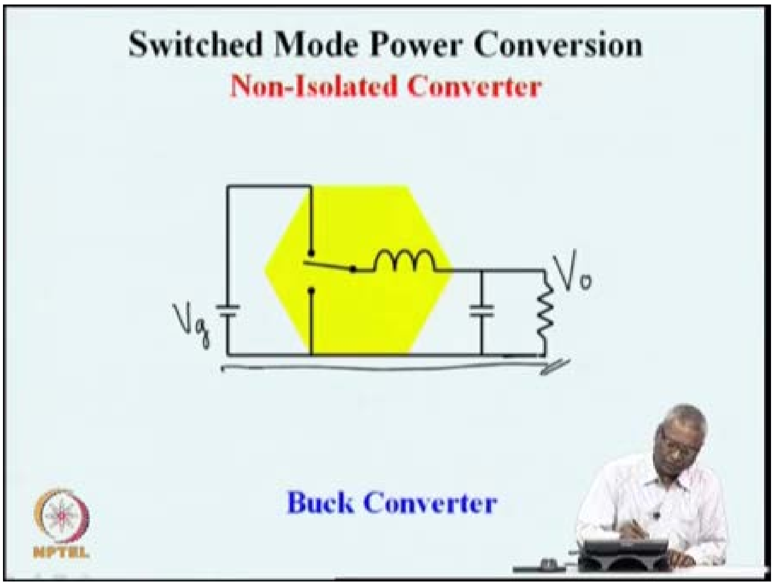
Switched Mode Power Conversion

Prof. Ramanarayanan. V
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Module - 6
Lecture - 14
Isolated Converters - I

(Refer Slide Time: 00:29)



Switched Mode Power Conversion

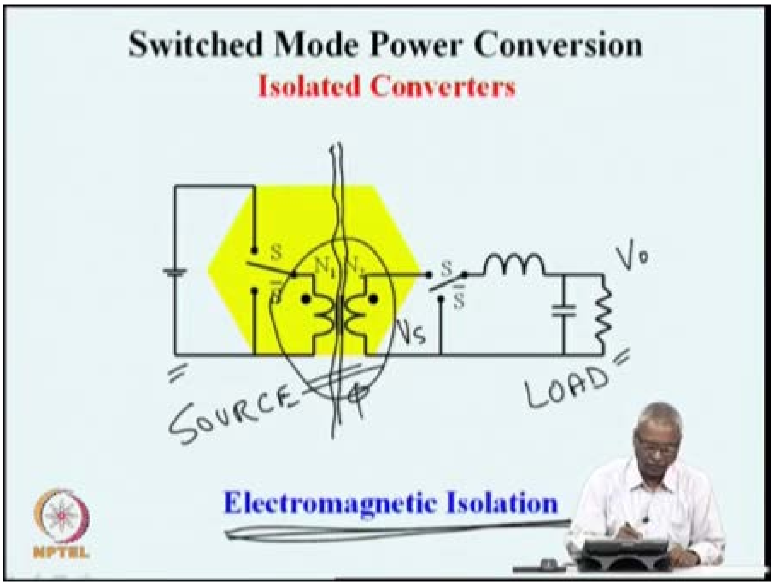
Non-Isolated Converter

Buck Converter

A good day to you all. In today's lecture we will continue the ideas that we had developed in the past into a new family of our converters. And these family of power converters will be called the isolated power converters. What we have seen in the earlier lectures, related to how this basic converter cell consisting of a single pole double cross switch and an inductor L was used in different circuit topologies to get a power converter, which will take in power at certain voltage Vg and provide power at a certain other voltage V naught .

All these converters had one polarity of the voltage common. The negative bus of the source and the negative bus of the load are at the same potential. So, these converters are called non isolated converters. The electrical potentials of the source side, and the electrical potentials on the load side are all floating with respective to a common 0. Such converters are non isolated converters. They have limited applications.

(Refer Slide Time: 01:53)



Switched Mode Power Conversion

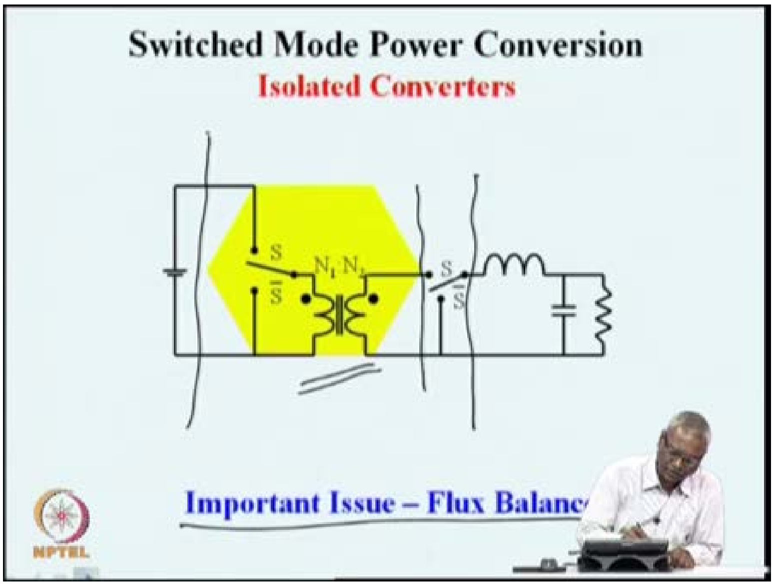
Isolated Converters

Electromagnetic Isolation

In general, a more general converter would try to provide power to a load connected at a potential, which is different from the source completely, so that there is a total electrical isolation between the source side and the load side. There is no common electrical potential on the load side and on the source side. They are completely isolated by a barrier. On one side is the source and on the other side is the load. Such converters are called isolated power converters. They are also called galvanically isolated power converters because there is no direct electrical connection between the source circuit and the load circuit. They are coupled through appropriate; in this particular case electromagnetic coupling a transformer which transfers the source side energy to a magnetic energy in the core which in turn gets coupled to the secondary side as a different voltage.

It is converted to the required output voltage v naught which is at a different potential. The isolation provided is electromagnetic isolation. These converters are called isolated converters. There are a number of converters which belong to this family. Most power converters belong to the isolated converters family for several reasons. One major reason is that it is necessary to supply power at a potential which is different from the source. So, you have to have an obituary potential isolation between them .another reason is safety. In many application you would like the load circuit load side circuit to be totally isolated from the source side circuit for safety of equipment or people who are handling that these are the reasons where requiring isolation. In power converters, the most common isolation is the electromagnetic isolation what we have written here.

(Refer Slide Time: 04:19)



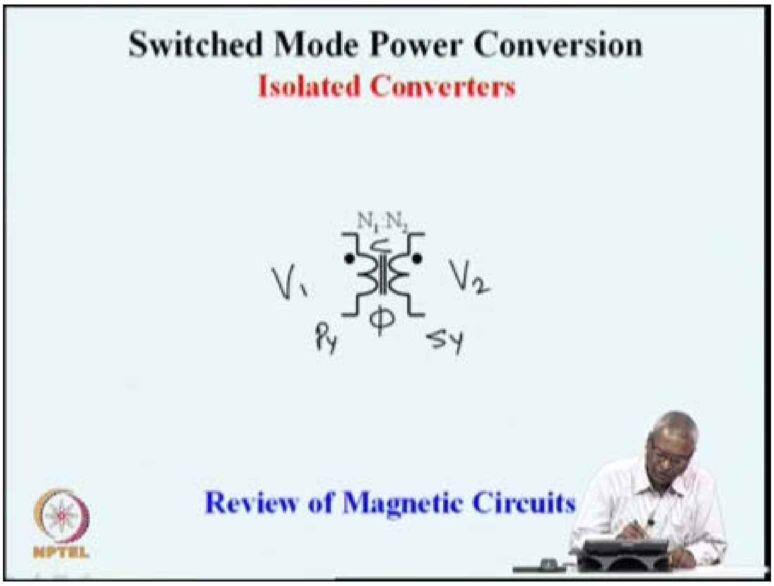
Switched Mode Power Conversion

Isolated Converters

Important Issue – Flux Balanc

So, in this lecture, we will try to look at the isolated power converter circuit topologies and how they got evolved from the non isolated circuit topology. Here, you can identify that the source plus the load plus the single pole double pole switch identical to the non isolated buck converter. What has now been added is another switch s p d t which is identical to s and s bar. It switches with the same relationships, on off relationship as this s and s bar. But, in between these two switches we have introduced an electromagnetic isolation. There are several important points, which have to be considered whenever we provide electromagnetic isolation. One of the most important issues is known as flux balance. In any electromagnetic transformer, it is necessary that the transformer operates with stable flux which is within the saturation limits of the core, electromagnetic core that is used for the transformer. This principle is that of flux balance.

(Refer Slide Time: 05:49)



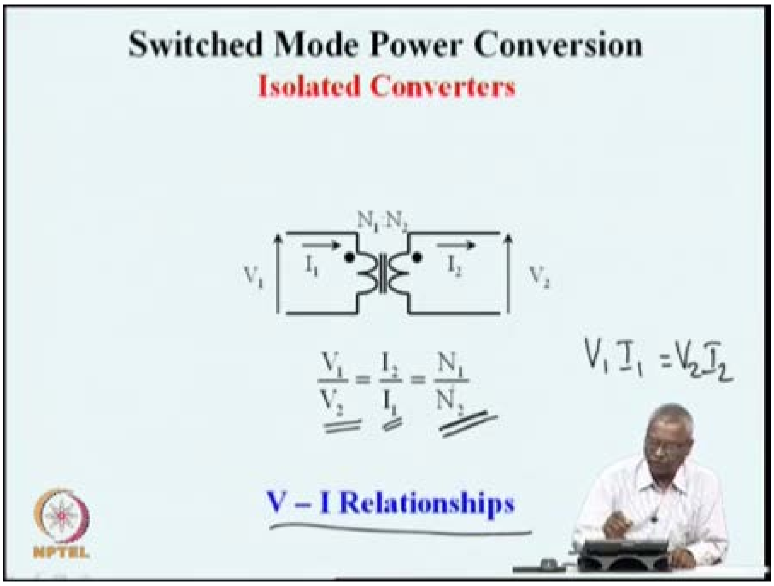
Switched Mode Power Conversion

Isolated Converters

Review of Magnetic Circuits

We will see in the next few slides what this flux balance is and how do we achieve the required constraints, required conditions, how are they achieved. So, we briefly review magnetic circuits which are essential to understand the operation of a simple electromagnetic power transformer. The transformer has a primary and a secondary. This primary and secondary are vowed on a common core and the core has certain flux. This is an electromagnetic power transformer. It is isolated with; it is excited with certain voltage on this side. The same frequency voltage of a different magnitude is obtained on V2. There is a relationship between the exciting voltage and the secondary voltage or the primary voltage and the secondary voltage through the number of turns N1 and N2 of the magnetic core.

(Refer Slide Time: 06:53)



Switched Mode Power Conversion

Isolated Converters

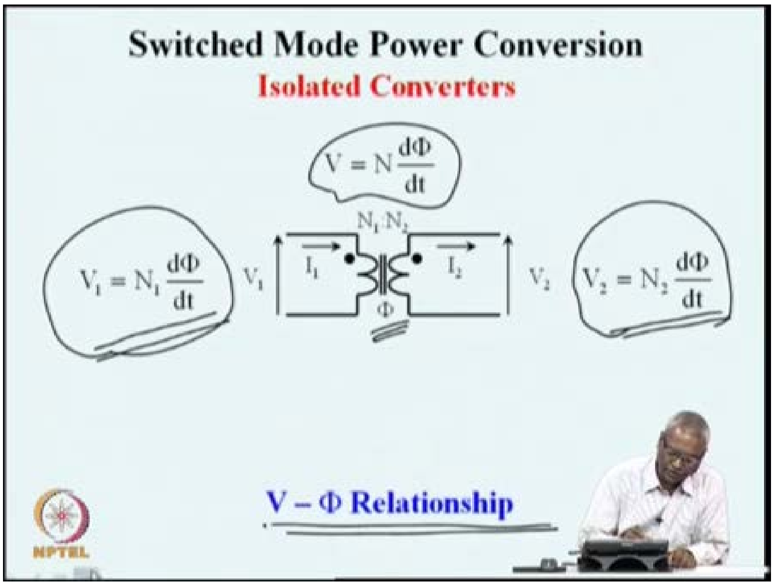
$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$V_1 I_1 = V_2 I_2$$

V – I Relationships

So, let us look at some of these ideas and then see what is meant by flux balance. The fundamental relationship in an ideal transformer is that the voltages are related to the number of turns V1 by V2. The ratio of the voltage V1 to V2 is the same as the ratio of the number of turns N1 by N2. V1 by V2 is N1 by N2. In a same way, the ratios of the currents I2 by I1 is equal to the reverse ratio of the number of turns. For example, I2 by I1 is N1 by N2. V1 by V2 is the direct ratio of the number of turns. I2 by I1 is the inverse ratio of the number of turns. This is very simple to understand because in a transformer where there are no losses V1 I1 is equal to V2 I2 that is, input power is output power. On account of that, you will see that the ratio of V1 by V2 will be the inverse ratio of I2 by I1. That turns out to be the number of turns ratio or N1 by N2. In general, this is simply called turns ratio of the transformer. The VI relationship of a transformer is given by the number of turns in the primary and in the secondary.

(Refer Slide Time: 08:16)



Switched Mode Power Conversion

Isolated Converters

$V = N\frac{d\Phi}{dt}$

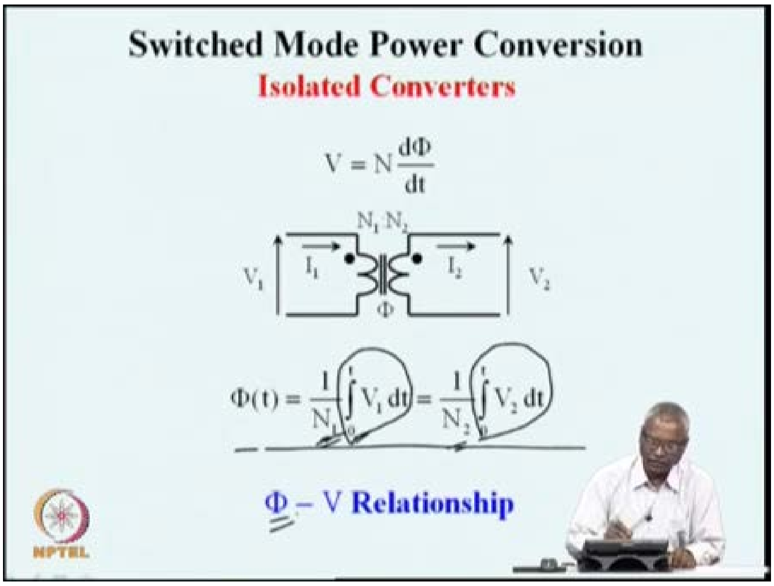
$V_1 = N_1\frac{d\Phi}{dt}$

$V_2 = N_2\frac{d\Phi}{dt}$

V – Φ Relationship

There is also a relationship between the excitation voltage and the flux in the core. If we represent the core flux as phi which is linking both the primary and the secondary and if this transformer is ideal where there are no losses; in such a case V1 is the primary voltage is equal to N1 into rate of change of the flux in the core N1 d phi by d t . The secondary voltage is N2 times the rate of change of flux. This is the relationship which is called the Faradays law of electromagnetic induction. V is N d phi by d t when applied to this case. On the primary side, V1 is N1 d phi by d t. Flux is common for both primary and secondary. On the secondary side, V2 is N d phi by d t or n two d phi by d t; phi being the common link common linking flux between the primary and the secondary. This relationship is the voltage to flux relationship.

(Refer Slide Time: 09:23)



Switched Mode Power Conversion

Isolated Converters

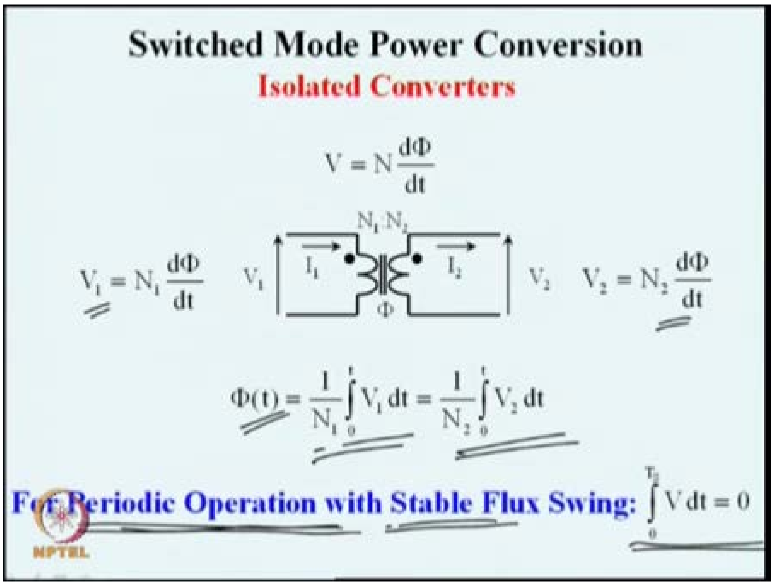
$$V = N\frac{d\Phi}{dt}$$

$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt = \frac{1}{N_2}\int_0^t V_2\,dt$$

Φ – V Relationship

If we go to the next step, what is the relationship between flux to voltage? That is inverse relationship of phi and V. We tried to invert this relationship and that turns out to be that the flux is nothing but integral of V d t over the period 0 to t divided by the number of turns N1 .This relationship is simply obtained as a inverse relationship of the Faradays Law. The core flux can be found out by integrating the primary voltage and dividing by primary turns or integrating the secondary voltage and dividing by the secondary voltage over the period of integration 0 to t. This relationship relates how from V1 or from V2 you can reach the flux in the core. This is the flux to voltage relationship.

(Refer Slide Time: 10:18)



Switched Mode Power Conversion

Isolated Converters

$$V = N\frac{d\Phi}{dt}$$

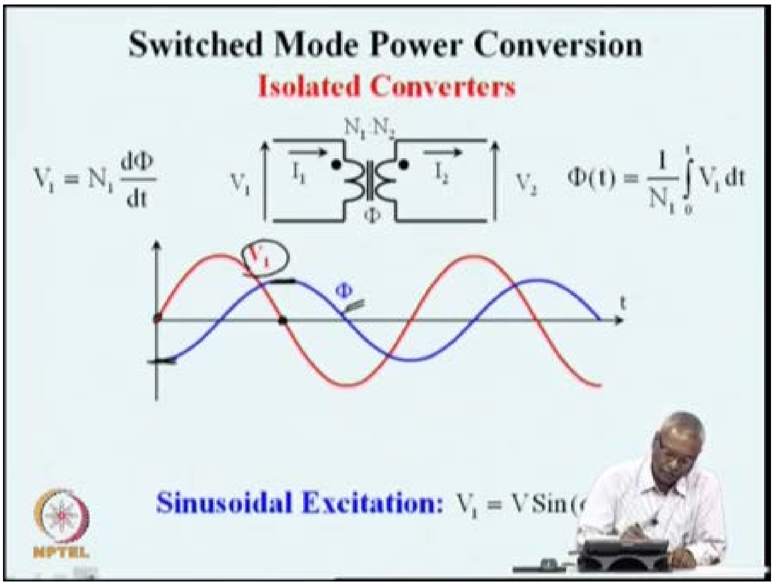
$$V_1 = N_1\frac{d\Phi}{dt} \qquad V_2 = N_2\frac{d\Phi}{dt}$$

$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt = \frac{1}{N_2}\int_0^t V_2\,dt$$

For Periodic Operation with Stable Flux Swing: $\int_0^{T_s} V\,dt = 0$

Now, if a transformer is operating in the AC standard application where the excitation is periodic, the primary voltage is a periodic voltage. Normally, it is a periodic sinusoidal voltage V1 is N1 d phi by d t and V2 is N2 d phi by d t. The flux is the integral of either the voltage V1 d t in integral 0 to t time zero to t divided by N1 or V2 d t integral divided by N2. This is the flux swing in a transformer core. The core flux is related to the volts second integral of the excitation voltage. For periodic operation, one of the important thing for periodic operation is that the flux swing is symmetrical. It starts from the same point and at the end of the cycle it comes back to the same point if it is a stable periodic operation. In such a case, to obtain a stable flux swing under a periodic condition, the volt second integral of the excitation voltage has to be 0. Now, this is the principle of flux balance if the flux has to remain stable then, over a period the volt second integral applied to that transformer has to be 0.

(Refer Slide Time: 11:53)



Switched Mode Power Conversion

Isolated Converters

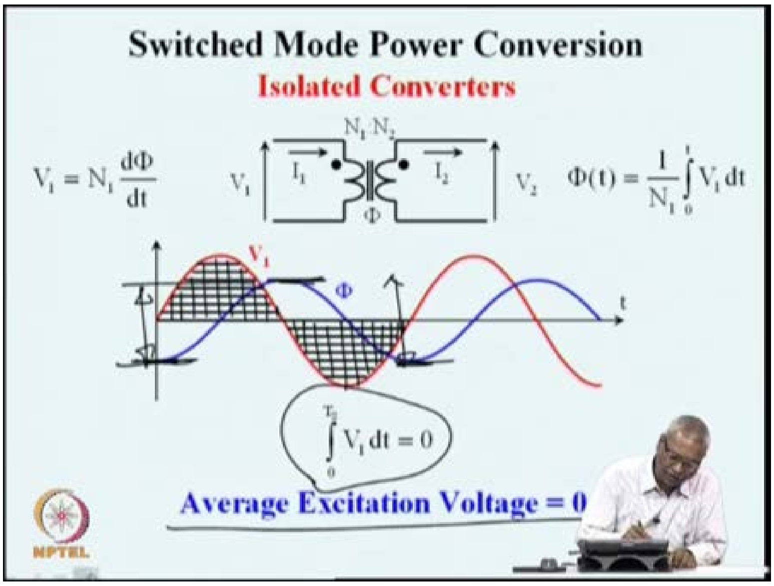
$V_1 = N_1 \frac{d\Phi}{dt}$

$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$

Sinusoidal Excitation: $V_1 = V\,Sin($

Now, let us see how this is seen in the standard sinusoidal excitation case. For example, if I excite it with a primary voltage V1, which is a sinusoidal voltage; the sinusoidal voltage integrated is the flux which you see here or the derivative differentiation of this phi will give you V1. In this curve, you see that wherever phi is maximum, where d phi by d t is 0, the voltage is 0. At all other points, the derivative the slope of this flux function is the voltage function or the integral of the voltage function is a flux function. These are the two relationships between v and phi.

(Refer Slide Time: 12:46)



Switched Mode Power Conversion

Isolated Converters

$$V_1 = N_1 \frac{d\Phi}{dt}$$

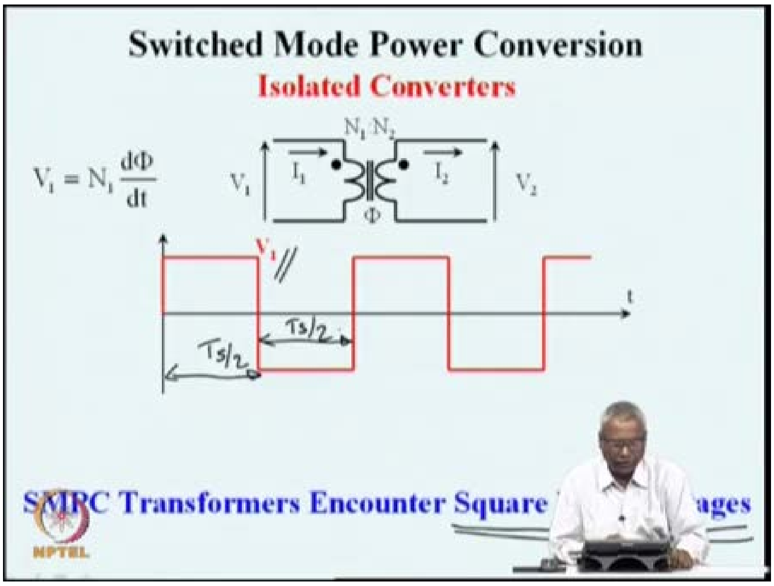
$$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$$

$$\int_0^{T_s} V_1\,dt = 0$$

Average Excitation Voltage = 0

If you see this curve, you can see the swing of the flux from the minimum to the maximum. This swing is decided by the volts second balance or the double hatched area that I shown here. The swing in the next half cycle from maximum flux to minimum flux is equal to the volts second area that I am just now seeing in the double hatched line. So, if the positive swing in the flux and the negative swing in the flux have to be equal, if the positive swing and the negative swing have to be equal under steady state; what it means is that the overall cycle volt second integral has to be 0 or the area under the positive curve, positive half and the area under the negative half have to be equal to each other. The same thing can be mathematically expressed in another way; that the excitation voltage the average value of the excitation voltage as to be 0. This is what we call as the principle of the flux balance.

(Refer Slide Time: 13:53)



Switched Mode Power Conversion

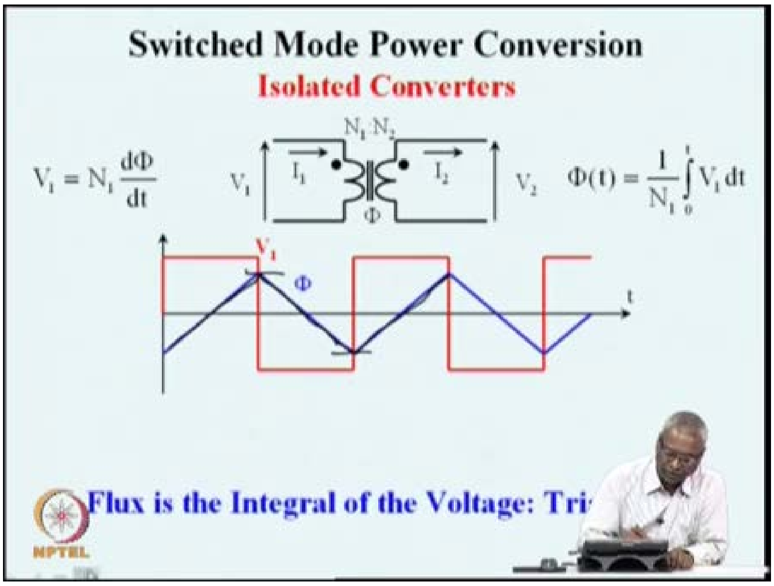
Isolated Converters

$V_1 = N_1 \frac{d\Phi}{dt}$

SMPC Transformers Encounter Square ages

But in a power converter, in a switched mode power converter, we do not apply sinusoidal voltages to transformers. Invariably, we apply voltages which are square wave in nature; certain voltage for some time and some other voltage for some other time and so on. Here what I show is a square wave excitation of a transformer V1, the primary voltage V1 is a square wave of some frequency a square wave has positive half equal to the negative half. This is T s by 2 and this is T s by 2 for half the period the voltage is plus V1 and for the next half period the voltage is minus V1.

(Refer Slide Time: 14:46)



Switched Mode Power Conversion

Isolated Converters

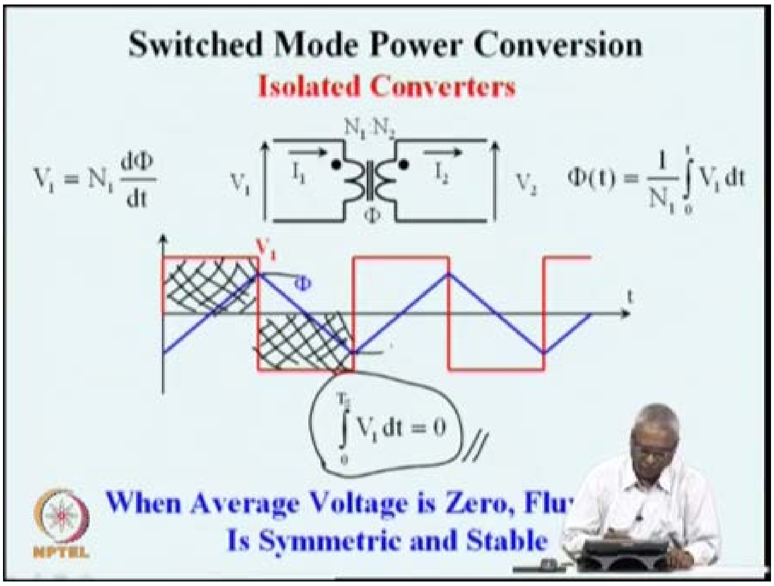
$V_1 = N_1 \frac{d\Phi}{dt}$

$\Phi(t) = \frac{1}{N_1} \int_0^t V_1 \, dt$

Flux is the Integral of the Voltage: Tri

So, in such a case if we try to see what is the flux? That flux is nothing but the integral of the voltage. So, you see that the flux is now a ramp. It is a triangle wave which is nothing but the integral of this V1 d t or V1 is the slope of the flux curve. In this half period, flux is constantly raising. So, the straight line; the slope is constant and equal to V1 here. In the negative half, the flux has a negative slope and a constant slope and you see a negative voltage applied to that. If the average voltage is 0 and if the time period is a half then, V1 and minus V1 are equal. So, the net average voltage applied to the transformer is 0 over a period, and because of that, the flux swing is symmetrical in such a transformer. In such a transformer, the flux swing is plus phi by 2 and minus phi by 2 and it is symmetrical.

(Refer Slide Time: 15:51)



Switched Mode Power Conversion

Isolated Converters

$V_1 = N_1 \frac{d\Phi}{dt}$

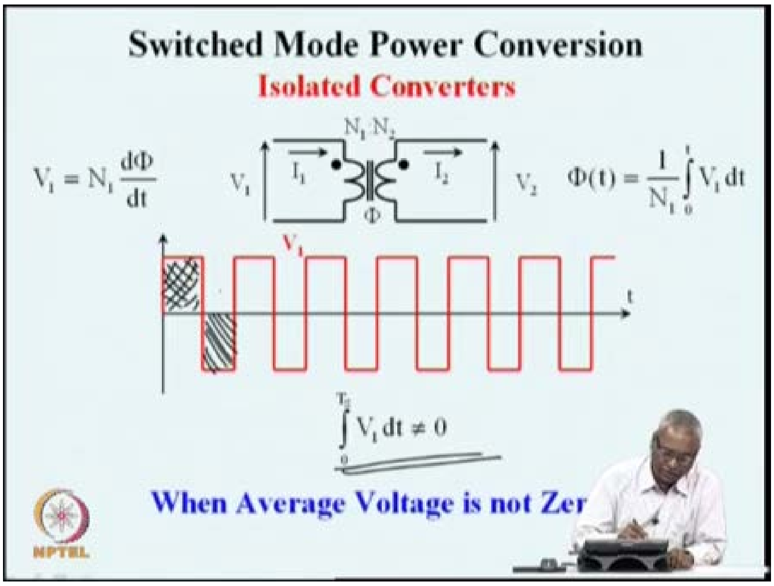
$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$

$\int_0^{T_s} V_1\,dt = 0$

When Average Voltage is Zero, Flu
Is Symmetric and Stable

The integral of one full cycle what you see as the hatched voltage here in one half is the same as the hatched voltage here in the other half with the result that the average voltage is 0. The flux has a stable periodic value with plus phi by 2 as the maximum flux and minus phi by 2 as the minimum flux.

(Refer Slide Time: 16:23)



Switched Mode Power Conversion

Isolated Converters

$V_1 = N_1 \frac{d\Phi}{dt}$

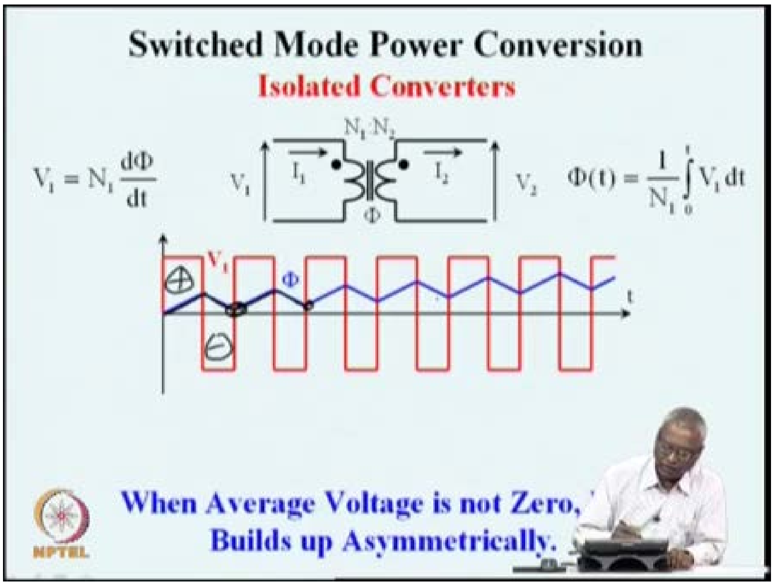
$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$

$\int_0^{T_s} V_1\,dt \neq 0$

When Average Voltage is not Zer

Supposing if the voltage applied is not symmetric for example, if this voltage what you applied during the positive half and the duration of that; the product of that is not equal to what is applied in the negative half. If the average if the volt second over a period is not equal to 0, in such a case what happens? If the average voltage is not 0, what will happen to the flux? This is the question which will give us the precautions to be taken if you wish to operate a switch mode power converter with transformer isolation.

(Refer Slide Time: 16:58)



Switched Mode Power Conversion

Isolated Converters

$V_1 = N_1 \frac{d\Phi}{dt}$

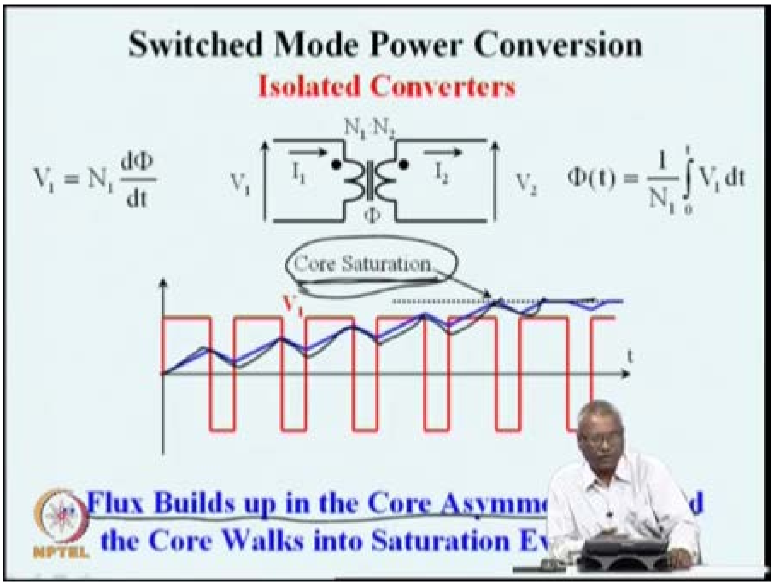
$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$

When Average Voltage is not Zero,

Builds up Asymmetrically.

You see here this positive half voltage and the negative half voltage volts second area are not equal. On account of that, in every cycle there is a small accumulation of voltage flux. There is a small accumulation of flux. In the first cycle, during positive half flux increases and during negative half, flux decreases. Because the positive volts second and the negative volt second are not equal, flux reaches a net value at the end of one cycle and in the next cycle it acquires a little more of flux and so on, and slowly the flux builds up. You can see that the flux is now asymmetric and it builds up cycle by cycle. In every cycle, a little bit of flux is accumulated and over a period of time the accumulated flux shifts, moves the flux in the transformer to one side either positive or negative and this asymmetric operation is not desirable.

(Refer Slide Time: 18:06)



Switched Mode Power Conversion

Isolated Converters

$V_1 = N_1 \frac{d\Phi}{dt}$

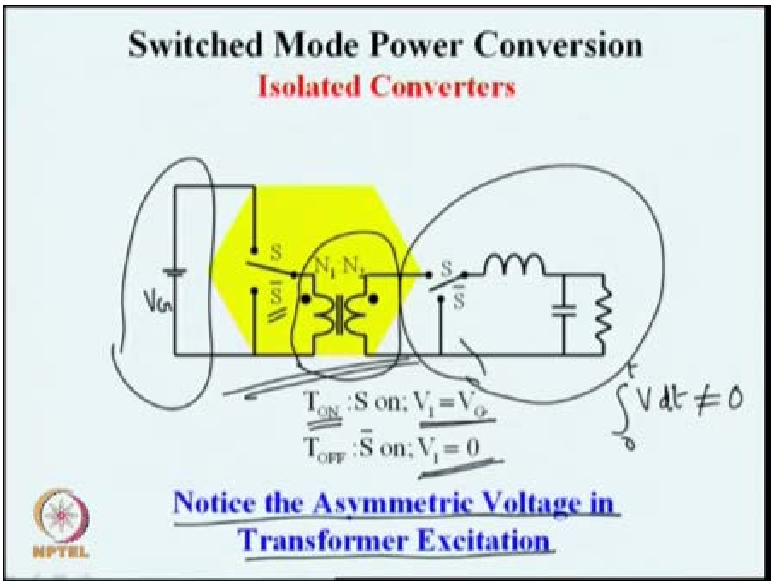
$\Phi(t) = \frac{1}{N_1}\int_0^t V_1\,dt$

Flux Builds up in the Core Asymm **d**

the Core Walks into Saturation Ev

What happens because of this asymmetric operation? The flux builds up flux builds up in the core asymmetrically and once it reaches the saturation level, the flux cannot build up any more because every magnetic material has a saturation flux density beyond which the material is not capable of supporting additional flux. So, in such a case, as the flux is building up, you can see that eventually, it hits a maximum and saturates. We say that the core has now saturated or the flux has reached a limit beyond which the core is not capable of sustaining additional flux.

(Refer Slide Time: 18:53)



Switched Mode Power Conversion

Isolated Converters

T_{ON} : S on; $V_1 = V_G$

T_{OFF} : $\bar{S}$ on; $V_1 = 0$

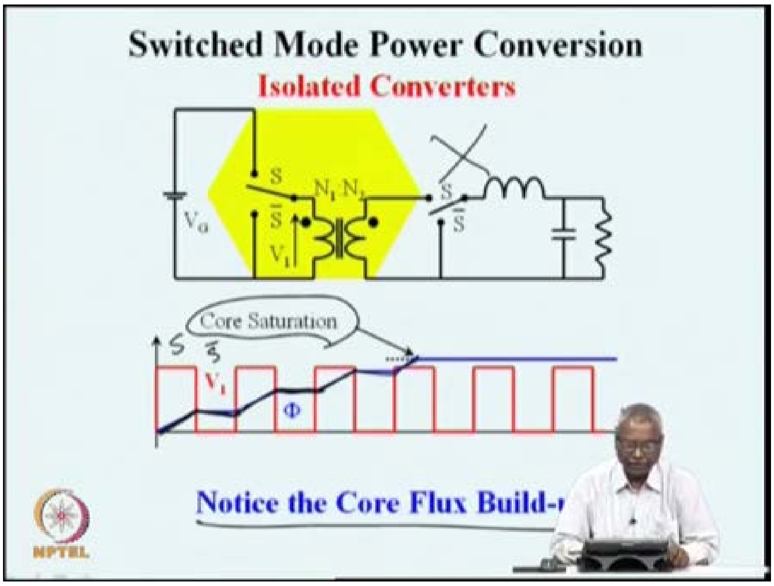
Notice the Asymmetric Voltage in Transformer Excitation

What is the consequence of this? The consequence of this is saturation in the core. Saturation in the core will make the transformer to act like a short circuit. A large current will be drawn. The source will be overloaded and so on. Now, in this particular case we are looking at the isolated converter which was obtained by simply introducing an electromagnetic transformer to a standard source and our standard buck converter with isolation in between. So, this is what we proposed as a circuit topology for isolated power converter. Notice that during the on time when the switch is on, the voltage across the transformer is VG same as supply voltage.

During the on time, the primary of the transformer through this switch S is being subjected to a voltage of VG. During the time when the switch is connected to S bar, the switch is connected to S bar and the transformer primary end is connected to 0 and we see that when the switch S bar is on the voltage V1 or the primary voltage to the transformer is 0. We are applying during a part of the cycle, a positive voltage and during the next part of the cycle is 0 voltage. It is very obvious that over one cycle, there will be a net volt second in the circuit.

You will have integral 0 to t V d t will not be equal to 0 because on one side it is positive volts second and in the other side it is 0 volt second. So, there is nothing to balance and so this transformer will saturate eventually. So, in a standard converter if we simply introduce an electromagnetic isolation without taking adequate measures to balance the flux in the core; in such a situation this transformer will be subjected to asymmetric flux excitation.

(Refer Slide Time: 21:12)



Switched Mode Power Conversion

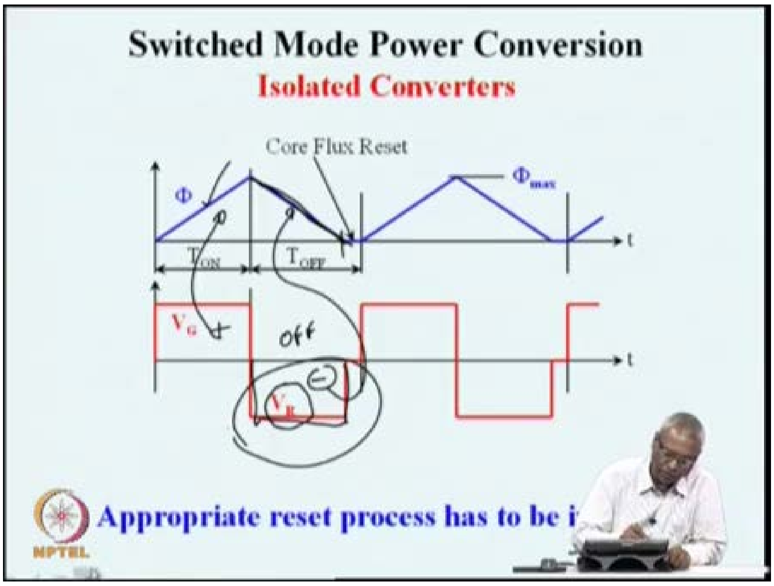
Isolated Converters

Notice the Core Flux Build-

The transformer will saturate which is not a very desirable thing if you build such a convertor and operate it at a certain switching frequency with S bar and S as shown here in this circuit, you see that the voltage of light to the transformer is unipolar. It is positive during the switch S on time and it is 0 during the S bar on time. Because of this, the net volt second across the transformer is only positive. It is not 0 and because of that the core flux is building up every cycle. It builds up during the positive voltage during the 0 voltage flux does not die d phi by d t is 0 and because of that phi remains constant.

Next cycle again, current flux builds up and the off period flux remains constant. It is very easy to see that over several cycles, the flux will reach higher level where it will saturate. Core saturation is certain to take place and so this type of operation is not permitted. Simply taking these switches, introducing transformer will not provide us the isolation features. Then, how does one handle this? So, let us look at the mechanism of reducing the flux to 0.

(Refer Slide Time: 22:51)



Switched Mode Power Conversion

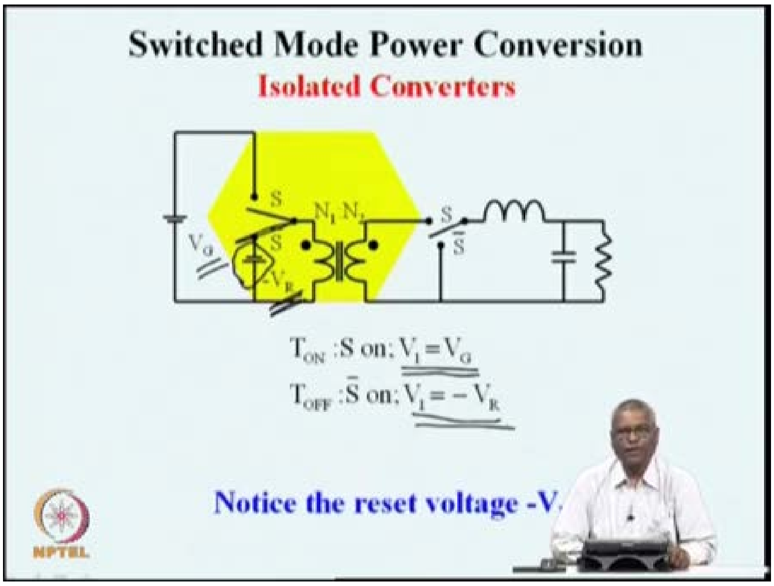
Isolated Converters

Appropriate reset process has to be i

We saw in the previous one, the flux remains at high level during the off period because we are not applying any voltage to the primary but if you want to reset the core; the core as built up during on time flux as built up and during the off time instead of allowing it to remain there, we would actively bring it down to 0 and keep it at 0, then start the next cycle. If such an operation is possible then, you can see that in every cycle, the core flux builds up and dies to 0, remains at 0 then, again builds up and so on. In such a situation, the core flux will not build up eventually and the core will not saturate eventually. This is something which we have to provide in the circuit topology.

We have to provide a mechanism of core flux reset or bringing the core flux back to 0 at the end of every cycle. Now, how this, how do you do that? From this core flux, you can see that if I want to bring the flux down, if I want to have a negative change in flux then, we know that d phi by d t is relating to the voltage, so I have to apply some negative voltage to the primary during the time I wish to reset the core, if the core as to be reset, apply a negative voltage to the transformer primary during the off time. See if that is done during the on time because of this positive voltage, the core flux is building up this positive voltage results in a positive slope and during the negative time, negative off period, this negative voltage will provide a negative slope to phi and we have an opportunity to reset the flux all the way down to 0. The appropriate reset process is by providing here reset voltage to the transformer.

(Refer Slide Time: 24:45)



Switched Mode Power Conversion

Isolated Converters

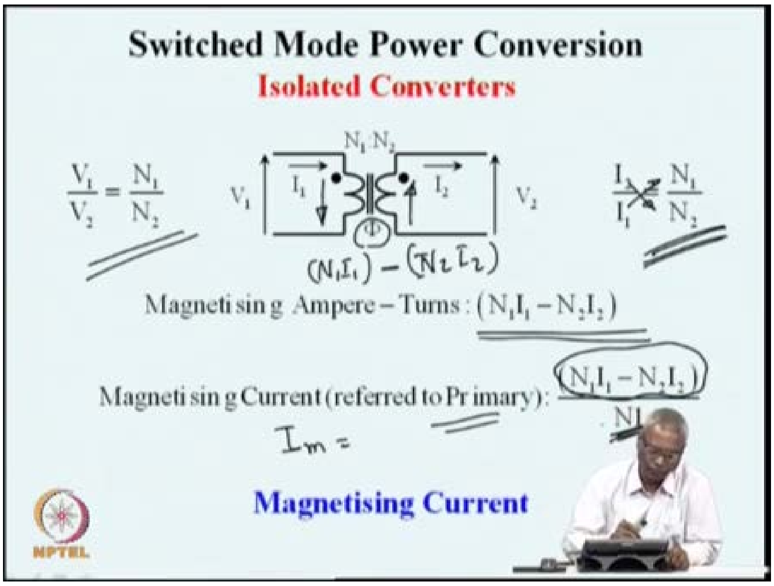
T_{ON} : S on; $V_1 = V_G$

T_{OFF} : $\bar{S}$ on; $V_1 = -V_R$

Notice the reset voltage -V

Now, in the same circuit, what has been done is a reset source as been added. I call that as minus VR. The source voltage is VG. When the switch is connected to S, the transformer will result in flux build up during the on time because of the voltage VG. During the off time because the switch is now connected, here the transformer is subject to a negative voltage, negative voltage of magnitude VR. So, you see that during the on time, a positive voltage is supplied to the transformer and during the off time, a negative voltage is supplied to the transformer. Now, we have an opportunity to balance the flux because in one direction, flux is increasing and in the other duration, flux is decreasing. So, if we correctly select the durations, it is possible to make the flux come back to 0 at the end of every cycle.

(Refer Slide Time: 25:44)


Switched Mode Power Conversion

Isolated Converters

$\frac{V_1}{V_2} = \frac{N_1}{N_2}$

$\frac{I_2}{I_1} = \frac{N_1}{N_2}$

$(N_1I_1) - (N_2I_2)$

Magnetising Ampere – Turns : $(N_1I_1 - N_2I_2)$

Magnetising Current (referred to Primary): $\frac{(N_1I_1 - N_2I_2)}{N_1}$

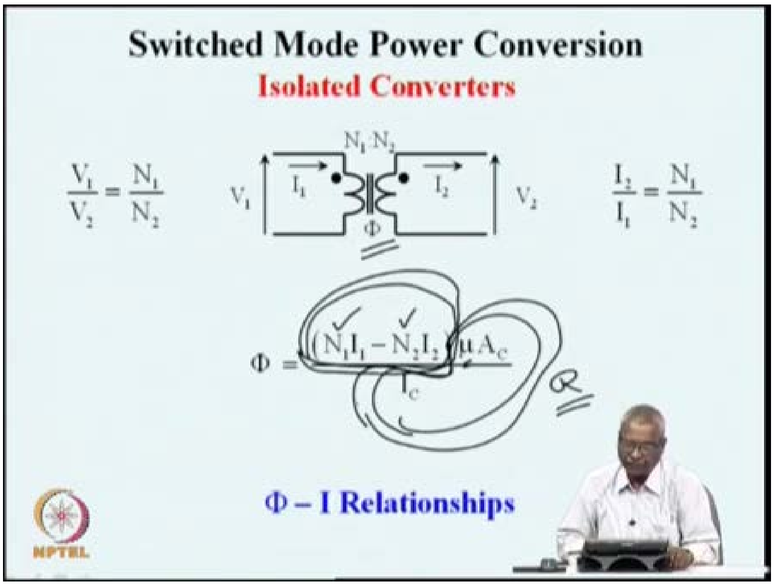
$I_m =$

Magnetising Current

So, what we see is that process how is this reset been done. Let us look at the transformer with one non ideality. The ideal transformer has the relationship that V1 by V2 is equal to N2 by N1 by N2 and I2 by I1 is equal to N1 by N2. Now, in the ideal transformer, N1 into I1 is equal to N2 into I2. What you see from here? The product N1I1 and the product N2 I2 are equal. On account of that, in an ideal transformer, there is no net flux because the magnetizing in the core takes place because of N1 I1 in the direction shown here minus N2 I2 in the direction shown there. So, the net ampere turns in the core is N1 I1.

The secondary ampere turn is n N2 I2. Because these both are, one of them is flowing away from the dot and the other is flowing towards the dot. The net magnetizing ampere turns is a difference between N1 I1 and N2 I2 or we say that the magnetizing ampere turns is N1 I1 minus N2 I2. Now, this can be seen as a equivalent magnetizing current on the primary side or on the secondary side. The magnetizing current is nothing but the net magnetizing ampere turns divided by the turns in the primary if you want primary current or secondary. If you want the secondary referred magnetizing current, you can see that this current is called the magnetizing current I m which is N1 I1 minus N2 I2 divided by N1. This N1 is to refer the total magnetizing current as if it is a current flowing through N1 only. So, this is the magnetizing current refer to the primary. If we wish to get Magnetizing current refer to the secondary, it will be N1 I1 minus N2 I2 divided by N2. Okay?

(Refer Slide Time: 28:10)



Switched Mode Power Conversion

Isolated Converters

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

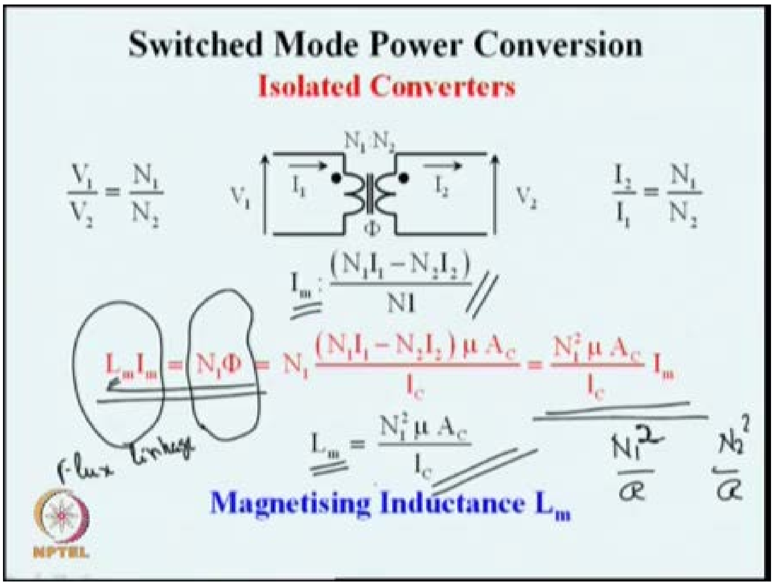
$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$\Phi = \frac{(N_1 I_1 - N_2 I_2)\mu A_c}{l_c}$$

Φ – I Relationships

Now, the flux is decided by whatever is the ampere turns divided by what is known as the reluctance of the machine. So, this quantity which is the denominator, the magnetic core length L divided by the magnetic area A and then the magnetic permeability mu L divided by A mu; we have seen this as the reluctance of the magnetic circuit R and the net flux in the core is related to the magnetizing ampere turns divided by the reluctance of the circuit. In an ideal transformer, this quantity will be 0 because N1 I1 and N2 I2 are equal. In a real transformer, these two will not be equal and the difference between the primary ampere turns N1 I1 and the secondary ampere turns N2 I2 is what is establishing the core flux phi. So, this is a net ampere turns in the core N1 I1 minus N2 I2. This is the reluctance of the magnetic circuit and we see that flux is the ampere turns divided by the reluctance of the magnetic circuit.

(Refer Slide Time: 29:27)



Switched Mode Power Conversion

Isolated Converters

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \qquad \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$\underline{\underline{I_m}} : \frac{(N_1 I_1 - N_2 I_2)}{N1}$$

$$L_m I_m = N_1 \Phi = N_1 \frac{(N_1 I_1 - N_2 I_2)\,\mu A_C}{l_C} = \frac{N_1^2 \mu A_C}{l_C} I_m$$

flux linkage

$$\underline{\underline{L_m}} = \frac{N_1^2 \mu A_C}{l_C}$$

$$\frac{N_1^2}{\mathcal{R}} \qquad \frac{N_2^2}{\mathcal{R}}$$

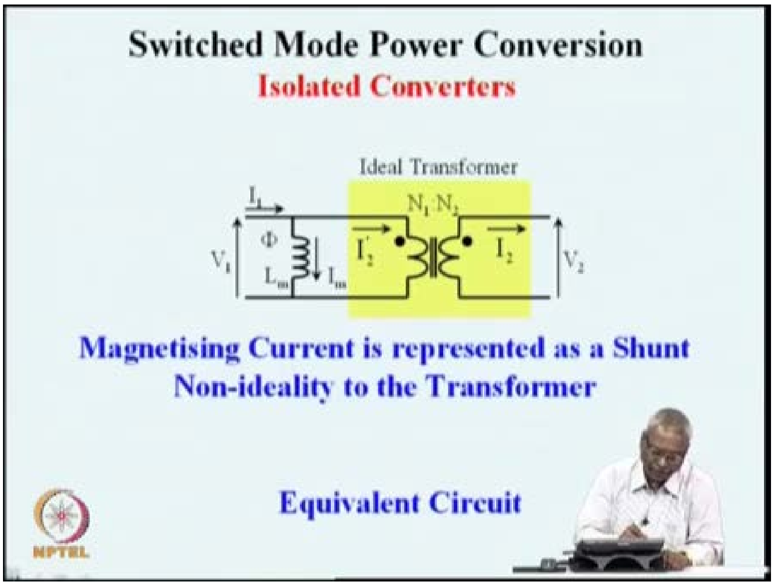
Magnetising Inductance L_m

Now, if we say that the magnetizing current referred to the primary is N1 I1 minus N2 I2 divided by N1, this is the primary reflected magnetizing current. We also have another relationship which is the electrical side relationship of the link flux linkage and the magnetic side relationship of the flux linkage. Flux linkage in electrical side is given by L into I or magnetizing inductance L m multiplied by the magnetizing current I m is the flux linkage in the core. It is also the same as N1 into phi which is the flux linkage in the core multiplied by the number of turns in the primary.

Here, we have taken the I m as the magnetizing current referred to the primary. It will be equal to m 1 phi. If you replace phi as N1 I1 minus N2 I2 by reluctance, this multiplying by N1 and then replacing this entire thing by I m into N1 will give rise to a relationship here, which is the total flux linkage N square N1 square mu A c by L c into I m. This is the total flux linkage and if you wish to find out what is L m, divide this quantity divided by I m.

What is left with is the magnetizing reluctance. Magnetizing reluctance is nothing but if it is referred to the primary side, it is N1 square divided by reluctance. Reluctance is a common quantity both for primary and secondary. N1 belongs to the primary turns. N2 belongs to the secondary turns. So, if you want magnetizing current refer to primary, it is N1 square by reluctance and if you want the magnetizing inductance on the secondary side, it will be N2 square divided by reluctance. This is a relationship between the various quantities of interest to us. L m magnetizing inductance related to the number of turns on the primary and the reluctance of the magnetic circuit.

(Refer Slide Time: 31:53)



Switched Mode Power Conversion

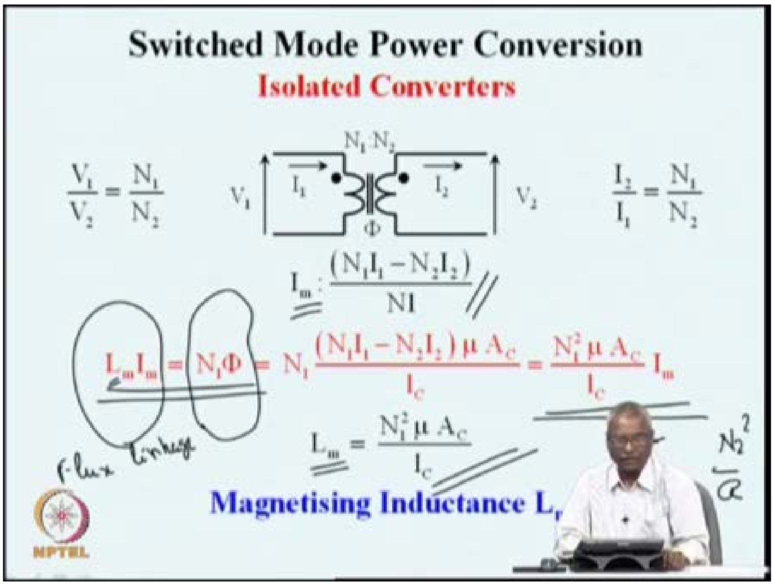
Isolated Converters

Magnetising Current is represented as a Shunt Non-ideality to the Transformer

Equivalent Circuit

So, what we can do is that the entire magnetization process?

(Refer Slide Time: 31:59)



Switched Mode Power Conversion

Isolated Converters

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

$$I_m : \frac{(N_1I_1 - N_2I_2)}{Nl}$$

$$L_mI_m = N_1\Phi = N_1\frac{(N_1I_1 - N_2I_2)\mu A_c}{l_c} = \frac{N_1^2\mu A_c}{l_c}I_m$$

Flux Linkage

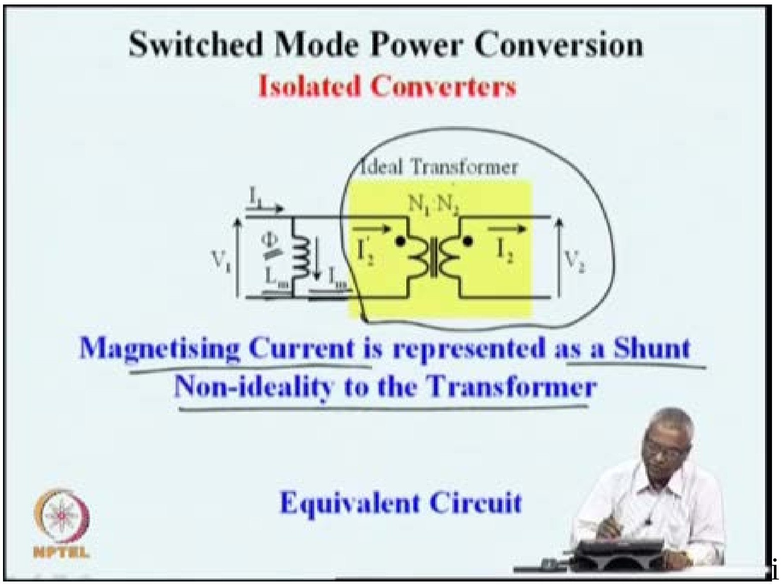
$$L_m = \frac{N_1^2\mu A_c}{l_c}$$

$$\frac{N_2^2}{\mathcal{R}}$$

Magnetising Inductance L

What we had seen in the previous slide?

(Refer Slide Time: 32:06)


Switched Mode Power Conversion

Isolated Converters

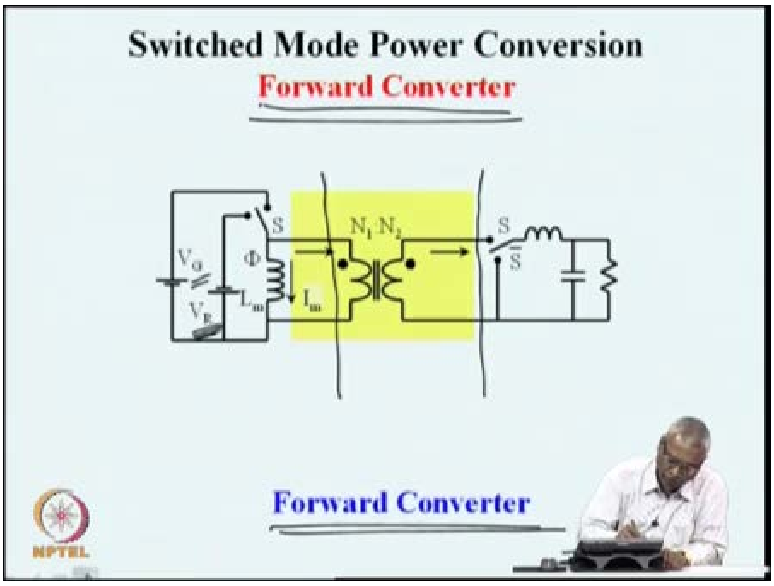
Magnetising Current is represented as a Shunt Non-ideality to the Transformer

Equivalent Circuit

As L m I m is what the flux linkages, it can be separated as a separate part of the equivalent circuit. What we have here is the ideal transformer where this I2 dash and I2 are the ideal primary current and secondary current. N1 times I2 dash will be equal to N2 times I2. Because this is ideal transformer, there is no flux in this ideal transformer core. All the core flux we have separated in a magnetizing inductance L m into which a current of I m is flowing.

This product L m I m is setting up a flux in the core which is phi. So, when we represent this magnetic process in a transformer, as a ideal transformer plus a magnetizing inductance then, it is much easier for us to develop many of the new topologies that we are going to look at. The magnetizing current is represented as a shunt non ideality of the transformer. Now, this transformer because it has no flux accumulation and we can have any type of switching even if the volt second is not balanced for this ideal transformer, it is ok. This is the equivalent circuit.

(Refer Slide Time: 33:18)



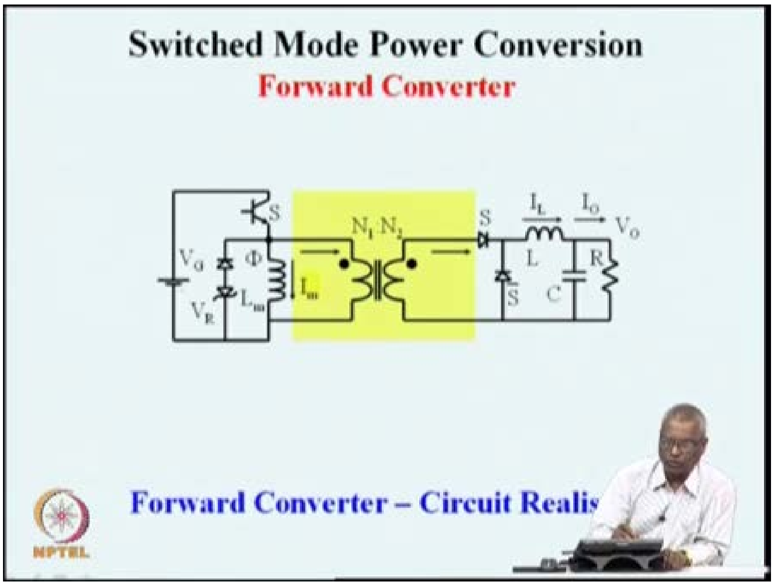
Switched Mode Power Conversion

Forward Converter

Forward Converter

So, let us look at now the convertor which is which is called the forward convertor. This circuit topology is called the forward convertor. It is one of the very first isolated power convertors which we are now considering. It is a forward convertor, we have a buck convertor up to this point. Then a transformer isolation has been introduced. This transformer has both the non ideality as well as the ideal property. We represent the ideal property of the transformer by this and then connect the magnetizing inductance as a parallel non ideality as a shunt non ideality, to this we connect a voltage of V g and V r, a voltage which is applied to the transformer during non time V g and a voltage that is applied to the transformer during the off time called V r because V g and V r are of opposite polarity. You can see that now we have introduced a mechanism of resetting the core.

(Refer Slide Time: 34:28)

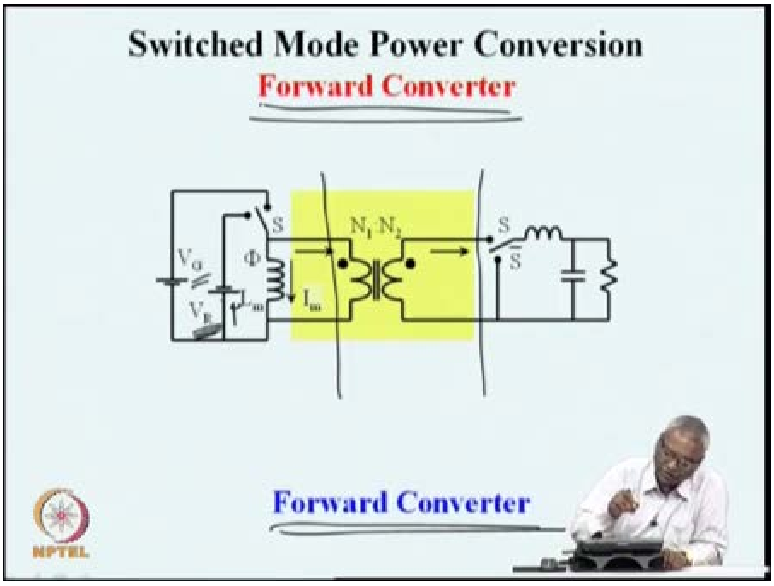

Switched Mode Power Conversion

Forward Converter

Forward Converter – Circuit Realis

We will have to now work out what the other quantities of interest are...

(Refer Slide Time: 34:35)

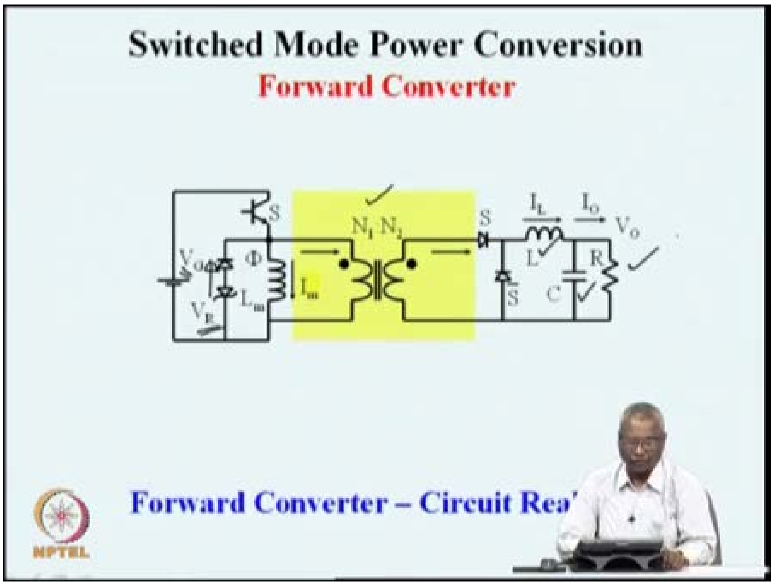

Switched Mode Power Conversion

Forward Converter

Forward Converter

Now, the circuit realization of this circuit VR is not provided by a source because in this circuit, in the previous circuit that we had seen, the magnetizing energy eventually flows to flows through this VR, during the time S is connected to the reset circuit. See in such a case, power is being supplied into VR. Power is not being drawn out of VR.

(Refer Slide Time: 34:59)



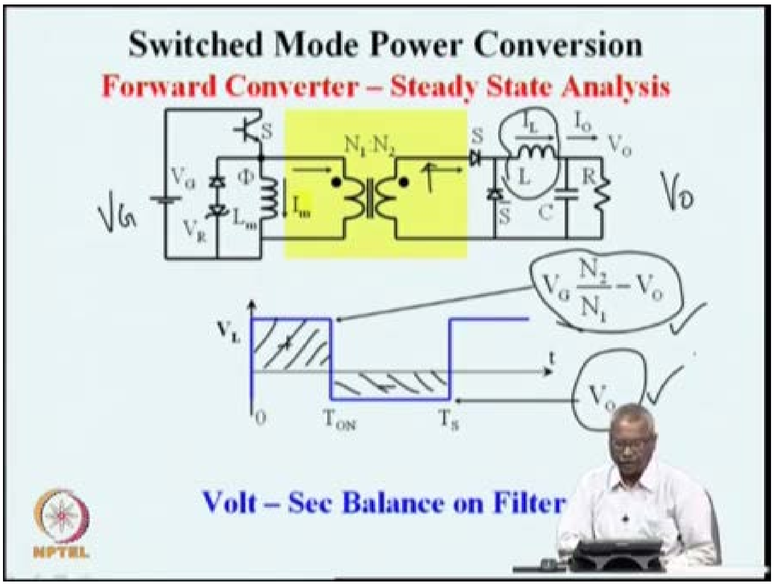
Switched Mode Power Conversion

Forward Converter

Forward Converter – Circuit Rea'

It is dissipated in VR. If that is the case, VR can be a dissipated circuit element and the way to realize this circuit is to connect to the transformer parallel a circuit which has a constant voltage. This circuit, when current is flowing through this magnetizing through this reset branch, you will find that the current is in the direction of diode volts, so no voltage drop. The current is against the direction of the zener, so you have a zener voltage drop with a minus sign and that will be equal to our reset voltage and supply voltage is VG. The transformer has turns ratio of N1 to N2 and the usual reacting elements of Lc are there and this is the load resistance R. Now, this is the circuit realization of a very simple forward convertor.

(Refer Slide Time: 35:45)



Switched Mode Power Conversion

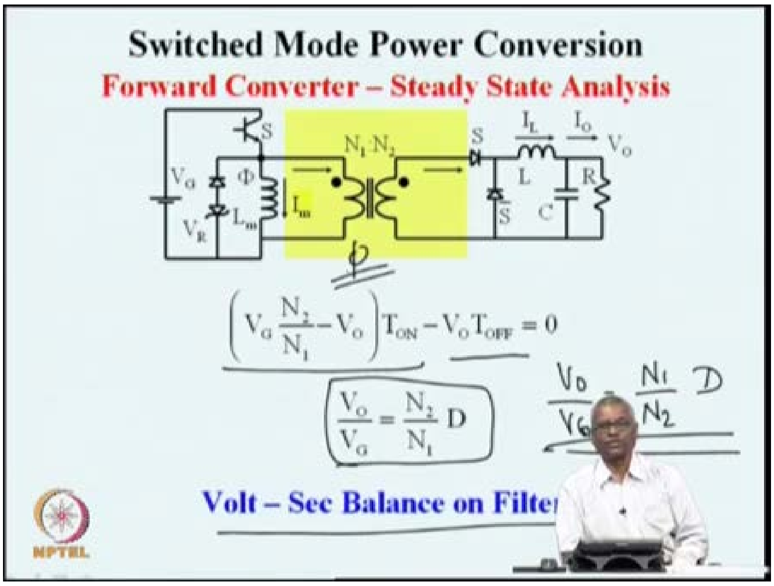
Forward Converter – Steady State Analysis

Volt – Sec Balance on Filter

So, let us look at how the voltage relationship between the input and the output will occur in this case. We go back to the old method. Whenever we want to find out the relationship between VG and V naught, we carry out a volt second balance condition on the inductor or we find out what is inductor voltage during the positive half, and what is a inductor voltage during the negative half.

If the inductor has to have a sustained operation, this positive half must be equal to the negative half. If such is the case, then the inductor will have flux which does not keep accumulating or keep dropping down. So, for steady state operation, the voltage across the inductor must satisfy the condition that over one full cycle, the volt second balance across the inductor will be 0. In this case during the on time, the voltage across the inductor is VG. We consider all the switches to be ideal. VG into N2 by N1 is the voltage at the secondary point and that voltage on the left hand side of the inductor and V naught is there on the voltage on the right hand side of the inductor. So, during on time the voltage across the transformer primary is VG into N2 by N1 minus V naught, but during the off time the voltage across the transformer across the inductor is just V naught.

(Refer Slide Time: 37:20)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\left(V_G\frac{N_2}{N_1}-V_O\right)T_{ON}-V_OT_{OFF}=0$$

$$\boxed{\frac{V_O}{V_G}=\frac{N_2}{N_1}D}$$

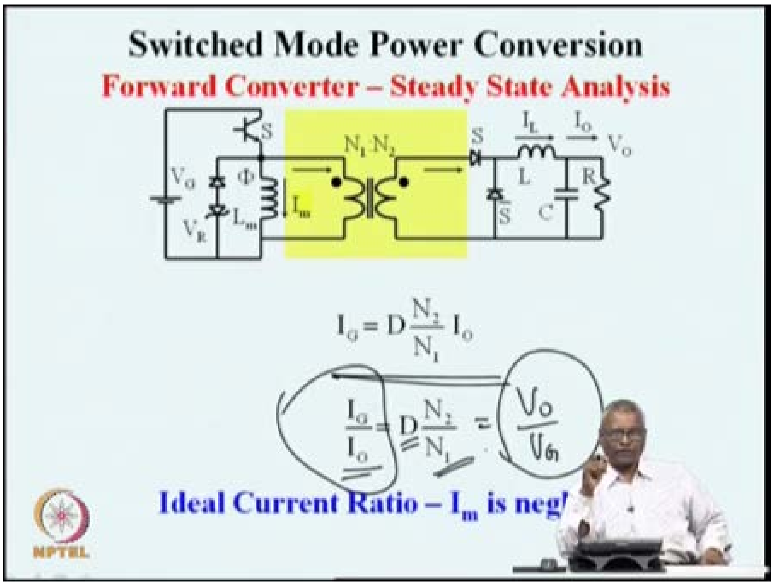
$$\frac{V_0}{V_G}=\frac{N_1}{N_2}D$$

Volt – Sec Balance on Filte

If we balance the volt seconds between these two, you find that T ON multiplied by the on straight voltage minus T half multiplied by half way to half straight voltage has to be 0. If this equation is 0, then we get our famous voltage conversation ratio relationship. The output voltage is related to the input voltage through a turns ratio which is corresponding to the transformer multiplied by the duty ratio which we had seen in the non isolated power convertor.

This volt second balance, if we carry it out on the inductor we will get the relationship between V naught and VG. This is as before; nothing new in this. But, because the transformer has flux build up and we have mechanism; we need mechanism not to build up the flux. We want to find out the process of magnetization of a transformer and then modify the circuit so that there is no core flux saturation build up is taking place.

(Refer Slide Time: 38:28)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

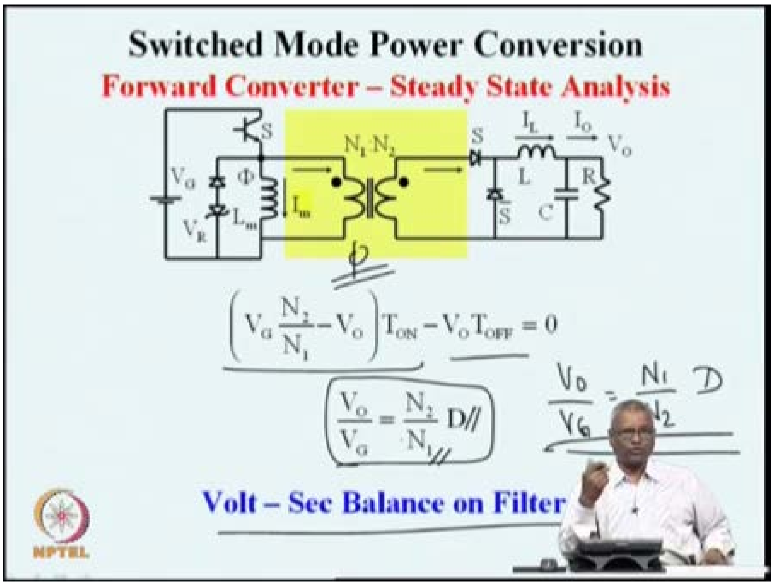
$$I_G = D\frac{N_2}{N_1} I_O$$

$$\frac{I_G}{I_O} = D\frac{N_2}{N_1} = \frac{V_O}{V_G}$$

Ideal Current Ratio – I_m is negl

Now, the relationship between IG and I naught does not change. The reason is, you see that everything is been ideal. This I m is also 0. We are assuming that current I m is neglected. See in such a case, the primary current average is nothing but the secondary reflected current IL into N2 by N1 multiplied by the duty ratio D. It is really the average current IG and from this, you can write the current ratio is duty ratio multiplied by N2 by N1. This is the same as V naught by VG. We have seen that under ideal conditions, the forward voltage transfer ratio and the reverse current transfer ratio will be identical. In the non isolator convertor, it was D. In the isolator convertor, we have a additional term which is the turns ratio of the transformer. Now, we have added one more degree of freedom; one more degree of design freedom.

(Refer Slide Time: 39:42)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\left(V_G \frac{N_2}{N_1} - V_O\right) T_{ON} - V_O T_{OFF} = 0$$

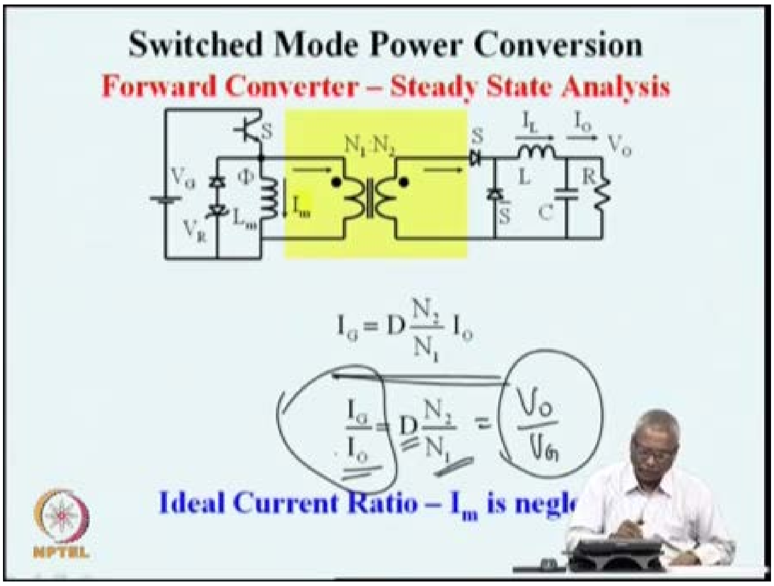
$$\boxed{\frac{V_O}{V_G} = \frac{N_2}{N_1} D} //$$

$$\frac{V_0}{V_G} = \frac{N_1}{N_2} D$$

Volt – Sec Balance on Filter

For example, from a given voltage of V naught, it is V given voltage of VG, it is possible to obtain the same V naught with two different quantities for the turns ratio and the duty ratio of operation. Now, it is possible to delink the ratio of V naught by VG from just D. It is now a function of N2 by N1 and D. So, it is possible to operate such a converter at a very low duty ratio with large turns ratio or with the higher high duty ratio with a low terns ratio. So, we have added an additional degree of freedom for the designer. You can get the same voltage conversion ratio from two different converters employing two different turns ratio and two different duty ratios.

(Refer Slide Time: 40:39)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

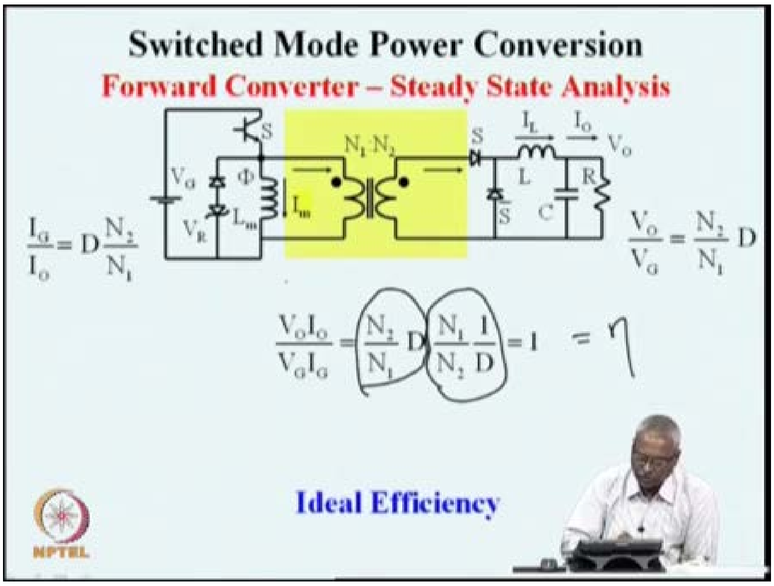
$$I_G = D \frac{N_2}{N_1} I_O$$

$$\frac{I_G}{I_O} = D \frac{N_2}{N_1} = \frac{V_O}{V_G}$$

Ideal Current Ratio – I_m is negl

The current ratio in the ideal converter is the same as the reverse of the voltage ratio.

(Refer Slide Time: 40:53)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\frac{I_G}{I_O} = D\frac{N_2}{N_1}$$

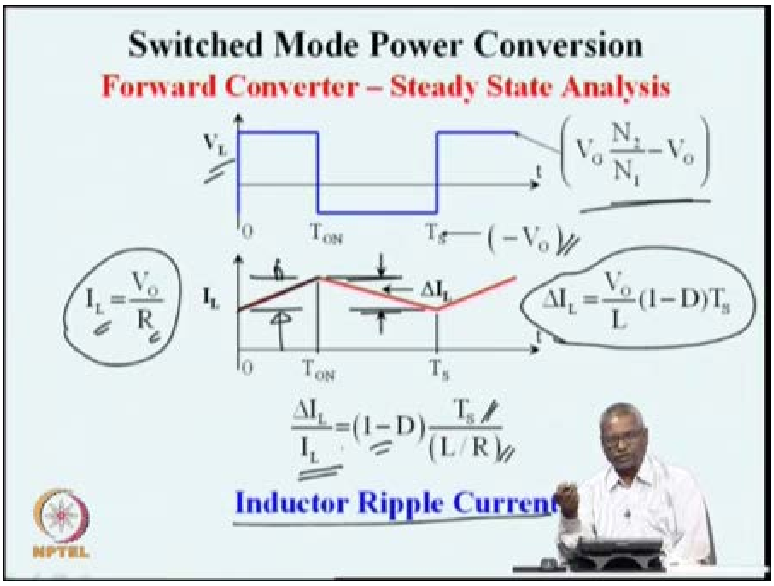
$$\frac{V_O}{V_G} = \frac{N_2}{N_1}D$$

$$\frac{V_O I_O}{V_G I_G} = \left(\frac{N_2}{N_1}\right)D\left(\frac{N_1}{N_2}\frac{1}{D}\right) = 1 = \eta$$

Ideal Efficiency

When you multiply both of them, you get the efficiency which is 1. In an ideal converter, the efficiency is 1 because the V naught by VG is N2 by N1 into D and I naught by IG is N1 by N2 into 1 by D. You multiply them, you get V naught I naught by VGIG is equal to 1 and this is nothing but efficiency. What we define, the input power or output power divided by the input power is the efficiency. That efficiency is 1. You know ideal switch mode converter with isolation as shown in this case.

(Refer Slide Time: 41:29)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\left(V_G\frac{N_2}{N_1} - V_O\right)$$

$$(-V_O)$$

$$I_L = \frac{V_O}{R}$$

$$\Delta I_L = \frac{V_O}{L}(1-D)T_S$$

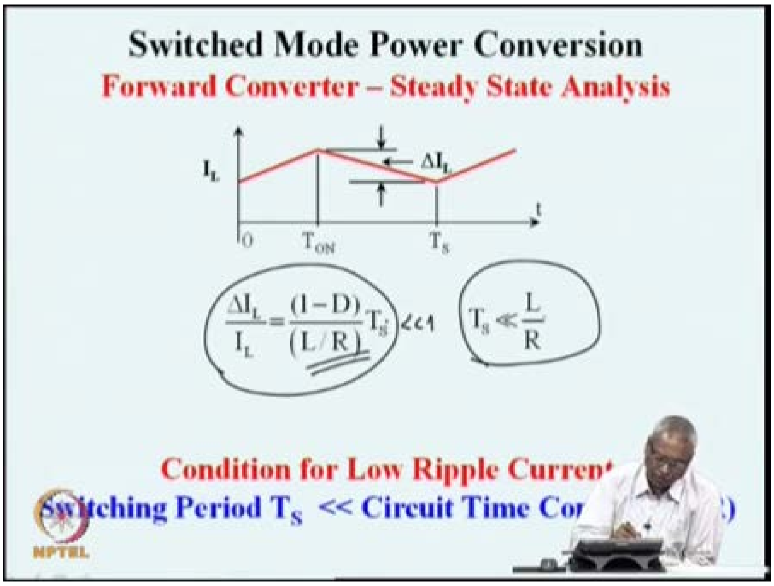
$$\frac{\Delta I_L}{I_L} = (1-D)\frac{T_S}{(L/R)}$$

Inductor Ripple Current

In such a converter, what will be the current ripple in the conductor? This is something which we have done several times before. Inductor current ripple is always related by the inductor voltage. If the inductor voltage is integrated, that will give us what is the current ripple on the inductor current. Here, the inductor voltage is VL and that is equal to VG into N2 by N1 minus V naught during the on time. It is minus V naught during the off time. If you integrate this quantity, you should be able to get how the current raises during the on time which is this and how the current falls during the off time which is what I have shown by the arrow here. The IL is V naught by R which is the output ratio and delta L can be written based on the slope.

Here it is voltage is V naught inductor is L V naught by L is the slope and the duration is one minus DTS. So, this relationship is delta IL represented as a function of V naught LD and TS. This relationship is the same as the load current which is V naught by R. In a dc to dc converter, the output voltage divided by the output resistance decide the output current and output current in this converter is identical to IL or the inductor current. Now, if you add, combine these two you get the current ripple in the inductor. It is now a function of TS by L by R and multiplier of 1 minus D or what it says in other words that the switching frequency determines the current ripple. The natural time constant inversely determines the current ripple and 1 minus duty ratio directly relates to the current ripple.

(Refer Slide Time: 43:33)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

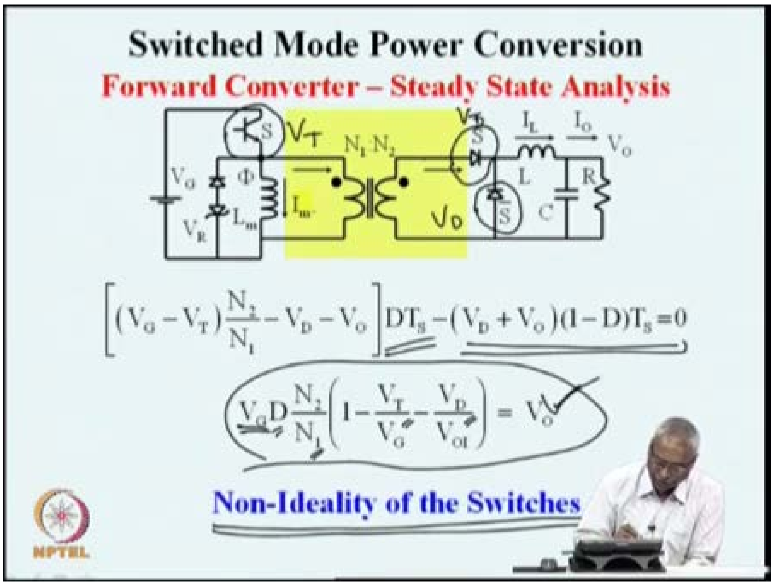
$$\frac{\Delta I_L}{I_L} = \frac{(1-D)}{(L/R)} T_S << 1 \qquad T_S \ll \frac{L}{R}$$

Condition for Low Ripple Curren

Switching Period T_S << Circuit Time Co

If current ripple has to be small, we need this quantity to be very much less than 1 and that is obtained by getting this dominant ratio. Here, TS has to be very much less compared to l by R. If TS is very much less in comparison with the circuit time constant l by R then, in such a converter you will find the current ripple in the inductor will be negligible.

(Refer Slide Time: 44:05)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$\left[(V_G - V_T)\frac{N_2}{N_1} - V_D - V_O\right]DT_S - (V_D + V_O)(1-D)T_S = 0$$

$$V_G D\frac{N_2}{N_1}\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_O}\right) = V_O$$

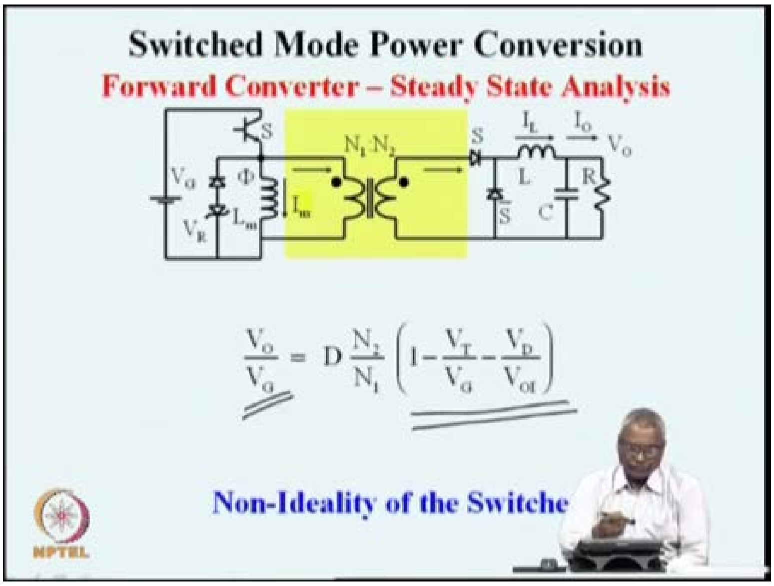
Non-Ideality of the Switches

Now, just as we have been doing in all the other converters, it is only a matter of keeping account of the various voltage drops, if we wish to know the non ideality of the switches. The switches have a voltage drop. For example, this switch will drop by voltage of VT whenever it is on. Whenever it is off, no current is flowing through that and this switch whenever it is on, it drops a voltage of VT which is VD in one direction and this switch drops a voltage of VD in the other direction during the off time.

So, all the voltage drops in the converter. If we neglect all the other things, you will find that the volt second balance on the inductor is determined by VG minus VT which is the voltage across the transistor, the difference between them is now across the transform primary. So, the primary voltage into N2 by N1 will be the voltage across the secondary. From that, you subtract one diode drop VD and then on the other side is voltage V naught. So, you subtract another V naught. So, this quantity, this is voltage applied across the primary for the on duration.

Similarly, the voltage applied across the secondary during the off duration across the inductor during the off duration. So, from this it is possible to relate VG in terms of V naught. VG is now a function of V naught through several variables. They are duty ratio, turns ratio N2 by N1 and then the conduction ratio of the transistor. Similarly, conduction ratio of the diode VD by ideal output Voltage. So, this is the non ideal performance of an isolated transformer which has a voltage drops across the switches.

(Refer Slide Time: 46:10)



Switched Mode Power Conversion

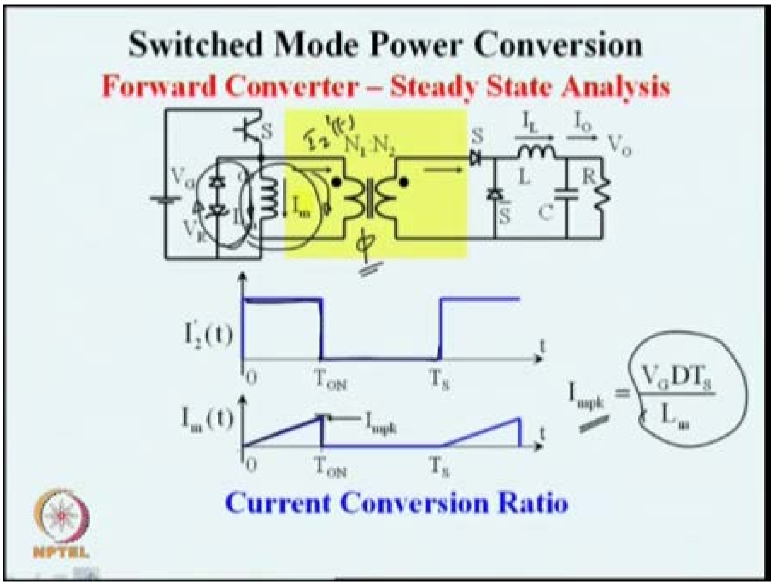
Forward Converter – Steady State Analysis

$$\frac{V_O}{V_G} = D\frac{N_2}{N_1}\left(1-\frac{V_T}{V_G}-\frac{V_D}{V_{OI}}\right)$$

Non-Ideality of the Switche

This quantity can be simplified, so that the ratio of this voltage is the ratio of this quantity 1 minus VT by VG minus VD by V naught. This represents the non ideality of the switches.

(Refer Slide Time: 46:30)


Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$I_{mpk} = \frac{V_G D T_S}{L_m}$$

Current Conversion Ratio

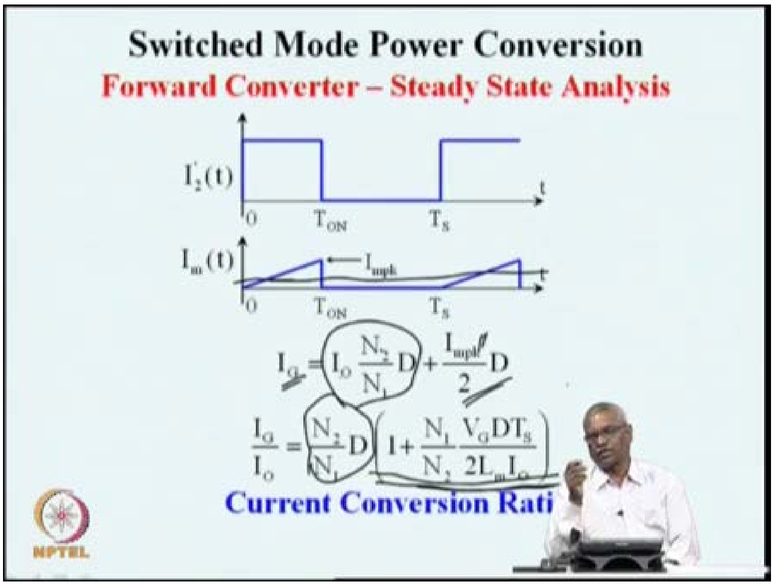
Now, we can try to see what happens to the current conversion ratio. See, earlier all the converters that we looked at, the current conversion ratio did not change at all because we have never come across up to now any converter which has a shunt non ideality. We had a series non ideality of switch diode resistance resistance resistance and so on but we had not had a trans converter which had a shunt non ideality. Forward converter is a first converter which we come across which has a shunt non ideality which is I m. On account of that, this I2 dash T will be the same. I2 dash is the secondary current. I1 dash is the primary current I naught. I naught is what is flowing through that.

If you reflect to the primary you get a steady current of I2. This is what is flowing in the idealized transformer but the magnetizing inductance we have separated as a separate process. The establishment of flux in the core is decided by a certain current in the transformers. We have defined all those currents N1 I1 minus N2 I2 as the net magnetizing ampere turns. The net magnetizing ampere turns divided by the flux density is the net net ampere. Net magnetizing ampere turn is divided by the reluctance is the net flux. Now, if you see the magnetization process because of the positive voltage is applied to the transformer VG during the on time V transformer magnetizing current increases and corresponding to this I m peak, the magnetizing current peak, certain amount of flux is established in the core.

Then, when we switch this off this magnetizing current comes to 0 because this has been switched off but the inductor current can never come to 0. The switch current can come to 0 because switch has no associated stored energy. So, when this current comes to 0 and if the inductor current is continuing where does the current go? It has a path here through this and then back here. So, you see that because the main switch has completely switched off, it is not supporting any energy in the inductor. Inductor finds an alternate path which can keep the energy flowing or will conserve the energy in the core and this will be the path for that.

So, if we now write the equations for the primary current I m it is this; VG divided by 1 m multiplied by the on duration DTS. If this is the volt second balance divided by mutual inductance, what we have is the peak magnetizing current seen in this picture. But, now during the off time the current through the inductor continues to flow through the demagnetizing circuit. In the demagnetizing circuit the voltage is constant because it is made with the zener.

(Refer Slide Time: 49:54)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$$I_G = I_O \frac{N_2}{N_1} D + \frac{I_{mpk}}{2} D$$

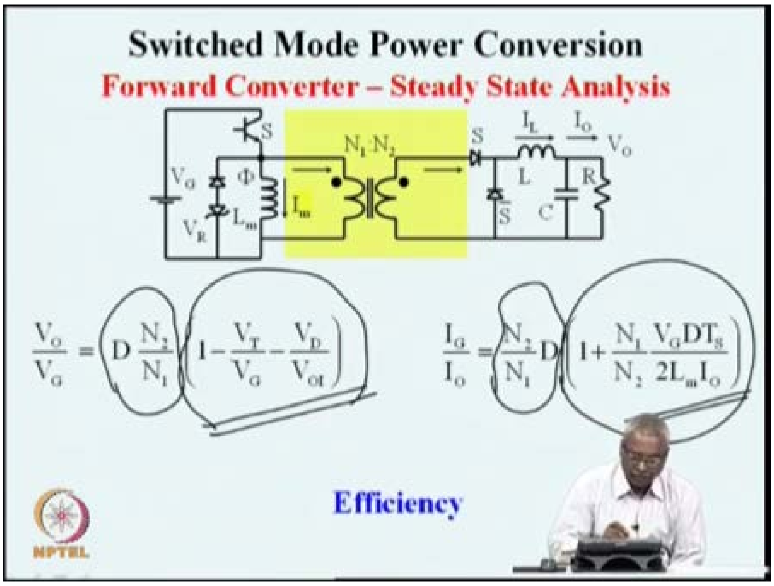
$$\frac{I_G}{I_O} = \frac{N_2}{N_1} D \left(1 + \frac{N_1}{N_2} \frac{V_G D T_S}{2 L_m I_O} \right)$$

Current Conversion Rati

So, during this demagnetizing interval, the voltage remains voltage across the transformer remains constant. So, that will result in the flux being reset gradually. So, in the current conversion ratio because this is the additional current which is been drawn from the source to the magnetize the transformer. The actual input average current is the load current reflected I naught N2 by N1 into D and the average contributed by the peak magnetizing current of the transformer and this is very easy to find the area of contribution by this is I peak into DTS, which is this duration there is a total ampere turns divided because the average value is one half of this current is a triangle one half and this base and that multiplied by D will be the actual reflected current on IG.

So now, if we find the ratio of IG to I naught; it has the ideal gain N2 by N1 into D. But now, all the other variations have been combined into a single correction term, which is 1 plus N1 VG DTS by L2 to L m I naught. So, from this you can see several things. For example, if supply voltage is high VG is high then, you will find that I g's component half magnetizing current is high. So, also duty ratio and switching time T all these quantities directly relate the average input current. On the other hand, there are four other quantities which indirectly determine the magnetizing current N2 two times L m and then multiplied by I naught; this division of I naught is to normalize the magnetizing current with reference to I naught. So, this relationship is the current conversion ratio and because the converter has non idealities both in the shunt sense and in the series sense, you see that there are now two correction factors.

(Refer Slide Time: 52:09)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

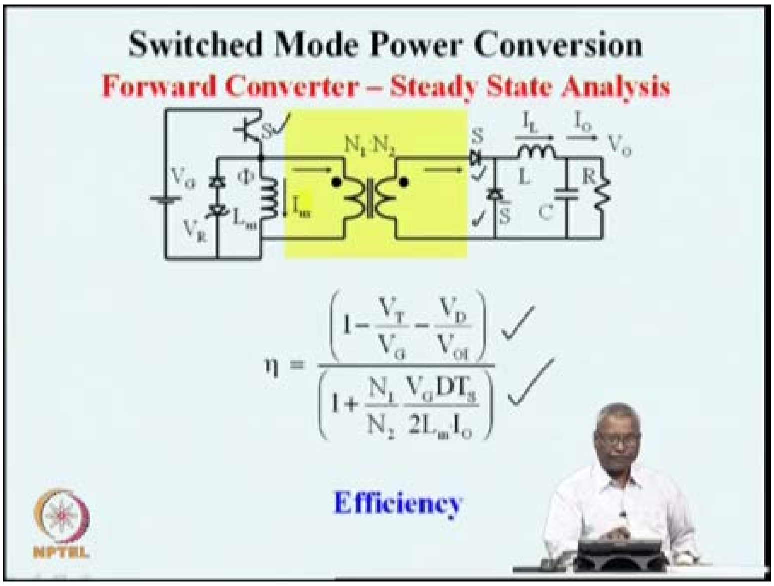
$$\frac{V_O}{V_G} = D\frac{N_2}{N_1}\left(1-\frac{V_T}{V_G}-\frac{V_D}{V_{OI}}\right)$$

$$\frac{I_G}{I_O} = \frac{N_2}{N_1}D\left(1+\frac{N_1}{N_2}\frac{V_G D T_S}{2L_m I_O}\right)$$

Efficiency

The shunt non ideality has a correction factor because of this magnetizing current. The switch non ideality has a correction factor as shown here. The ideal part remains the same. Ideal part remains the same. So, we can say that this is the fraction by which the voltage conversion has changed from 1. This is the ratio by which the current conversion has changed from 1. What you notice here is that, the dc current on account of the magnetization current is going up on the input side. The dc voltage on account of the several switches is going down on the output voltage. The efficiency is now the product of these correction terms.

(Refer Slide Time: 53:09)



Switched Mode Power Conversion

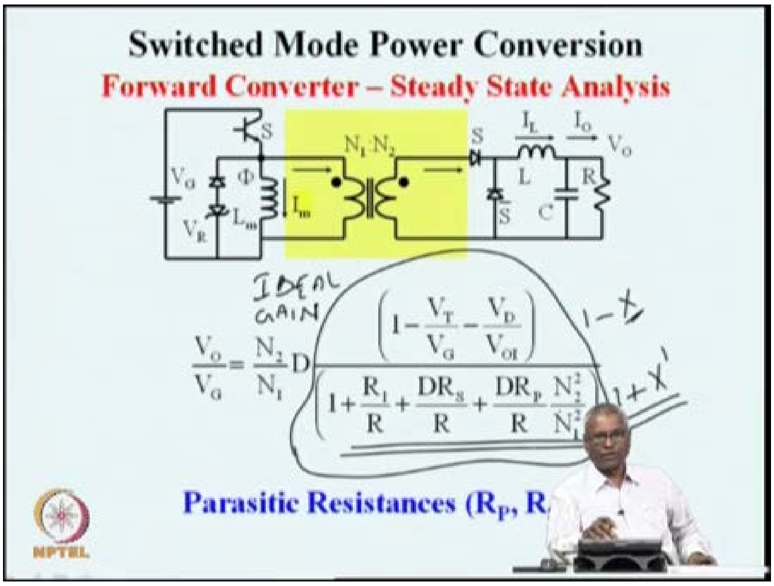
Forward Converter – Steady State Analysis

$$\eta = \frac{\left(1-\frac{V_T}{V_G}-\frac{V_D}{V_{OI}}\right) \checkmark}{\left(1+\frac{N_1}{N_2}\frac{V_G D T_S}{2L_m I_O}\right) \checkmark}$$

Efficiency

You will find that the efficiency is now a correction factor because of the switches. The switches contribute a correction factor 1 minus VT by VG minus VD by ideal output voltage. The magnetizing current of L contributes to 1 plus N1 by N2 VG by 2L m DTS by I naught. So, efficiency is this composite number here.

(Refer Slide Time: 53:38)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

IDEAL GAIN

$$\frac{V_O}{V_G} = \frac{N_2}{N_1} D \frac{\left(1 - \frac{V_T}{V_G} - \frac{V_D}{V_{OI}}\right)}{\left(1 + \frac{R_1}{R} + \frac{DR_S}{R} + \frac{DR_P}{R}\frac{N_2^2}{N_1^2}\right.}$$

$1 - x$

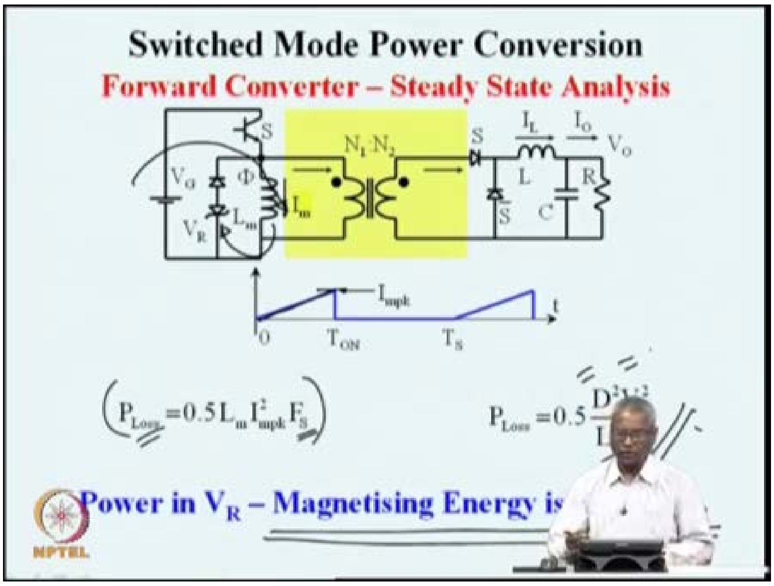
$1 + x'$

Parasitic Resistances (R$_P$, R

If there are resistors on the parasitic paths, for example, primary has a resistance. Secondary winding of the transformer has a resistance and the inductor has a resistance. If such a resistive paths are there, all that we have to do is only to write the volt second balance equation again and keeping in this account, the drop in voltage on account of R P R S R L and so on. Once that is done, you will have additional terms which are contributing to the efficiency being less than 1.

This numerator quantity is less than 1 minus some quantity and the denominator is 1 plus some quantity. In an ideal converter, this x and this x dash both are 0 but in a real converter this has some effect/penalty; the output voltage drops because of the series voltages of the devices. There is a similar penalty on account of the conducting paths all over the place, so this is in the denominator with 1 plus X dash. So, whatever is the additional term other than the ideal gain; this is our ideal gain. N 2 by N1 multiplied by D duty ratio. All the other terms are contributing to deterioration of voltage gain and deterioration of current gain.

(Refer Slide Time: 55:22)



Switched Mode Power Conversion

Forward Converter – Steady State Analysis

$P_{Loss} = 0.5 L_m I^2_{mpk} F_S$

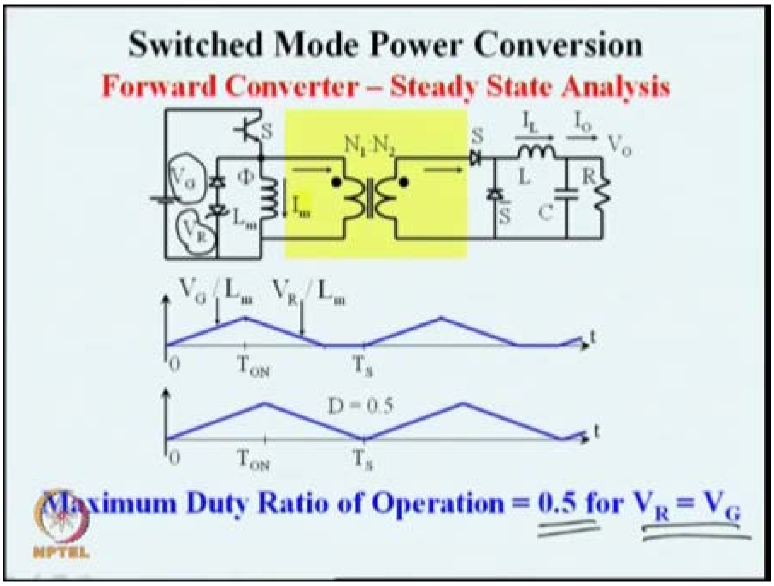
$P_{Loss} = 0.5\frac{D^2V^2}{L}$

Power in V_R – Magnetising Energy is

If you put both of them together, what you get is the efficiency in the power converter. Then, we have the loss in the power converter also can be found out because every time the switch is turning on, certain amount of energy transfers from the source to the inductor from here to this point. But then, during the off period this energy is completely transferred to VR or the zener diode. Whatever energy was first built up 0.5 Lm I m P square multiplied by switching frequency; this is the total energy. It has been taken from the source. Every cycle this is a total energy but in every cycle 0.5Lm Im square is taken in. In one one second, there are FS number of cycles.

If you multiply these two, this is the power loss or the energy loss per second which is equal to the power loss. This can be modified and put in slightly different form. This relates how much energy loss is there in the circuit on account of the magnetizing inductance, switching frequency, operating duty ratio, operating source voltage. If all these numbers are known, it is possible to find out the power loss in the device.

(Refer Slide Time: 56:46)



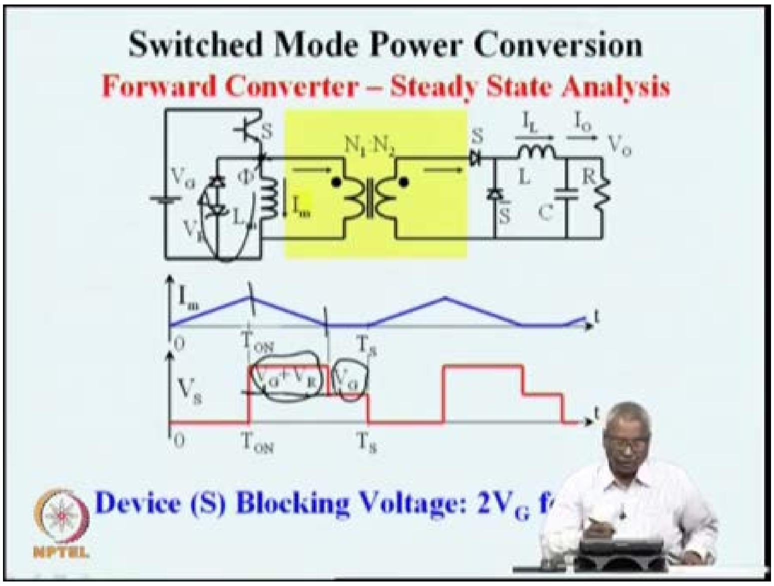
Switched Mode Power Conversion

Forward Converter – Steady State Analysis

Maximum Duty Ratio of Operation = 0.5 for $V_R = V_G$

Now, what we have done is we have introduced here reset voltage against supply voltage of VG. In most converters, the preferred value of VR is the same as VG. We tend to make designs where VR and VG are equal. In such a situation, the core flux increase and the core flux decrease; will take the same time if you do not want the flux to build up. So, in such a case the maximum duty ratio of operation is limited to 0.5 in forward converters.

(Refer Slide Time: 57:27)



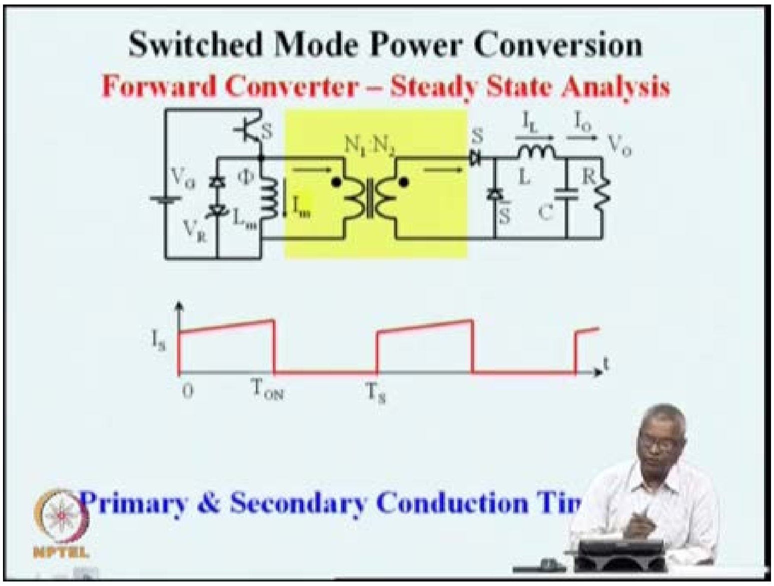
Switched Mode Power Conversion

Forward Converter – Steady State Analysis

Device (S) Blocking Voltage: $2V_G$ f

The voltage wave form across the switch if you see during the time the flux is building up, the voltage across the switch is 0 because it is conducting and during the off time this device is losing its energy in the zener. So, the voltage at this point is VG minus minus V R or total of VG plus VR; that is additional voltage during the reset time. After the reset is over, there is no current in the inductor. The voltage at this point is the same as the voltage at this point which is minus VG which is this quantity. So, you can see that one of the important consideration is that during the off time the device is experiencing double the voltage.

(Refer Slide Time: 58:18)

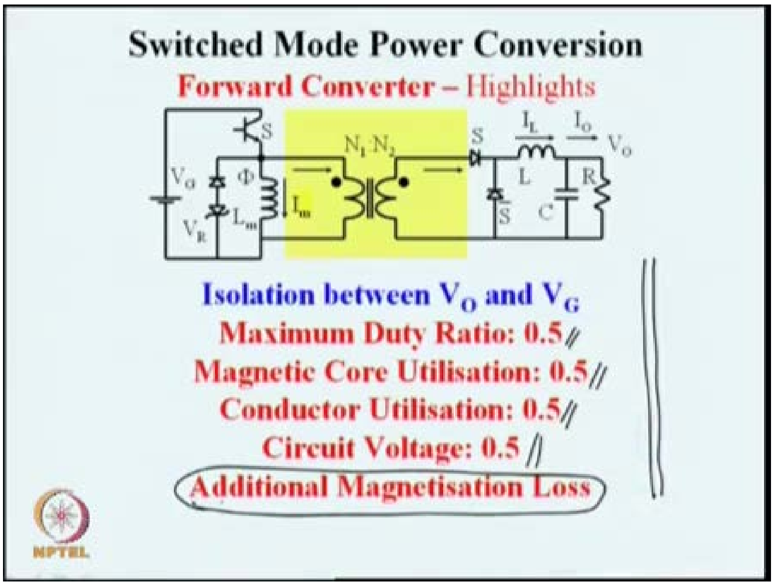


Switched Mode Power Conversion

Forward Converter – Steady State Analysis

Primary & Secondary Conduction Tir

On account of this, the primary and secondary conduction times are forced to be equal. (Refer Slide Time: 58:29)



Switched Mode Power Conversion

Forward Converter – Highlights

Isolation between V_O and V_G

Maximum Duty Ratio: 0.5

Magnetic Core Utilisation: 0.5

Conductor Utilisation: 0.5

Circuit Voltage: 0.5

Additional Magnetisation Loss

You cannot have a forward converter whose duty ratio is more than 0.5. So, what we will do now is we will conclude at this point with one type of forward converter where maximum duty ratio is limited to 0.5. Magnetic core is utilized only in one direction. Again, 0.5 on account of that the conductors are utilized only half the time, because the windings are carrying the current only for 50 percent of the time.

The circuit voltage is limited to half, because the maximum voltage on the device is VR plus VG which is 2 VG. So, all these on every count a forward converter is only half utilized in effect half, half, half, half; only one sixteenth of the potential utilization and further there is an additional magnetization loss. We will stop here with this, and then in the next lecture continue with many other isolated converters, where many of these problems are addressed.