Switched Mode Power Conversion
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Lecture - 35
Regulation of Multiple Outputs – I

Good day to all of you. So today, we continue from where we left off from the last class remember that we were discussing the topic of trying to regulate multiple output windings. So, most of the power supplies generally have more than one winding, it could be a 5 volt winding, 15 volt plus minus 15 volt supplies, 3.3 volts. So main various of these standard voltages, which are needed to drive many of the control boards or some other applications. So, in general you will have 3 to 5 isolated power outputs, but you could you can only control one of the outputs through the duty cycle control.

So, we were discussing that what do we do with the other outputs, which are unregulated, and how do we regulate them. We discussed couple of methods; one of them was to put a linear regulator at the output of the unregulated power output, power supply output. The linear regulator will have a small differential between its input regulated input and the final output, and this small differential voltage is what is going to cause a power loss.

However, we discussed that we mentioned that we would put the linear regulator in those windings, which are processing lower power, the compared to the control winding which is processing very high power. The other method was to replace the linear regulator with a non isolated dc, dc converter like a buck converter, which has a local control, which is supplied by either the output voltage or the unregulated voltage of the power supply output, there by trying to achieve regulated final output. We shall today discuss 2 other methods.

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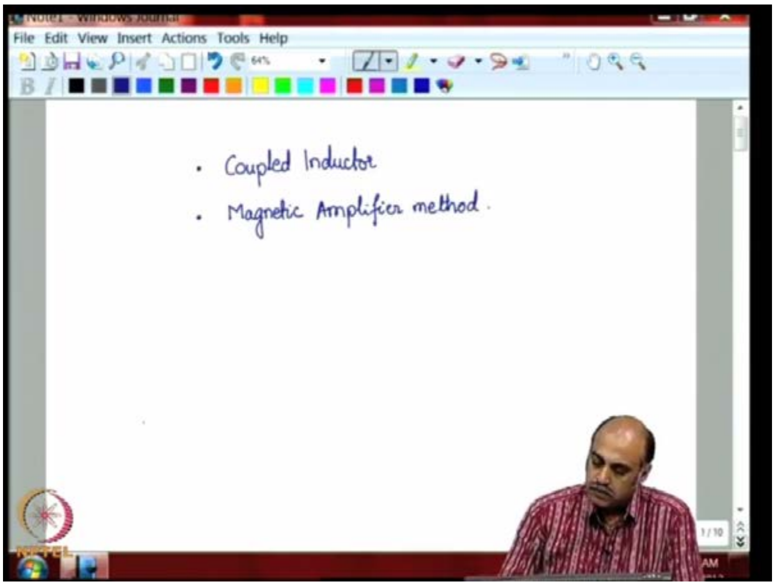

The method of coupled inductor and another method the method which is normally called the magnetic amplifier method. So let us take these methods one by one, and try to understand how they operate. Let me take the example of a forward converter, isolated forward converter.

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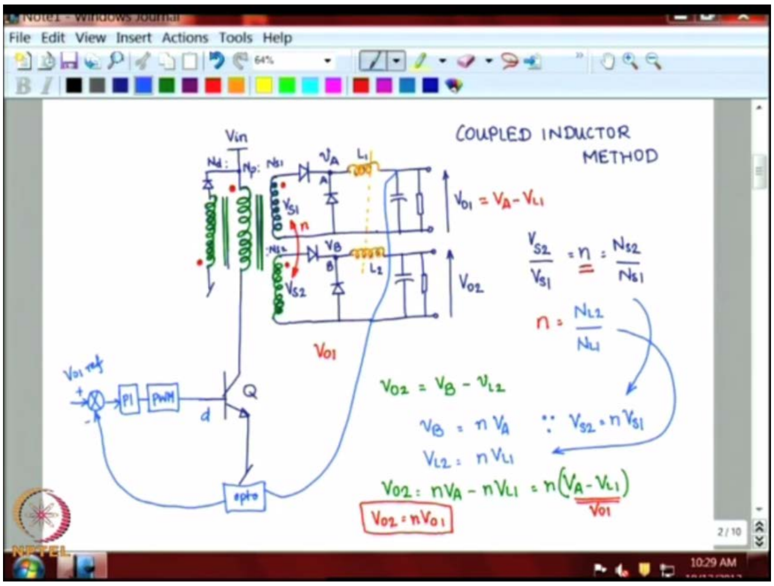

We have the supply V in there is a forward converter transformer, which is connected in this fashion to a power semiconductor switch. I am indicating the power semiconductor switch by a B J T; however this B J T could as well be an M O S F E T or an I G B T.

Now, the forward converter has a demagnetizing winding which is connected in this fashion is coupled with the primary, however the dot polarities are opposite in this fashion. And there are other windings, now these are the secondary windings that I will be drawing winding 1, winding 2 and so on there could be many other winding, just now for the purpose of discussion. Let us say that we have 2 windings which mean 2 isolated power supply outputs.

Now, the dot polarities for these are in this fashion and they are then connected to the standard bug type topology, because forward converter is a bug derived converter. So this is one of the outputs, and we shall call as V naught 1, the other output similarly, another bug derived topology to that secondary output connected in this fashion. And with some load resistance and we shall call that one as V naught 2 V naught 2. Now, under the normal conditions the, the primary and I am going to mark that in a different color, so these windings will all be on the same core. This will be on the same core and so also the demagnetizing winding in this fashion.

So, all the green colored windings represent one transformer, the forward converter transformer. Now the inductance I am going to represent in another color, now this inductor and this inductor are wound on the same core they are coupled. So, these two are coupled, and that is why it is called the coupled inductor method, coupled inductor method.

So, let us do some more naming this is secondary V S 1, this is secondary V S 2, I will call this as point A, and the voltage here is V A, I will call this as point B and the voltage here is V B. This is inductor L 1 and this is inductor L 2 they are coupled, so in the design of this particular coupled inductor. Let us make the following put the following constraint let us say V S 1, so let us say V S 2 by V S 1 is equal to n, what I mean is this ratio to this ration is n, do not confuse it to the ratios between secondary is.

So, let us say if this is the primary winding, this is the secondary winding, this is the demagnetizing winding, and this is the secondary winding 2, which is N S 2 by N S 1. So this ratio is the ratio between these two windings n. So, we will try to maintain the same ratio n even for the inductor windings these two inductor windings meaning if, if you have N L 2 by N L 1, where N L 2 is the number of turns on inductor for the inductor L 2, and N L 1 the number of turns on the inductor L1.

So, the idea here is that we try to maintain the ratio of the secondary inductors, windings and the ratio of the secondary windings themselves to be same. The inductors are coupled with this ratio the secondary windings are coupled with the same ratio that is the basic concept here. And now, now let us say that one of the windings is controlled and only one of the winding needs to be regulated by the coupled inductor method. Now, let us take V naught 2, V naught 2 is actually V B minus V L 2, V naught 2, the voltage here this voltage minus the drop across the inductor V L 2. Now, what is the relationship between V B and V A?

Now, V B is equal to n times V A, because V S 2 is equal to n times V S 1 this is coming from here. And what is the relationship between V L 2 and V L 1? V L 2 is equal to n times V L 1 and that is coming from this. So, therefore V naught 2 equals n times V A minus, n times V L 1 which is equal to n times V A minus V L 1 by substituting for V B this here, and for V L 2 there so that you get n V A minus V L 1. Now, this is nothing but V naught 1, we may write here V naught 1 which is equal to V A minus V L 1, V A minus the drop across L 1 would be V naught 1. So that is what we are indicating here therefore, this becomes V naught 1 and overall V 2 is equal to n times V naught 1.

So, it is an interesting relationship, now let us say we control one of the outputs through duty cycle control. Then the other output is related only by a fixed physical parameter which is the winding ratio and automatically the other also be controlled, because of the coupling, so this basically the concept. So if you feedback this through to the opto into the control circuitry here, plus minus, we have a V naught reference from which V naught reference specify that it is V naught 1 reference, then the output of that goes through pi controller.

And then goes through P W M drive circuit to, so that the duty cycle here gets controlled by sensing of V naught 1 once sensing V naught 1, the regulated, V naught 2 and V naught 1 are regulated in this fashion by only a fixed factor n. So, if V naught 1 is regulated V naught 2 is also automatically regulated, so this way regulated output of the other winding are also achieved, so this is an interesting method. However, in practice you will not get a tight regulation as indicated by this equation to understand that we have made some assumptions inherently saying that the diodes are ideal or if they are not ideal these voltages cancel off and they do not affect the final output.

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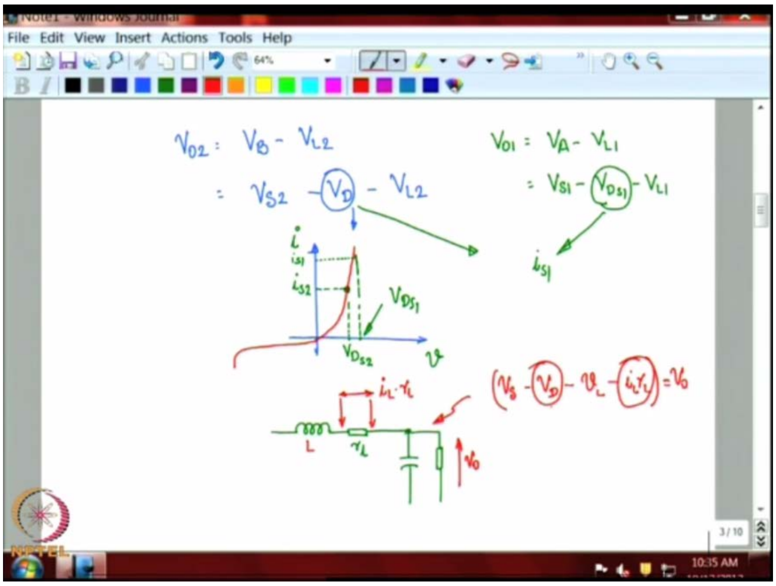

But in actuality if you see, when we write V naught 2 which is V B minus V L 2, it is actually V S 2 minus V diode drop minus V L 2. Now, this diode drop is nothing but the diode drop of this component and the diode drops of the components is actually obtained in this fashion. So if I am having the i V characteristic of this diode, of this diode static characteristic. And let us say we have the forward characteristic which is something like this for the diode. We are not so much interested in the reverse characteristic for now, now depending upon the amount of current that flows.

So, let us say we have some particular amount of current i s 2 that flows the operating point, I have wrongly named the axis I am going to correct that this is this is the V and this is the i, and that is the sum current i s 2 flows here. The voltage across the device V D S 2 is at this value, now for the first winding which is given as V A minus V L 2, V L 1 this is V S 1 minus V D of s 1 minus V L 1. Now this diode drop corresponds to this component here, and this component will be carrying a current i s 1 through the secondary and let us say it is higher power and therefore, higher current.

So, it is somewhere here i s 1 and its corresponding diode drop V D S 1 will be much different from V D S 2. And therefore, and therefore, there will be a mismatch between these values they will not exactly cancel as we have put the equations like this. So, if you include into this those V D drops, you will see that there is cross mis regulation which occurs, and it will not the tightly regulated like this equation the idealized equation as shown here. So I just indicating to you what is the effect come in due to just one component, so the voltage drop across V A and also across L 1 vary what we have not considered here further is the resistance winding resistance of the inductance.

So, if this is a small value of resistance due to the winding of the inductance, these two would cause an non ideal term to come in the voltage drop across this is nothing but i L if this is L into r L. So in actuality the voltage here would be V S minus V D minus V L minus i L r L would be equal to V naught. So this term and this term are load dependant and they will be different in both the windings, so there will not be an exact match between these two in terms of the coupling ratio n.

Because of that what you could say is you will get a regulation better than not regulating and the regulation of the regulated 1 would worsen a bit compared to not coupling. However by coupling you will get a regulation in both the windings to an extent that it is better than not regulating, but not as could as the linear regulation solution as we proposed earlier. But in the linear regulated case there is dissipation so the efficiency will be slightly lesser, but in the case coupled inductor case the efficiency will be better.

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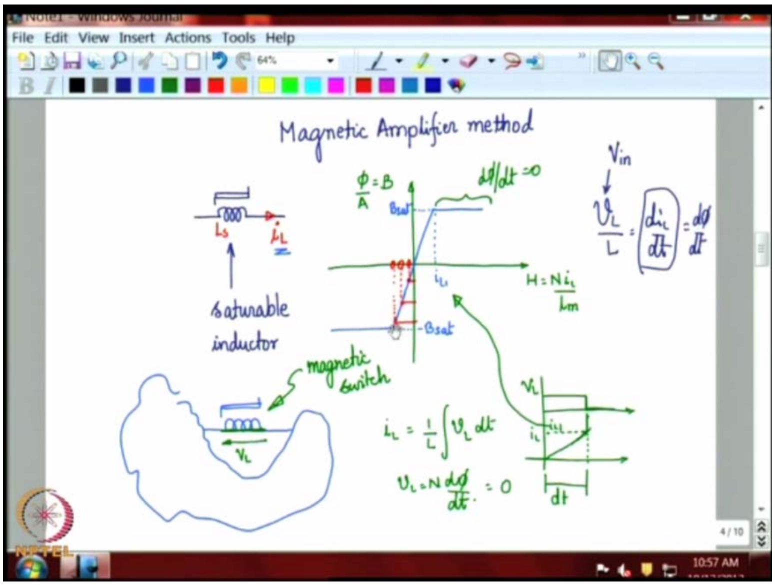

So, let us see one more technique, the magnetic amplifier technique method. Here the core principle is the manner in which you are going to saturate an inductor; we are going to put an extra inductor component. And will call that one as a saturable inductor that is we will allow that to saturate indicated like that so this is called a saturable inductor, we would like to saturate under certain conditions. Now, if you see that we have a current i L that is flowing through the inductor we will call this as L S the saturable inductor. If you look at this inductor its static characteristic called B H curve, B is called the flux density which is equal to phi flux by the area of the cross section of the core. And on the x axis, we put H the magnetic field, which is given by N i L by mean magnetic length the path length.

Now, if you take the B H curve like that, you may have already seen or studied earlier the B H curve for all the magnetic material is in this fashion. So, this area is the area where the core as saturated both here in the positive side and the third quadrant around here this is the linear operating region. And you see that when it traverses in one direction it takes this path, and when it is coming down it takes the other path and this is called hysteresis effect. Anyway hysteresis effect is only going to cause loss, this is a kind of a low pass filter effect we will try to understand this without the Hysteresis. So, what I am going to do is erase this and make much simpler curve, so this is the saturation region awake more idealistic to understand it is easier and this is the B H curve. So beyond this it will saturate let me call B sat, B sat so what it basically means is if you gave i L if you give a value of current i L greater than i L 1, then this inductor will saturate.

Now, to this inductor if I now apply a voltage to this inductor if you now apply a voltage like that give some circuit. And if that voltage is V L then the current i L is given by 1 by L integral of V L d t, and if V L is a constant you will see that the current is increasing V L is constant, V L current i L will increase in linear manner, it keeps on increasing and as i L keeps on increasing till it reaches let us say a limit i L 1. The moment it reaches this limit, the core saturates it will not no longer go like that in fact at that point, it will start taking a point in this fashion the current will steeply increase the voltage across the inductor will 1 it becomes 0, because there is no d phi by dt.

Thus the voltage across the inductor is also n d phi by dt, and in this zone d phi by dt equals 0. And therefore, the voltage across the inductor become 0 this falls down and because falls down the current will shoot because the external circuits is 0 impedance, 0 voltage and if it is not limited the current can shoot. So, we say that at this point the inductor as saturated the voltage across it, as become 0 as it is now a short circuit it has though the inductor as not there. So this is the principle we will be using we will make a inductor to provide impedance for some period of time.

Let us say dt, and then make it saturate and make it into a plain conductor during which time it will not act as an impedance. And it will allow the power, the power to, the voltage to pass along to the other side, so basically the inductor is being used as a magnetic switch. Therefore, it is called a magnetic amplifier, and will see how we will use this concept that we just discussed in the context of our converter regulation.

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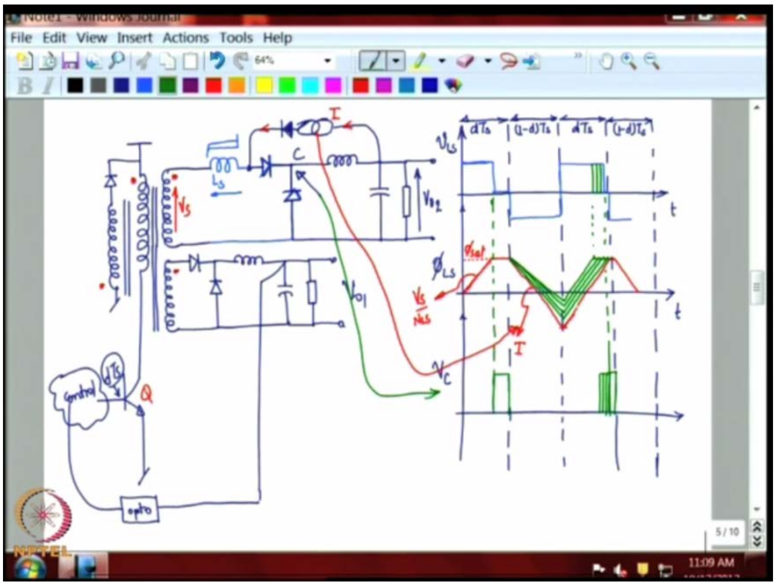

Let us take let the typical forward converter, so let we put in this circuits switch; let me here we have a demagnetizing winding which will included. Now, let us say we have 1 winding and to that winding, we now include the let us say we have the other winding which is the regular controlled winding with the standard buck derived circuit. And this is actually the one that is fed back and use for control. Now, the other unregulated winding is to be controlled in the following manner using saturable inductor, now here let us include the saturable inductor L s and then we have our regular circuit diode. So, this is; this is the unregulated winding V naught, this is V naught 1 which is regulated. Then one more item this point you are going to heal in some controlled current source which is been taken from the output, and fed in here we may also put a diode here such that it is only in 1 direction.

So, this is the circuit that we need to discuss now how does this operate, now let us say the switch Q. So Q is ON, when the Q is ON, the dot end becomes positive the dot end here becomes positive and at this point just, because the inductor was freewheeling, but the inductor here is presenting an impedance. So, there is a voltage drop across this therefore; this voltage does not carry forward and appear here to turn off this diode. So the voltage drop across this is entirely matched by this supplied voltage the inductor is continuing to freewheel.

However, because of this voltage there is a current flow where there is a voltage across this and current flow in this direction which starts flowing in this fashion, in this path you may ask how is it going against this diode. If the inductor current this freewheeling is let us say for example, 10 amps and if this, this saturable inductor current is around 1 amp, then it is n minus 1, 9 amp flowing in this direction. So, as long as this current is less then this inductor freewheeling current, you will have a path through this to reach back again here. So as this inductor current is increasing at some point this will saturate the moment which saturates this becomes a short, and once this becomes a short this voltage appears at this point and reverse biases the diode. Then it becomes a normal buck converter operation where the power is put into this inductor charging it up.

And then when this Q turns OFF, when this Q turns OFF this dot end becomes negative and the non dot end becomes positive, the inductor is freewheeling in this fashion. This diode is off this dot end is positive there should come in here and turn on this diode, now as for this inductor is concern through this inductor there will be a current flow in the reverse direction. Look at this source from the output there is a dc current, a dc current which is made to flow through in this direction this is off therefore, it will flow in this direction and back again to its negative point.

So, it will start flowing in this manner during the time when this is off. So when the current is flowing in this reverse direction through the saturable inductor, it is bringing down the flux within the core. When the current is flowing in the negative direction in this area it is bringing the inductance flux value negative, lower somewhere here. So, let us say the current as current value is up to this point if the current value negative value is in this point then the inductor would have reached here. If the negative value of the current is there, then the inductor flux would have reached here or if it was here the inductor flux would have reached here. So, you can make the flux value within the core to be any were on the locus it could be any flux value.

Now when you give a positive voltage, when you give a positive voltage this is turned on this is positive and the voltage across the inductor is positive the same value V in, n times into V in. The current rate is decided by voltage across the inductor by L will be di l by dt. If this is fixed then the current rate will be more or less fixed, of course this is; this is got from the unregulated voltage V in. So more are less the current rate will be near about h a fixed current rate, but the more important point is that the flux rate also is connected to the current rate. So flux will also increase from the point it was left previously during the off state, and keep continuing from that point to saturation. So note that if the inductor are brought to much lower value with the same current rate it will take a longer time for it to go up to reach saturation.

If the inductor is brought down to a value here it will take that much longer time to reach saturation. So, which means that, the inductor will present an impedance for a longer time in a period to the input source voltage, which means that freewheeling for a longer time, which means in the standard buck converter to notation. This will be the buck converter, the buck divide converter so this portion will be in the off time portion. If the inductor saturates less then it will take brought to value relative relatively higher up to the origin, then it will take a shorter time to reach saturation.

And therefore, this will lose its inductance property sooner and the voltage will come across here sooner and on time is more. And therefore, you have a modulation there, which can be used for adjusting V naught 2 locally here independent of this duty ratio, so that is the principle we are trying to follow. Let, let us understand some waveforms what is happening, let me draw some waveforms for you. Consider give some space this is your V naught 2 now let us have the voltage across V L S the voltage across that and let us also write the flux waveform in the core of the saturable reactor.

And then let us also see what is the voltage that is appearing at this point, and will call that point c and voltage at point c. So let us absorb these three, now let us divide the entire into time segments during d t s the switch Q is on during 1 minus d t s the switch q is off. So during d t s, and shall mark that portion 1 minus d t s and so on repeats d t s 1 minus d t s. Now this will corresponds to d t s here, what you apply as the signal to the transistor Q. Now, let us say that the moment the transistor Q is turned on, the voltage across V L S the arrow direction shown has taken some positive value like that. And let us say, the flux in the core was 0 to start with meaning we are here this is the point where we are beginning.

And the flux from here starts increasingly linearly, so let us say the V L S is constant starts increasing in this fashion at some point here its saturates let me call that as phi sat. And the rate at which it increase is whatever voltage you have V S, V S divide by N L S, where N L S is a number of turns on saturable inductor that is the rate at which it increase. The moment it saturates here the inductance loss its inductance property, the voltage across it becomes 0 and some there like that.

So, this continues still end of the on time, at which point the Q is switched off, the moment Q is switched off. The voltage goes negative, because the dot end becomes negative and the non dot end becomes positive this is freewheeling, and the voltage across the inductor starts taking an negative value. And this negative value is coming due to an application of this the negative current flowing through this negative dc current, and this dc current is flowing through opposite direction there has to be a negative voltage appearing across it.

And the effect of the negative flowing through that is to pull the flux down, the flux is linearly decreasing it is getting pulled down to this value to some level. And now, so let us say it is gone lesser than 0 and now you again switch on Q; switch on Q, which jumps positive. And this increases at some rate it has to go from negative earlier 0 to phi sat now this is the same rate these two are parallel lines, this has to go saturation this will take a longer time to saturation and it becomes zero here and so on and this will start coming down.

Now, this rate at which is coming down is controlled by the current source rate i here, so that this current source will actually determined this fall rate. So therefore, you can bring it to whatever level you would like to have the inductor come down to either here or here or here or here. And then from there this will go parallel to this line, this will be parallel lines because here the voltage is determined by the output. So, you could get actually different point of times when the inductor can actually go down, go to 0 like. So, now let us look at the, output wave shape you see the output at V C at V C if you look at here, it will be V S minus this and when the inductor saturates during this time, that voltage whatever V S voltage come down to C.

So at that time the inductor saturated, there is a voltage across C and so also here at this time inductance is saturated, there is a voltage across C. And if you vary the current that is allowed through the inductor to reset, you can get different voltages and then different outputs here. So this is the basic concept, we will study this further in the next class, and try to evolve a circuit in the next class.

Thank you.