G is the ideal output voltage. So, if we put this if we keep these ratios in mind we will find that the output voltage will differ by the ideal output voltage by a factor which will be less than one. So, this is the correction factor on the ideal conversion factor V naught by V G is now D which is ideal gain multiplied by a connection factor this correction factor is close to 1 but, it is less than 1 by these ratios: transistor voltage by source voltage, diode voltage divided by the output voltage.

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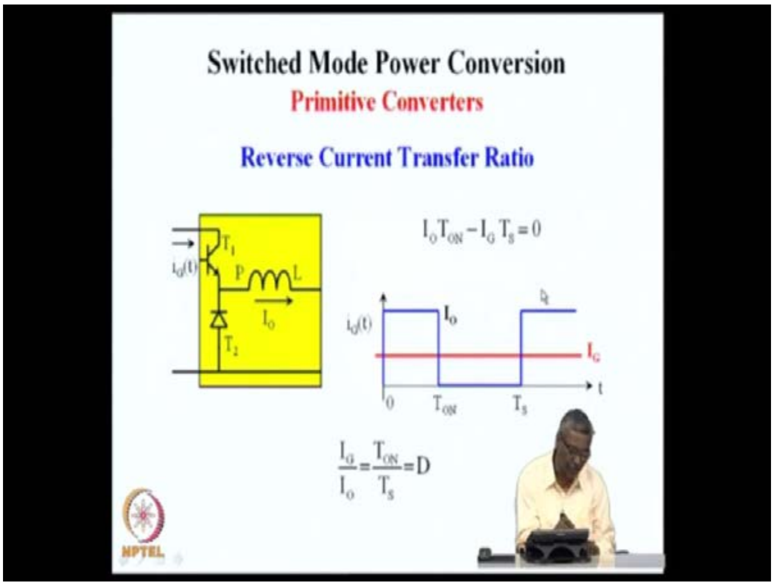

Another interesting thing is, even though the switches are replaced by real switches with non-ideality if we evaluate the average input current i G of t. What we see here is the average input current i G of t, we evaluate that there is absolutely no change in that. During T ON the current through the switch is I naught and during the OFF period current through the switch is 0. When you average it, we still get the same ratio I G by I naught is the same as T ON by T S which is a duty ratio. The important point to notice here is that the switch non-ideality has not affected the reverse current transfer ratio. It affected the forward voltage transfer ratio but, it did not affect the reverse current transfer ratio.

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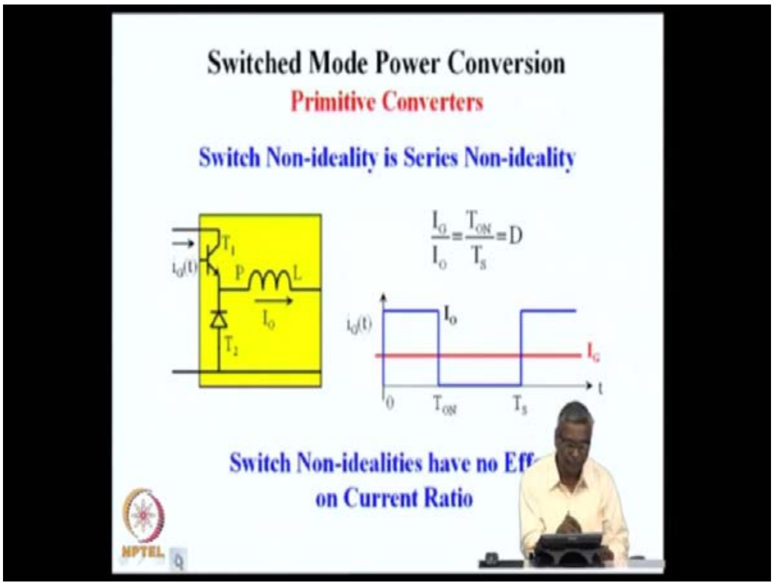

The reason is that all the switch non-idealities that we see here are series non-idealities and series non-idealities normally do not affect current ratios. This you can check as a homework exercise that these series non-idealities do not affect the current transfer ratio but, they do affect the voltage conversion ratio.

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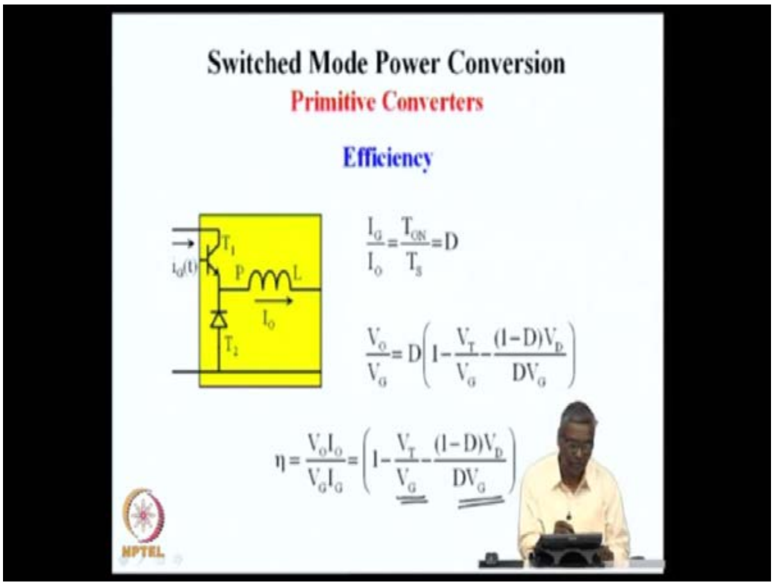

The interesting part is that, now the product of the voltage conversion ratio and current conversion ratio in the ideal converter was 1 which was the efficiency of the converter. In the non ideal converter, I naught by I G is 1 by D V naught by V G is D multiplied by this quantity. So, when you multiply these things together, the efficiency of the converter is the same as the correction factor that we found in the voltage conversion ratio or the power conversion efficiency is less than 1. There are some losses in the converter and this loss is seen by this number efficiency which is being less than 1. It is less than 1 by 2 ratio: First ratio is the input ratio which is the transistor drop in comparison with the source voltage and the second ratio is a diode drop in comparison with the ideal output voltage. So, by these 2 ratios, the efficiency is less than 1 and to that extent there will be losses inside the converter.

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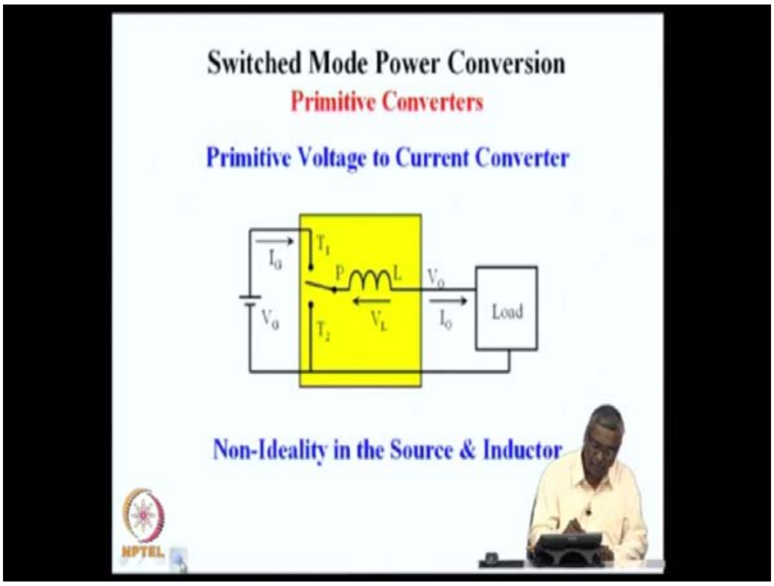

Now, we can look at one more type of non-ideality in the converter other than the switch drops, the non-ideality in the source and the inductor.

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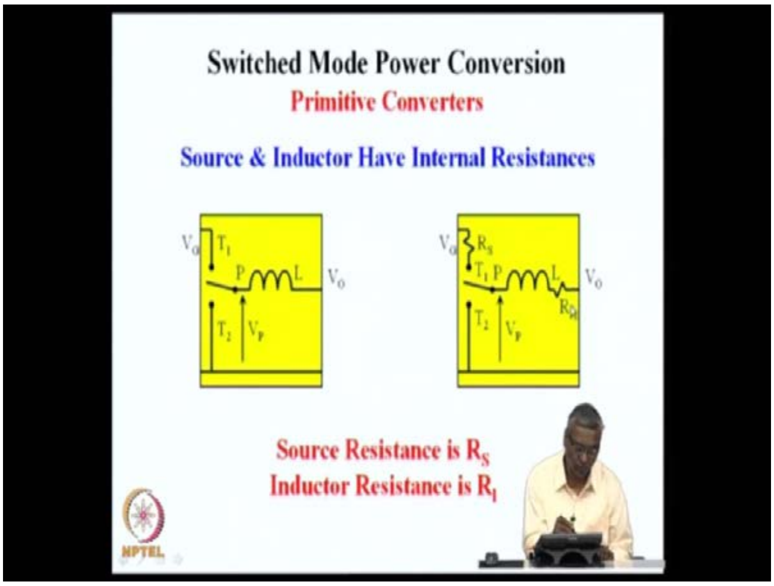

The source can have a resistor as shown here R S and the inductor can have similarly resistance of the winding R L. So, these quantities also give rise to some difference in the voltage transfer ratio. Because these are series non-idealities, they do not affect the current transfer ratio, current transfer ratio will continue to be as before but, let us look at the voltage transfer ratio.

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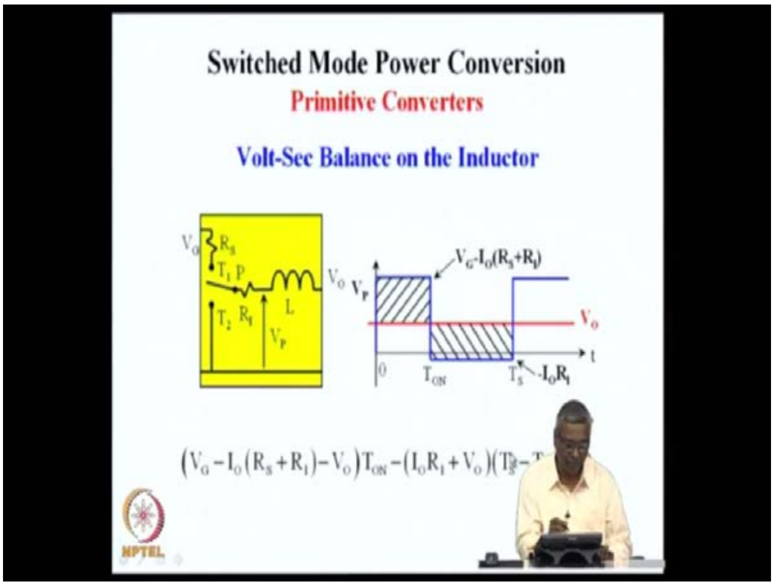

Now, the voltage across the inductor is now the pole voltage minus the output voltage V naught V naught is shown here by the red line. But, the pole voltage now consists of source voltage minus the inductor current multiplied by R S multiplied by R L I naught into R S plus R L and while freewheeling the drop is having a drop of minus I naught R L. And so, we notice that the voltage across the inductor during ON time has a non-ideality minus I naught R S plus R L and during the freewheeling time has a non-ideality of I naught into R L.

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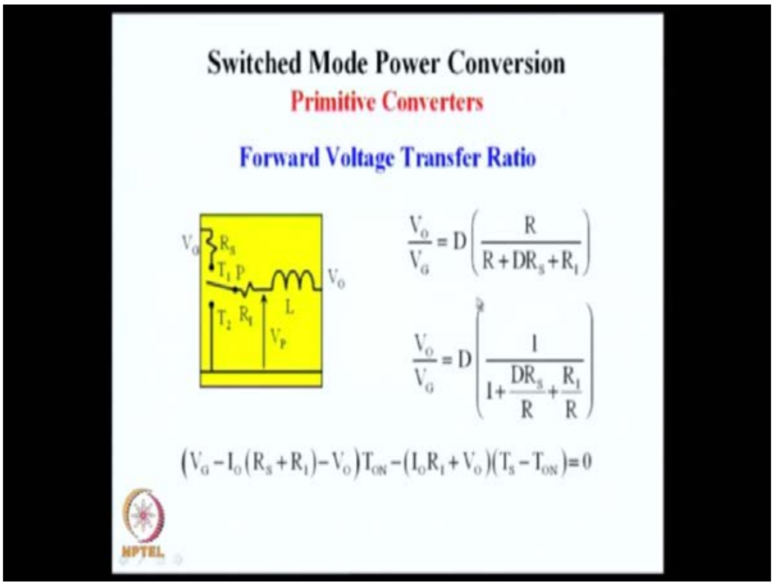

And if we combine these things and find out the volts second balance, this V naught by V G applying this average voltage across the inductor being 0, V naught by V G now has the ideal ratio D multiplied by a correction factor. Here also, the correction factor is less than 1, it is the load résistance divided by load résistance plus duty ratio time source résistance plus the inductor resistance and this number will be close to 1 but, less than 1 and that is what we notice here.

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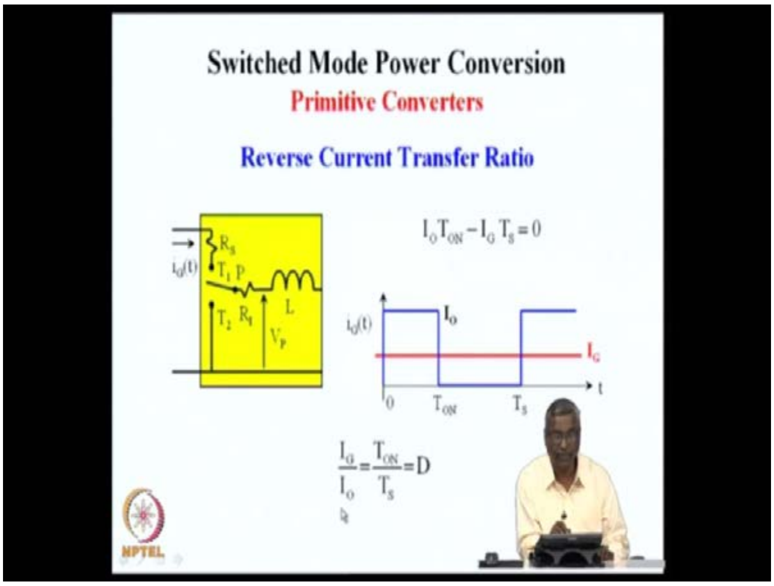

And just as before, the current conversion ratio is not affected by the presence of R S or R L because these are all series non-idealities. When we evaluate the average current it continues to be as before. And so, the ratio of I G by I naught is still the same as duty ratio.

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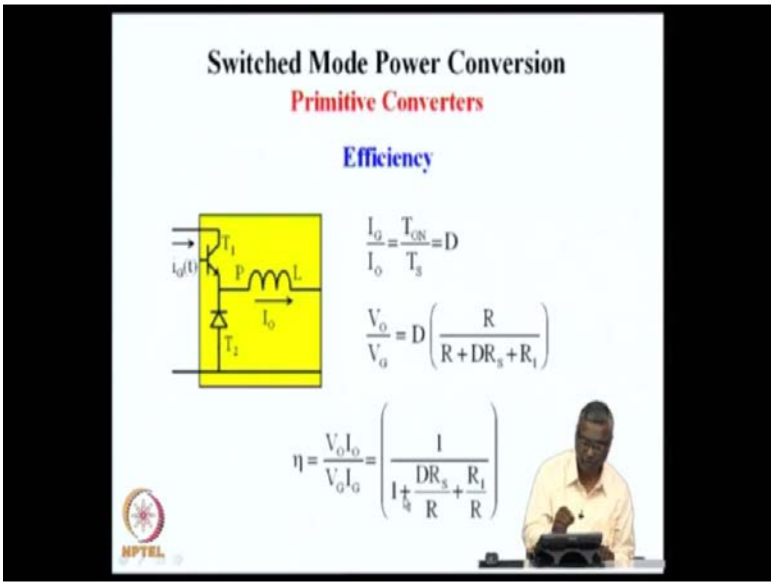

And the consequence of that is the efficiency of this converter is the same as the correction factor in the voltage conversion ratio 1 by 1 plus this R S into D by R plus R L by R. These ratios are small numbers so, in the denominator you will have 1 by 1 plus a small quantity. So, there will be some loss but, the overall efficiency will be close to. In typical converters, the efficiency will be better than 90 percent and these losses are because of the parasitic resistances.

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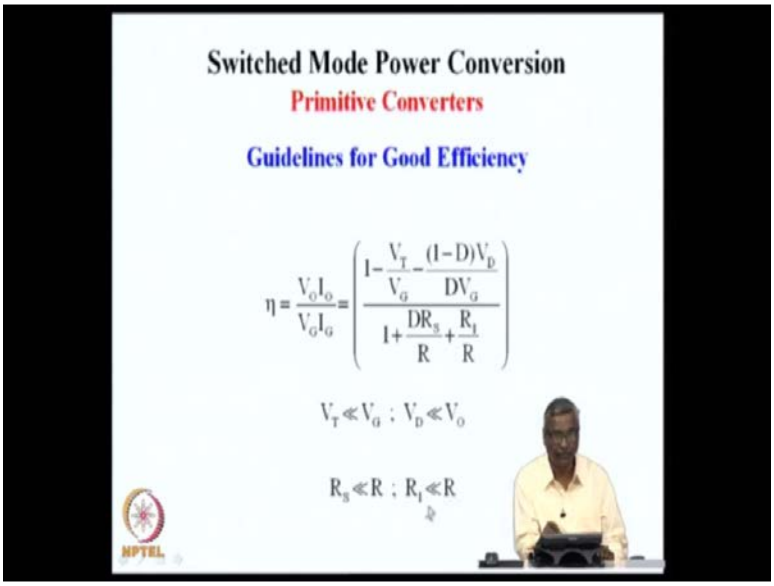

Now, when both switch, source and inductor all the non-idealities exist together, it is possible to work out all the average voltage across the inductor expressions and it is possible to find out the efficiency which consists of two different correction factors: One because of the switch non-idealities and the other because of the source and inductor non-idealities; 1 minus V T by V G minus 1 minus D V D by D V G, this D V D is the ideal output voltage and similarly, in the denominator there are a few ratios here, source resistance by load resistance, an inductor resistance by load résistance. This correction factor or the efficiency factor will be very close to 1 if all these non-idealities are quite small. So, in a converter if we want good efficiency these are the guidelines: The device voltage drop must be very less compared to the source voltage and the freewheeling by the voltage drop has to be very much less compared to the output voltage; the source resistance must be small compared to load resistance and load resistance must be small compared to the inductor resistance must be small compare to load résistance. If these guidelines are followed then, efficiency will be normally close to 1.

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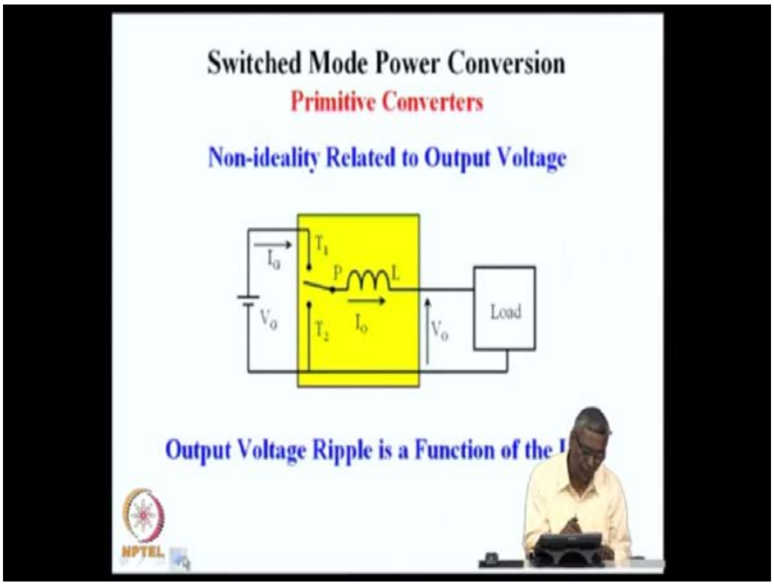

Now, we have another non-ideality which we have not seen up to now and that is the non-ideality related to the output voltage. We had assumed in the analysis up to now that the output voltage is a perfectly constant voltage V naught. But, in reality this output voltage also will have a non-ideality and this non-ideality is the variation in the voltage in V naught, V naught will not be perfectly constant but, it will be varying around a DC voltage. And how much of ripple voltage is present on V naught is the non-ideality related to the output voltage. So, we had seen up to now several performance measures, one of them is V naught by V G called the forward voltage gain, the second one was I G by I naught called the reverse current gain. We started with an ideal converter, we saw that these gains the voltage transfer gain has or is affected by the non-idealities in the switch non-idealities in the source and so on. And we also saw that the inductor current is not perfectly constant, it has a ripple delta I naught and this delta I naught by I naught is related to the switching period divided by R by L time constant of the converter and if that has to be small, we said that switching period has to be very small compared to the L by R time constant of the converter. Now, we have the next non-idealities which is a relating to the output voltage. Output voltage ripple is a function of the load.

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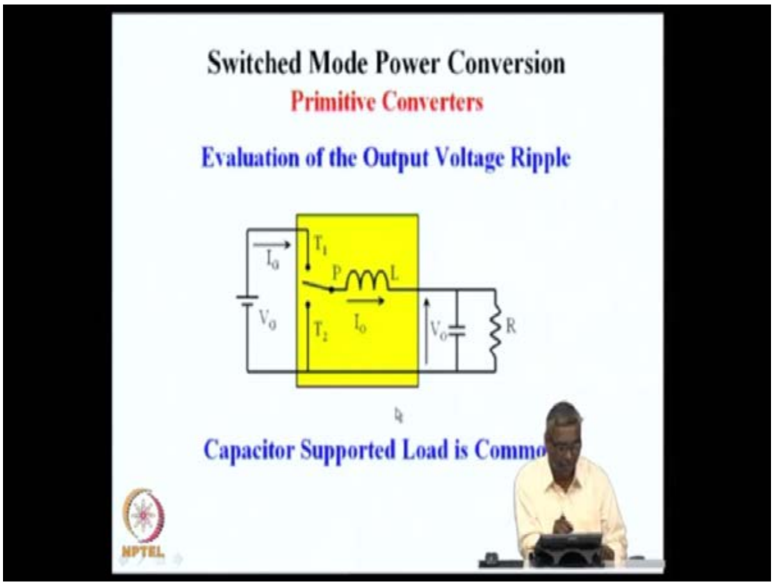

Typically, the load will be supported by a capacitor, what comes out of these I naught if is directly connected to R then, delta I naught by I naught and delta V naught by V naught will be the same. The current ripple and voltage ripple will be the same if it is a simple resistor. But, in most converters in order to reduce the overall energy storage requirement, the load will be supported by a capacitor as shown here. A capacitive support is provided to the load. So, in such a case how do we find out what is the voltage ripple on V naught on account of V performance that is happening in the converter.

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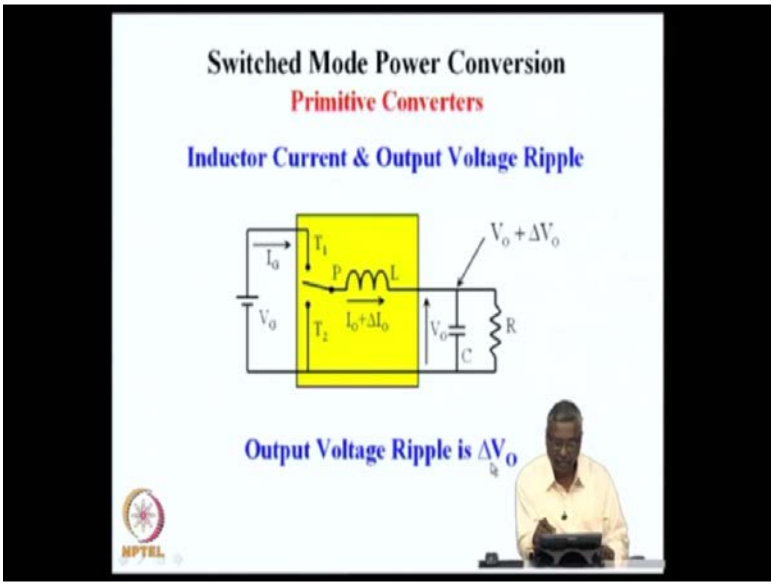

What we notice is that, this current in the inductor has the ideal value I naught plus a ripple delta I naught and this we had already evaluated to be a function of the switching period, inductance, duty ratio, V G and so on. Now, the next non-ideality we are looking is whether this output voltage V naught what is the amount of variations or the ripples that are present on that? So, what we want to now evaluate is the output voltage ripple delta V naught and if possible, what are the measures in order to make it a small as possible? We see that from the previous one it is I naught plus delta I naught is a current coming out of the converter and out of that this delta I naught is a ripple current or the high frequency current, I naught is the DC current. So, we may safely assume that the DC current will flow through R and the AC current or the high frequency variation current will go through the capacitance.

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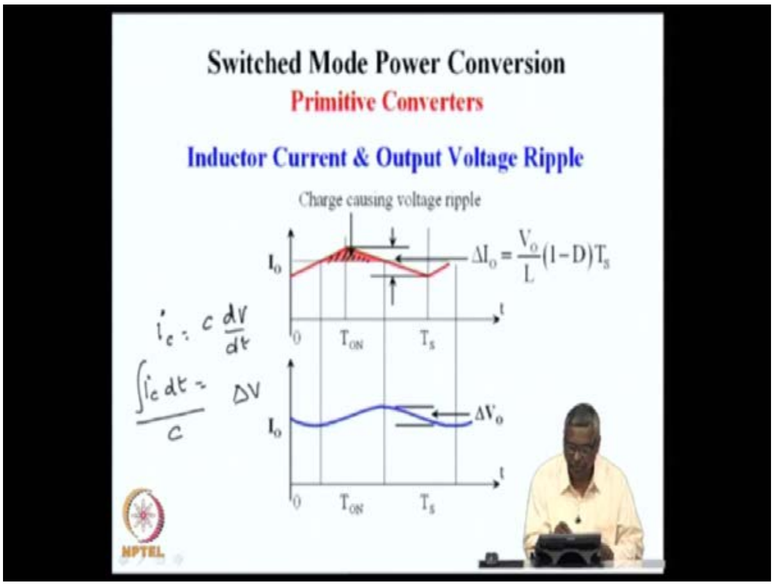

And so, any change in the capacitance voltage will be because of the current ripple that is passing through the capacitor. We know that in a capacitor the current is C times D V by D T. So, this can be written, if all these are simple triangular currents, we can write this as the integral of that divided by C will be delta V. So, the charge that is flowing into the capacitor which is the area of this triangle that we see here, is what is responsible for the capacitor exhibiting a voltage ripple delta V naught. Delta I naught we had seen earlier is V naught by L into OFF period and OFF period is 1 minus D times T S. So, if the ripple is known as V naught by L into 1 minus D T S, the area of this triangle is the charge that is transfer to the capacitor during the minimum to the maximum voltage.

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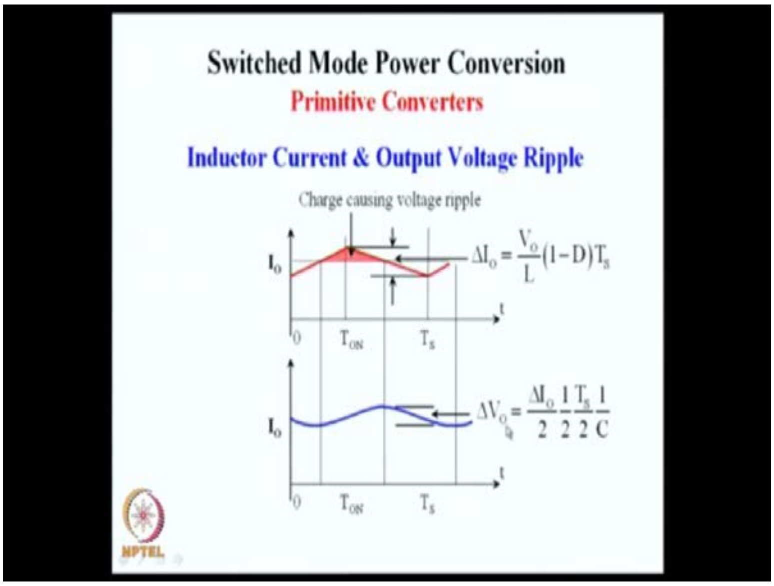

And we can write the delta V naught to be delta I naught by 2 is the height of this triangle and 1 half is for the area of the triangle. And the duration from here to here is what you see here, the duration from here to here is T S by 2 and this entire charge divided by C is delta V naught.

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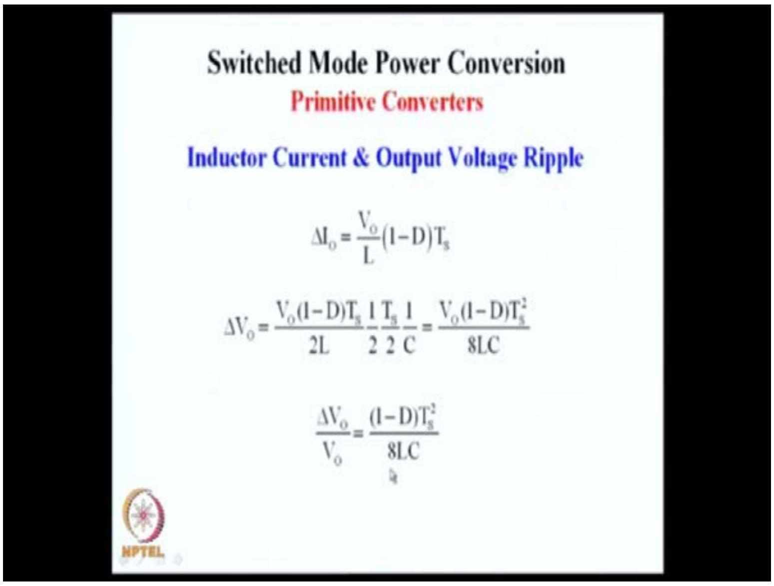

Now, we can evaluate delta I naught as V naught by L 1minus D T S, we have already seen this. Delta V naught is as far that the area of the or the total charge divided by C and that works out to be V naught 1 minus D T S square divided by 8 L C. And if we take the ratio as of importance to us voltage ripple delta V naught by V naught, it is 1 minus D multiplied by square of the switching period divided by 8 times the L C product.

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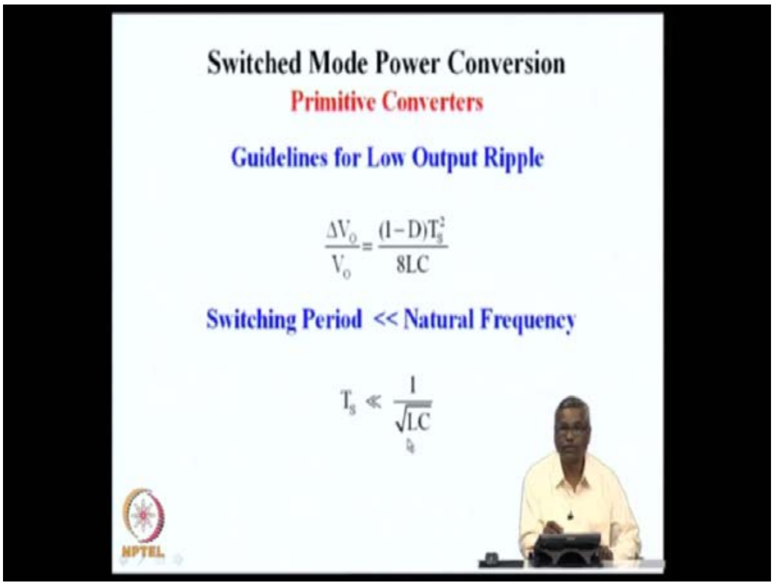

This quantity gives us a guide line for low output ripple. If delta V naught by V naught has to be very small then, the right-hand side expression has to be small or we might say that the switching period T S has to be very much less than the natural frequency or we might say T S must be very much less compared to 1 by root L C. This is a natural frequency of the converter what is on the right-hand side, what is on left-hand side is the switching period of the converter and if this inequality is satisfied the converter will have very low voltage ripple.

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So, in effect now, if we try to summarize how we found out the study state performance of the converter, there were several steps that we went through. Let us see those steps: The first measure that we defined was the voltage gain V naught by V G; the second measure was the current gain I naught by I G; then, we evaluated that the ripple on the inductor current delta I naught and we said that it has to be very much small compared to the DC current that is flowing in the inductor that gave rise to some guidelines. Similarly, the voltage ripple also we could evaluate has a ratio of high frequency ripple voltage divided by the DC output voltage. The DC output voltage is the useful voltage and the ripple voltage is the non-ideality on that. DC current is the useful current delta I naught is the non-ideality on that. V naught by V G tells us the control performance how we are able to control the output voltage from the input voltage V G. This current gain tells us how the load current is reflected on the source by the ratio I naught by I G. And we saw that there were under ideal conditions all these numbers had certain performance numbers and then, there were several non-idealities, the switch itself had certain drop in voltage during conduction and the source had a resistance, the storage element inductor had a resistance. So, when these are present how do we and account for all these quantities with the non-idealities present. And finally, the efficiency.

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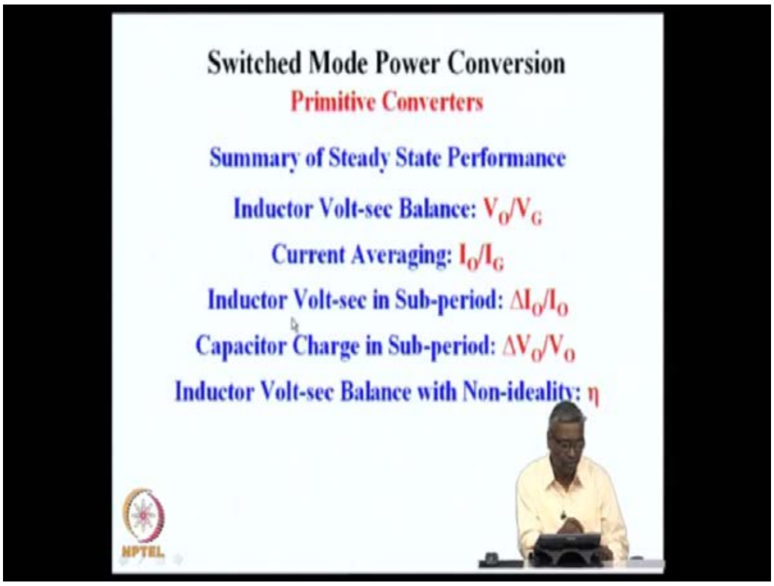

So, the method that we had followed is, voltage gain was obtained by the inductor volts second balance. That is a step, what we will notice in the converter circuits that we will be studying in the next session and so on is that these sequences is the same. We use volts second balance in the inductor to find out the ideal V naught by V G. Then, the current averaging is worked out to find out the ideal ratio of I naught by I G. Then, the inductor volts second in every sub period is calculated to find out what is the ripple in the inductor current and then, as a ratio with the average current it is possible to get a guide line on how to make sure that this non-ideality is as small less we want.

Similarly, the next step is, the capacitor voltage in the sub period and this is evaluated based on the capacitor charge, how much charge is transferred from the circuit to the capacitor in every sub period and that the charge is responsible for delta V naught, compare it with V naught to find out the guideline on the ratio delta V naught the V naught. And if we carry out the inductor volts second balance with non-idealities, it is possible to find out the efficiency of the converter. The non-idealities of the switch voltage drops; the non-ideality of the source resistance similarly, the inductor resistance all of them give rise to some additional losses.

In the ideal converter if the switch is ideal, if the inductor is ideal then, we see that there are no losses in the converter. But, when we introduce the non-ideality it is possible to find out the ratio of V naught by V G, I naught by I G, apply in the inductor volts second balance as well as current averaging and once these numbers are found out the product of these two will give us the efficiency V naught into I naught divided by V G into I G. We had seen that all non-idealities which are of series nature, series non-idealities like the switch voltage drop, the diode voltage drop, the source resistance.

In the previous one, we had seen the non-ideality in the switch which is a voltage drop, in the source which is a resistance, in the inductor which is a resistance. All these non-idealities, we saw that did not affect the current gain because all of them are series non-idealities and series non-idealities do not affect the current ratios in a circuit. And all these non-idealities because they give rise to a voltage drop in each one of those looks there associated with, the voltage gain is affected by them. And the ratio of V naught I naught V G I G is what is efficiency. And one ratio I naught by I G is not affected by any of the non-idealities, V naught by V G only is affected by the non-idealities. So, the efficiency will directly be the corrections factor in V naught by V G; that is also something we had seen.

So, in the converters that we are going to study hereafter in the next few sessions will be extensions of this primitive converter. In the primitive converter we have learnt several interesting things: We had understood the ideal performance functions, study state performance functions; we had understood the non-idealities associated with the inductor current inductor current which is associated with the stored energy in the inductor; capacitor voltage is associated with the store energy in the capacitor and the non-idealities in the inductor current and capacitor voltage or the ripple associated with the respective current and voltages. And the product of V naught by V G multiplied by I naught by I G is the efficiency. So, in effect the study state performance or just these 5 functions. The ideal functions are very easy to evaluate. In the non-ideal case also all that we use is only the inductor volts second balance. To find out the current ripple we find out we integrate the voltage across the inductor in every sub period. To find out the voltage ripple, we integrate the current through the capacitor in every sub period. And so, these 5 perform performance functions are the important once for every converter. And all these functions will we evaluated in a very very similar way in every one of those converters.

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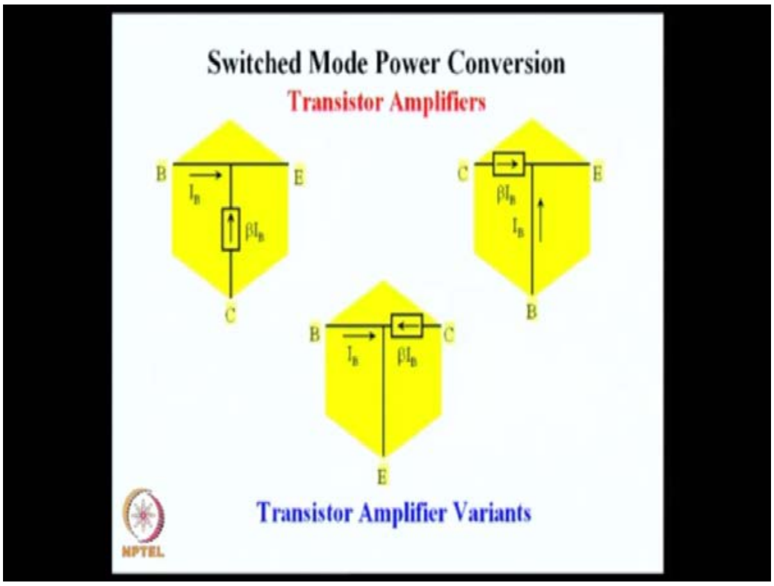

What we will see now is that, how the circuit that we had seen can be modified to obtain several other power converters. What you see in this picture is the equivalent circuit of several transistor amplifiers. The transistor has a base and emitter and a collector. The base current multiplied beta times is the collector current. So, it is possible to use this amplifier this transistor has an amplifier in several ways. You can use it in what is known as a common collector amplifier where, the input is between base and collector and output is between emitter and collector. We use a common collector amplifier. In the same way, we could use it has a common base amplifier where, the input is given between collector and base and output is taken from emitter and base circuit. This is a common emitter amplifier. This is normally the most common use a common arrangement for transistor amplifiers. So, common emitter amplifier, the input is in the base emitter circuit and the output is in the collector emitter circuit. It is very interesting that in a very very similar way we have three possible ways of connecting the primitive switch inductors cell.

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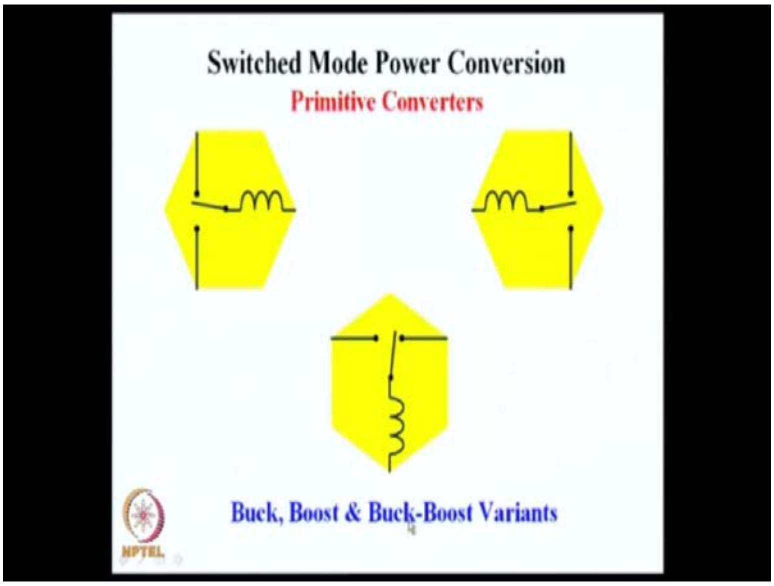

The switch and inductor, what we had analyzed up to now but, inductor at the front and switch at the back feeding to the load is the next configuration. Switch, inductor in the middle and switch connected both to the input and the output is the third configuration. Normally, these three circuits are known as buck converter, the boost converter, the buck boost converter in the power converter topologies or in the power converter terminologies.

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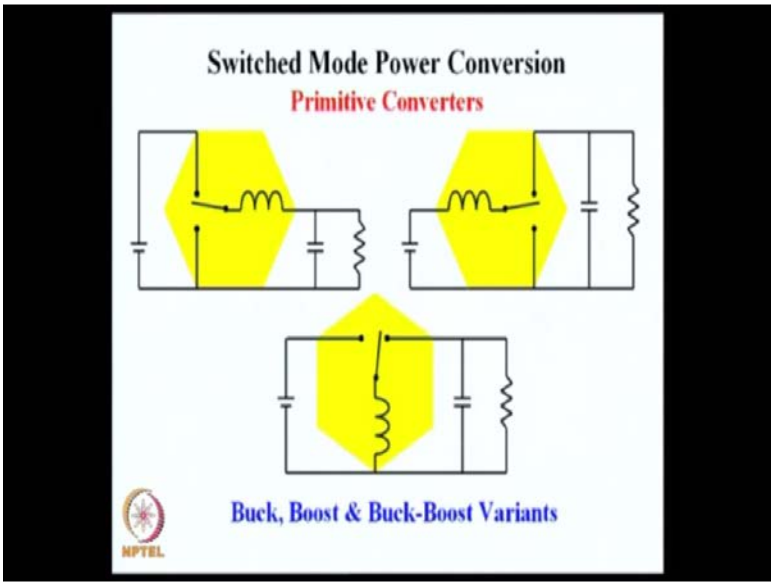

And you will find that these are the basic circuits which have come from the same primitive cell switch plus an inductor connected in this way is what we had analyzed up to now and the switch and the inductor connected in a different way where, the inductor is connected to the source and then, the capacitor the switch is connected to the load end is called the boost converter, this second one. And the third one is where the switch T 1 is connected to the source, T 2 is connected to the load and the inductor is in the common circuit. These 3 variants are the basic convertors. And in the next lecture, we will spend some more time on the other 2 converters, evaluating many of these performance functions of these converters. So, we will stop with this. The next lecture will be on the buck, boost and the buck boost power converters.

Thank you.