Power Management Integrated Circuits
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Lecture – 97
Dynamic Voltage and Frequency Scaling, Single Inductor Multiple Output (SIMO) DC-DC Converter

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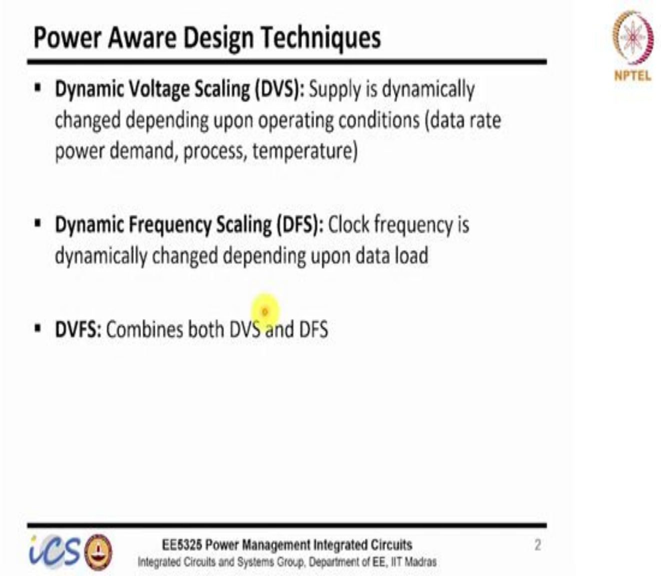

So, there are some power aware design techniques which requires specialized converters. So, one is your dynamic voltage scaling, which is quite common in processor and then dynamic frequencies scaling. And if you combine both it becomes DVFS. So DVFS is the most commonly used technique in processes where what you do depending upon the performance requirement, you increase or decrease the voltage as well as frequency.

So, when you are running your let us say digital circuitries, you know with the voltage that delay changes. So, if you are running your processor at 1 gigahertz, you want to minimize the delay. So, you want to operate at a maximum supply and if let us say you want to run at 1 megahertz and you do not want the same voltage because now, you can afford larger delay. But if you keep the same voltage, then there are some leakages in the circuit that will be more and you know that your power in any switching circuit is CV square f. So, if you reduce the voltage, you get the square factor and now you will reduce the frequency also see you get a cubic advantage there.

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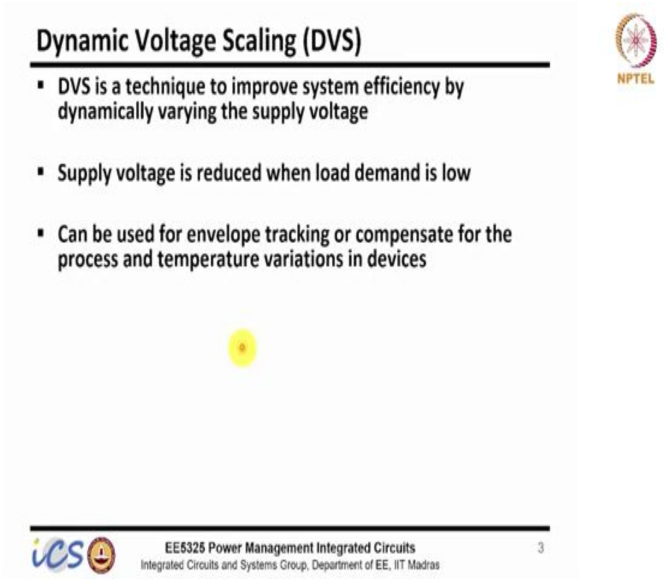

And that is why in most of the processor; if you performance reduces, we reduce the clock frequency as well as voltage ok. So, in dynamic voltage scaling, it is a technique to improve system efficiency by dynamically varying the supply voltage and supply voltage is reduced when load demand is low; can be used for envelope tracking or compensate for the process and temperature variations in the devices ok.

So, when we say process and temperature variation; so now, assume that you have designed your circuit mostly you designed at typical ok; so, but when you have to meet the spec, you have to look at the worst case. So, you want to run your circuit at let say 1 gigahertz, you want to make sure your timings are met at the slowest corner which means when you go to the fast corner your circuit is now over designed; so, you will oversize all your transistor everything.

So, you will be burning more current in the circuit and so, what do you do basically the dynamic voltage scaling, you design at a typical corner and if you have a someway to and I think we talked about this how you track the PVT, you can have varying oscillator and based on that you can. So, let us say you are able to track the process and temperature that will give you the code.

Once you have the information at what corner it is fabricated, you can change the supply voltage. So, if it is at the first corner, you can reduce the supply little bit. You will even though achieve the same delay or same timing; if it is at a lowest corner, you can slightly increase the voltage. So, that you do not need to oversize your transistors.

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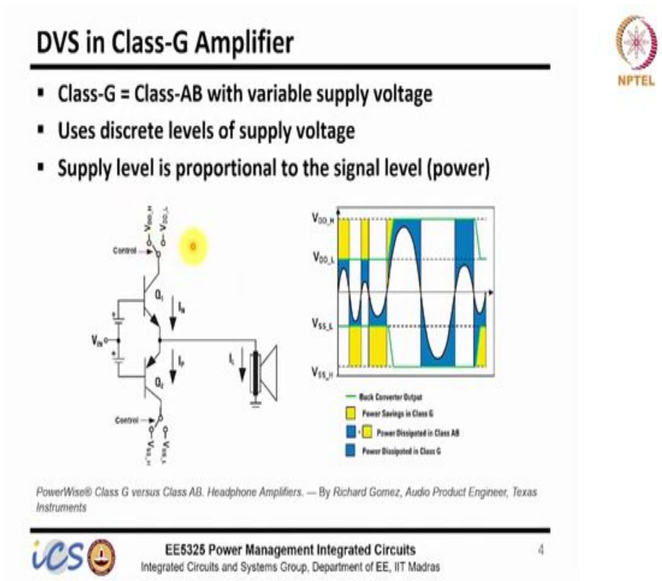

So, that is the advantage here with DVS. So, one example of DVS is class-G amplifier. So, you would have what class-H amplifier sorry class-G amplifier, there is a class-H also we will come to that and you would have at class-AB. So in the class-AB what we have actually? So, just like a LDO you have a dropout voltage; so, whatever the dropout voltage that will be a loss in your circuit. So, in the class-AB you have dropout voltage and that dropout voltage means whatever the overdrive you are using across this transistors it could be MOSFET also here it is a bipolar. So, that is lost ok. So, all these are; so, this is your Vdd. So, now if you say think that depending upon the output or input, I can vary the supply of this.

So, let us assume that your input is varying from 1 volt 0 to 1 volt or here I am using both so, you can say plus minus 1 volt ok; and depending on upon lets say this is audio amplifier. So, depending upon the volume, your input will change. So, let us say at the lower volume my input goes below 500 millivolt or so, then for when this is 1 volt. You need the supply to be more than 1 volt ok; you need some dropout across this, the collector to emitter voltage of this bipolar.

So, let us say that is 100 millivolt; so which means this should be at least 1.1 volt in order to achieve 1 volt at the output. Now, you reduce the volume and your amplitude input what are required here output is let's say below 500 milli volt which means I can keep this 600 milli volt.

So, now let us say I have two supplies at 1 volt I use this Vdd_H at 0.5 volt or below I use Vdd_L. So, 0.5 volt when it goes if you let us say you keep using 1.1 volt, the dropout it across the transistor is 0.6 volt. But, if I switched to this lets say 600 milli volt then we have a again reduce the dropout to 100 milli volt; so, you can reduce the losses in the circuit; so, efficiencies will be much higher. Now, how many supplies you use? It will depend that will define your average efficiency.

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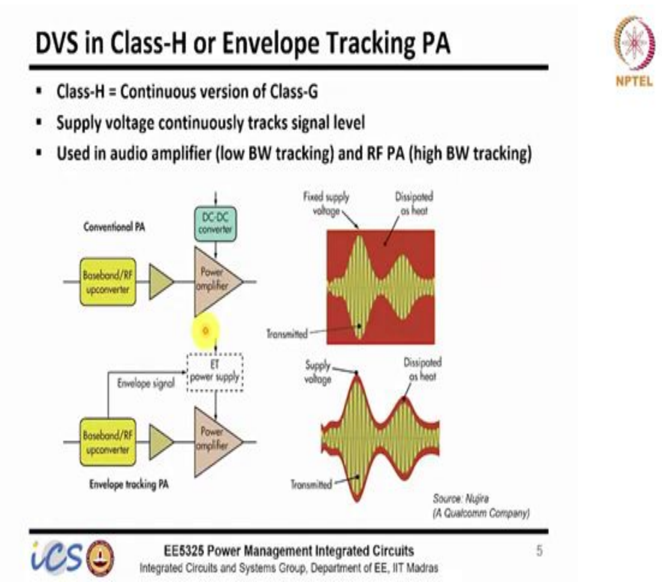

Now, there is another category which is called class-H and it is used the concept is used in the envelope tracking of power amplifier in most of your RF transmitters. So, now, this is your power amplifier and this is your DC-DC converter. If I keep the supply fixed again all these red portion, you see that is the loss and this is my signal; see if I track my supply with the signal like this and whatever dropout voltage you have defined let us say 100 millivolt always keep your supply only 100 millivolt higher than loop input which means your supply should be tracking the envelope of your signal. If you can do that, then your losses will be reduced and you can see a huge advantage actually your I mean instead of let's say you are getting a 60, 50 or 60 percent there, you can achieve 80 percent efficiency in the other case ok.

So, or in a other way you can think about in terms of LDO, if you keep the dropout voltage fixed irrespective of your output voltage, then your losses will be fixed; we can always achieve a high efficiency no matter what the voltage is. But if you keep the inputs supply fixed there at a lower supply voltage, dropout will increase your efficiency will drop. See you are doing nothing but regulating the dropout voltage by tracking your dropout with the shape of the signal that is all you done there and this is called class-H this is a another version of. So, class-G is more like a discrete in nature and you can use more level of supplies if you want, but class-H is a continuous ok.

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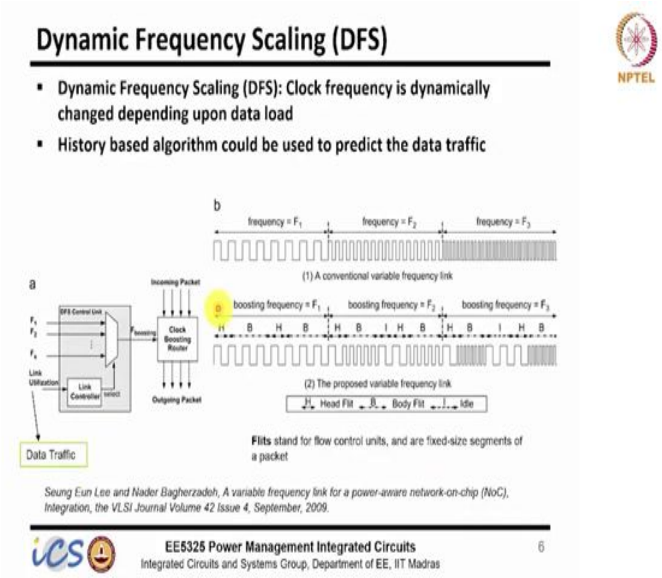

So then, dynamics frequency scaling the dynamic frequency scaling what do you do? You will just change the frequency based on the data actually. So, if data load is higher, you increase the frequency; data load is less, you reduce the frequency; so, dynamically keep changing and overall you can achieve a better system efficiency.

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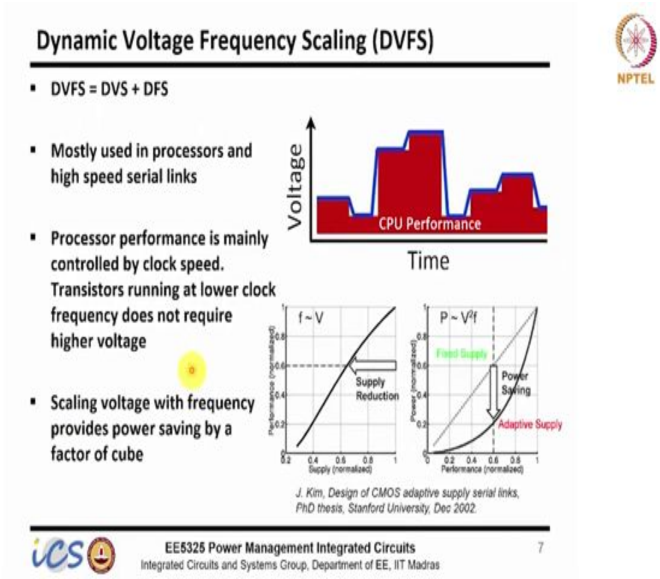

And this is how it looks like. So, you have a voltage and this is your CPU performance. When you are running at a lower performance, you reduce the voltage at peak performance you increase the voltage to with the max and here you see V square f. So, this is the only if you change only V ok, then reduction here compared to if we change V square f which is CV square f it is much higher. So, adaptively you can change the supply based on the performance. So, when your performance is very low, you get a cubic advantage here so, that is why this curve is more like non-linear.

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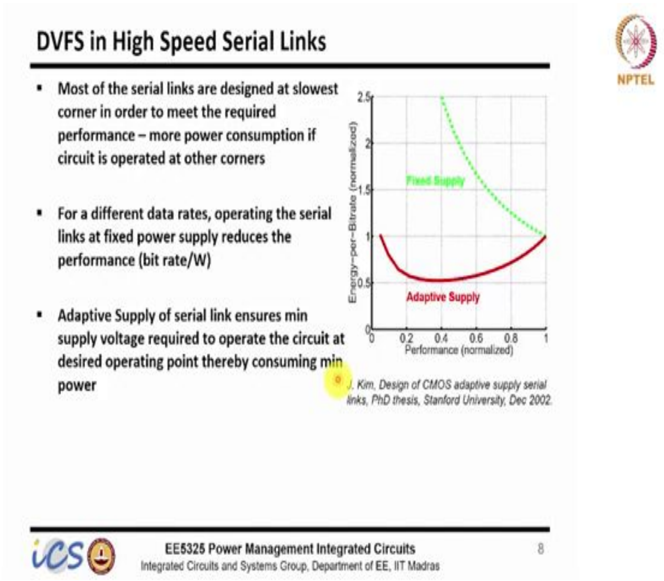

I can apply the same concept in high speed serial link also which have a CDRs like PLLs and all your clock drivers I was separating. So, this is energy per bit rate which is the performance defines the performance. So now, you can see here adaptive supply. So, when your performance is basically increasing here; what do you do actually energy per bit if you do not vary the supply, it will be much higher. Efficiency is measured in energy per bit here ok; but, if you use the adaptive supply you can see here your energy is per bit is like much less compared to this one.

So, think about your DC-DC converter; when you are running at a maximum load; your conduction losses are dominant. But if you keep the frequency same at light load your switching losses will start dominating efficiency will be less. So, you think from that perspective you can think this is the loss actually. So at light load, the loss is much higher if you do not change the frequency but here, we are changing those frequency and supply so, you try to maintain the efficiency of the system or loss of the system at the minimum possible.

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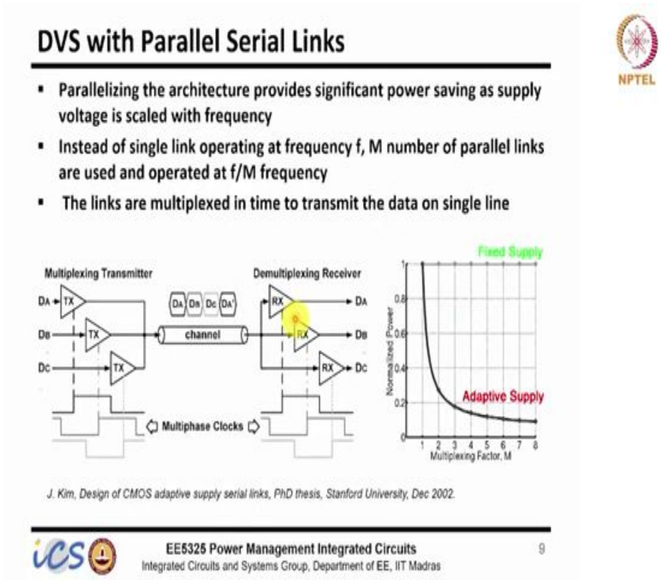

And this is at the thing they use like in multiple and based on the I think it is it is nothing but the muxing and the they try to change the number of these parallel basically transmitter they are using. So, normalized power here again multiplexing factor they change. So, multiplexing factor they increased when they are operating at a higher load and when the load changes reduces they reduce the multiplexing factor. So, it is just like you can say they are using multiple phases just like we saw in the LDO and you keep basically turning all the phases as your load reduces; so, they are using a single concept ok.

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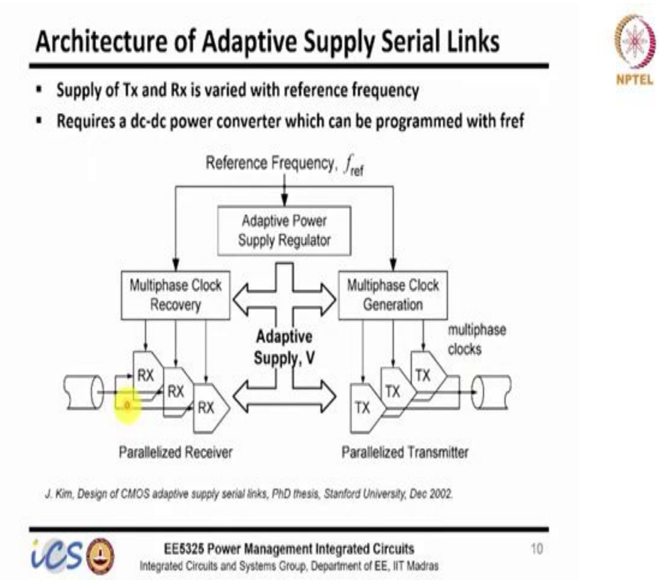

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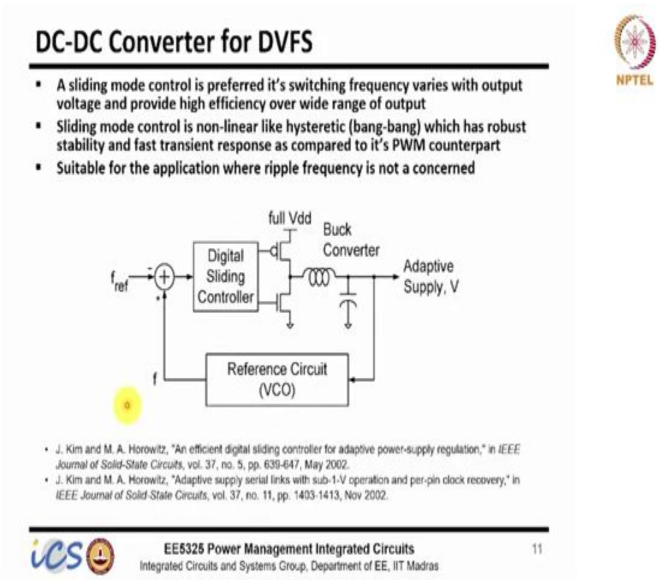

Then, how do you generate that supply? So, one simple concept here shown in this. So, if you are that Vdd is generated from DC-DC converter what do you can do? You can have a VCO at the feedback and have a reference clock. So, reference clock let us say you have a 1 gigahertz then, you want the frequency of this VCO to be 1 gigahertz; so, your buck converter will holds this control voltage which is your supply in such a manner that its frequency is 1 gigahertz ok.

So, hence VCO the reason we are using VCO because your delays are measured in terms of inverters actually. So, this VCO if it's implemented using ring oscillator which is nothing but the cascaded inverters; then it will represent your digital circuitry whatever logic gates and everything. So, if you can run this at a lower voltage, you can run the other circuitry also at the same voltage. So, it will now if your process is changing let us say went to at the slower corner, then this frequency will automatically go down and this loop will force this voltage to go high; so, that it is again logged at 1 gigahertz.

So, dropout would be depending on how you design. It is you can sustain 50 millivolt then other 50 millivolt; usually, this is the I am shown PMOS, but these amplifiers have a both n and p push and pull ok. So, it will have a source and sink both ok. So, you have to regulate the voltage of both it is not only one. But if we want to let us say only one side on the one side whatever the minimum voltage it goes, you always keep your supply 100 millivolt higher than that.

So, what you will do actually your reference will become your signal plus 100 millivolt; so, your V_ref is that then it will always regulate your output to V_in plus 100 millivolt that is what you have to do. If you have both sides like this, then you may want to regulate. So, the positive Vdd plus Vdd and minus Vdd both then you have to regulate both and then you will have a separate regulator obviously for both of the them. Single inductor multiple output SIMO.

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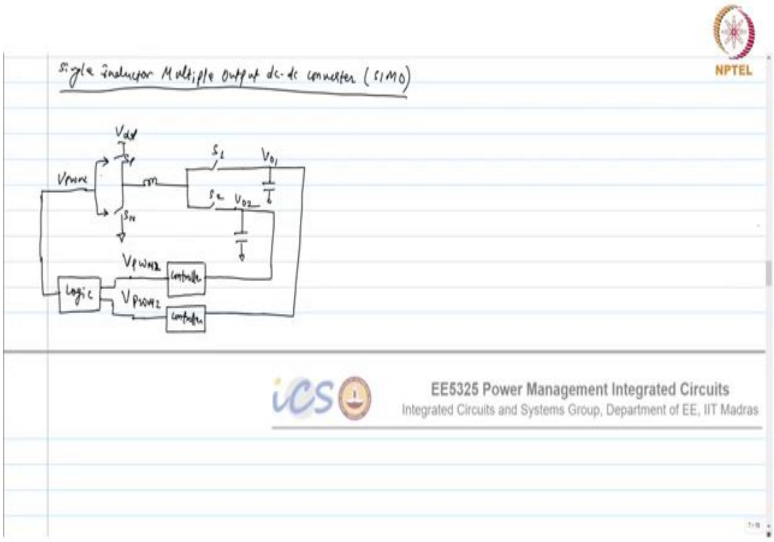

So, if I want to generate two output from the single inductor, so what I can do? So this is S_P, S_N, S_1, S_2. So, they are isolated outputs so, they should have their own capacitor. So, they will have their own load this is V_o1 this is V_o2. So, let us say this is your controller and when I say controller it has compensator and PWM everything inside. So, you will indirectly get PWM1.

Sorry this is 2 PWM, then what do I need to have? I need to have a some logic here because I have a single power stage one inductor so, I cannot feed 2 PWM in one so, I need to have some logic here. It is still generate here to the PWM and this logic is nothing I mean can somebody tell me what should be this logic. So, let us say what could be the so, we are sharing the same inductor.

Which means we can share in time.

Time multiplexing ok; so, for one cycle let us say, I am feeding one duty cycle; for another cycle, I am feeding another duty cycle correct.

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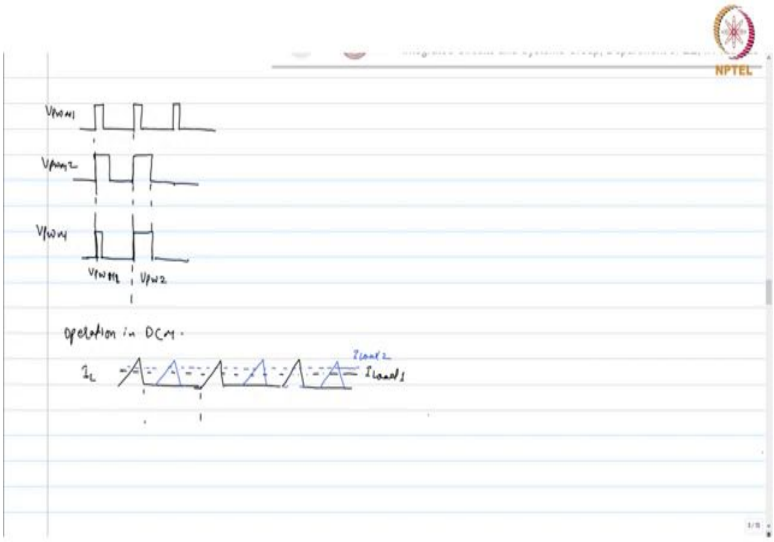

So, let us say this is V_pwm1; this is V_pwm2. So, the V_pwm I want to have here something like this and you keep repeating this. So, let us say my inductor current is ,operation in DCM, your inductor current will be doing something like this ok. What is the average current? I_load I am doing nothing here in between during this time your inductor current is 0.

So, I can utilize this and deliver current to the other way because this inductor is resting during this time. So, something like this and make this I_load1 and this will become I am just shifting, it is just to make sure I mean it could be different also not same.

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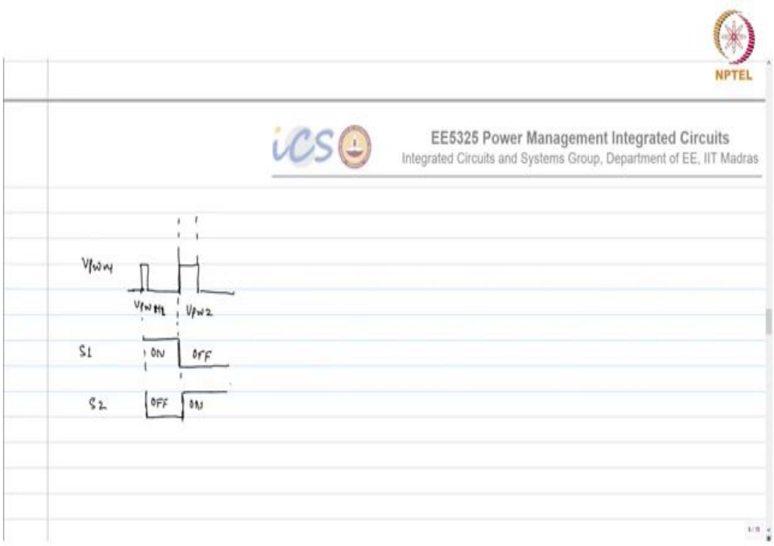

So, which means there is if I know I want PWM like this then ok. So, we have S1 and S2 switches. So, during this time S1 ON OFF and S2 will be OFF here ON; so, depending upon how much time you have how much basically the high Z time where inductor is resting you can insert that many output.

And that will depend on the load current; if I keep supply if let us say I increase the load current of this guy, then my high Z time will reduce I know the in the DCM, we keep increasing the OFF time then load current reduces. So, for the light load very light load you can even supply four or five outputs. So, that will basically it will be based on or how you are forced to reduce the frequency itself.

So, there are two ways if I want to cater to more loads, then I can operate at a lower frequency and insert more outputs there. So, for the DCM and this is possible in CCM also actually, but there are some issues with a cross regulation and all those inductor current is continuous.

So, for some portion you are supplying to the other guy some portion, you are supplying to this guy so, inductor current never goes 0 there. So, cross regulation may happen, but in this case so, this is more feasible with DCM operation or when you are supplying lower current. So, let us say with one inductor instead of doing let us say 100 milliamp 4 or 5 different converters, I can just use one inductor and just have a 4 or 5 output from there because inductor can easily handle four up to 400, 500 milliamp without any issue ok. But when you operate in continuous let us say I want to do a 5 outputs with 1 amp each.

So, the 5 amp has to come from the inductor only. So, inductor requirement will increase the current requirement. So, instead of having a 500 amp inductor you require a single inductor with a 5 amp so, that inductor size will be bigger actually.

So, it does not benefit much there, but when you operate in DCM the benefit is more with a and that is why you will hardly find any product single inductor multiple output which always operates in continuous or caters to high load current. Well, that is not very successful in terms of efficiency or cost, but we know that by default the inductor is resting. When we going DCM, we try to utilize that to supply the current to more outputs and you can generate different outputs and their control is not difficult here. It is very simple it means see if I have any ok.

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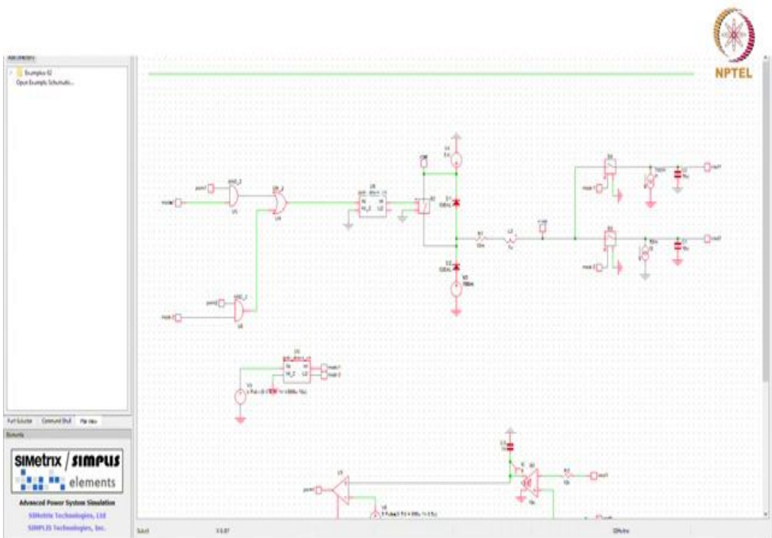

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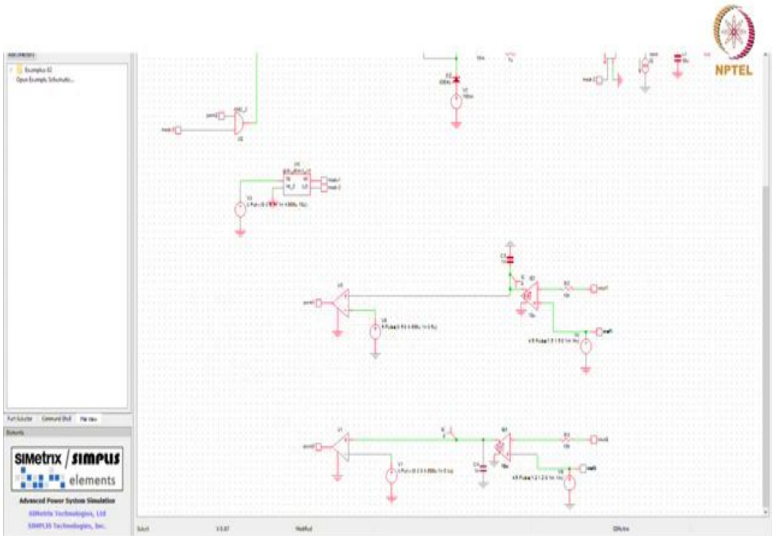

So, this is type one actually you can see only integrator in the loop and those two switches are S1, S2 which I had in the nodes. I have put a different a load current just to show you that it can derive different load currents also and it still regulate the output. So, this is your non synchronous because I have only diode at the bottom the reason have a non synchronous. I do not need to build a control to turn on the bottom fet.

So, just to simplify the control loop I just require like this and this is generating your control signal mode 1 and mode 2 this guy is actually the switch control S1, S2 and you can see mode 1 is mode 2 is lagging this DC-DC. So, that see let me remove this one. So, 3.6 volt and output I am regulating at 1.5 and 1.2.

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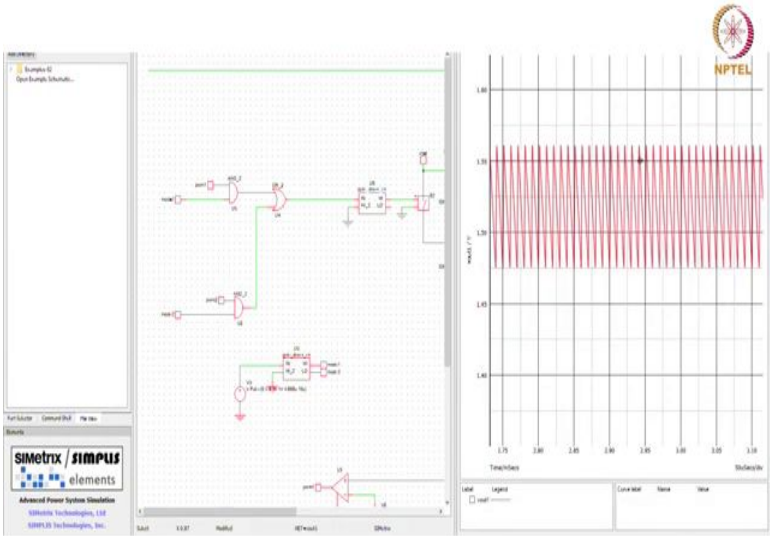

So, since it is in DCM it may take a little bit long to settle. So, by the way there will be discontinuity,you are turning off the switch. So, during when the time during which these switches are OFF, the current will be supplied by the capacitor that is why ripple will be little bit higher here compared to the standard buck.

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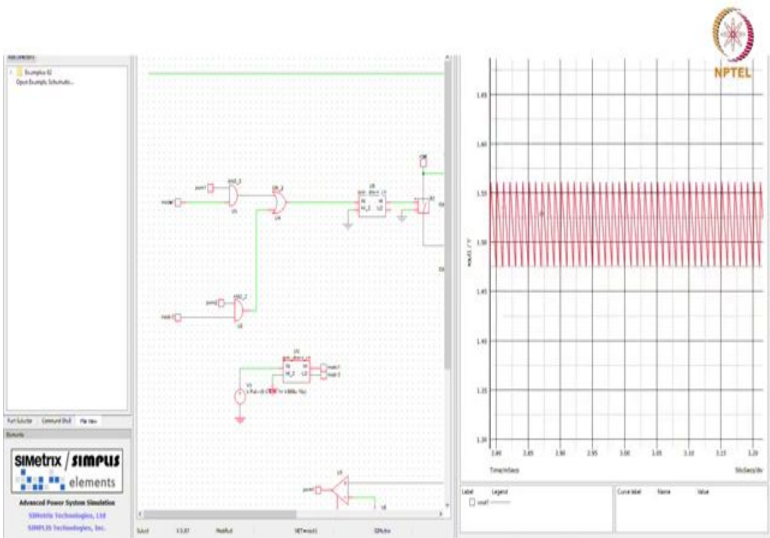

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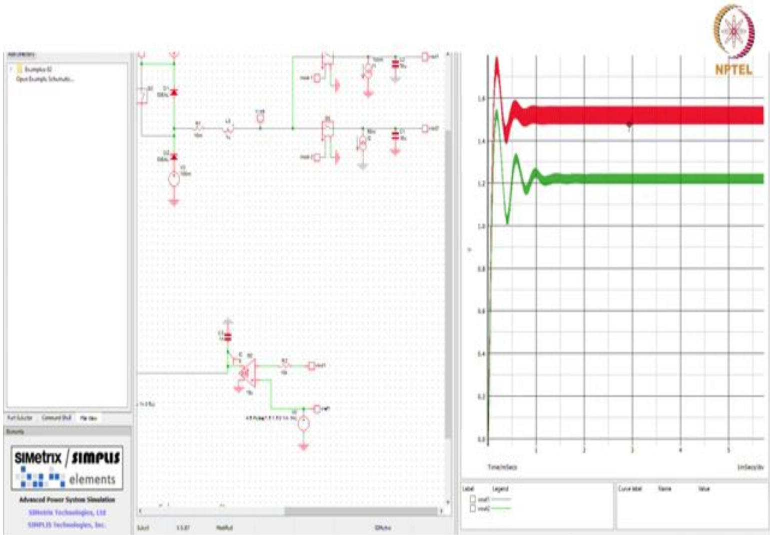

So, this is 1.5 volt on an average and this is 1.2 volt ok. So, they are regulated. Now let us see how the current looks like so, in one cycle the current should be same as 100 milliamp correspondingly and other cycle it should be 50 milliamp. So, this one has a less current so, one cycle you will see the peak current will be less compared to

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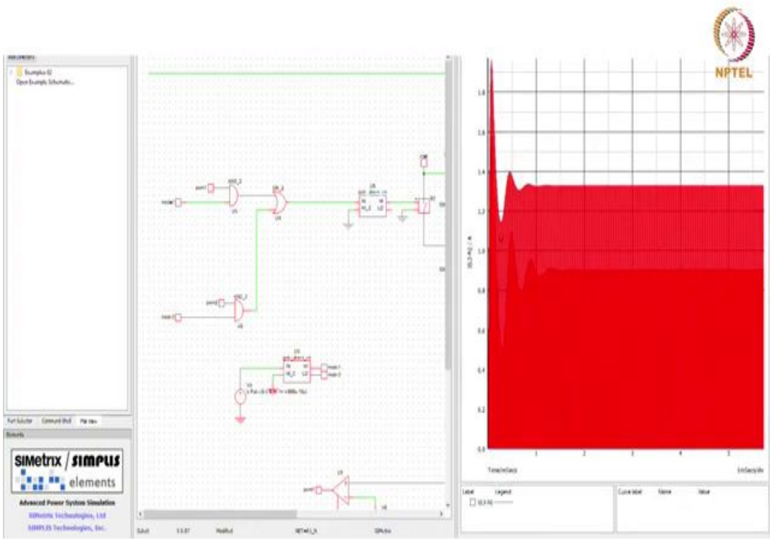

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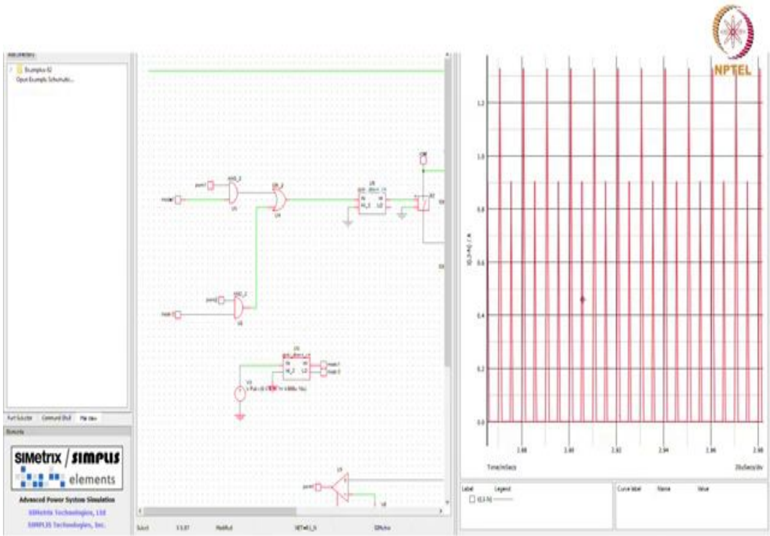

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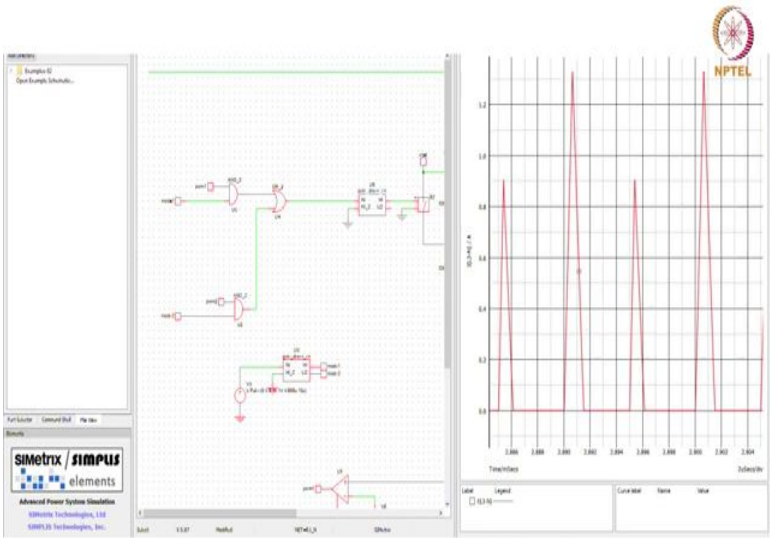

The other cycle and you will see the difference here. See inductor current; so, this is you during this time, you are turning on one switch; during this time you are turning on the other switch and that is why you see these differences and your switch duty cycle this will also different from first this.

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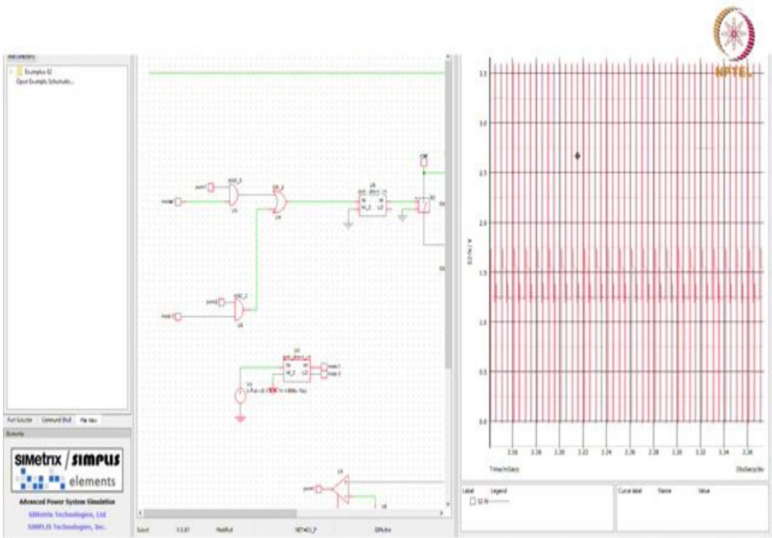

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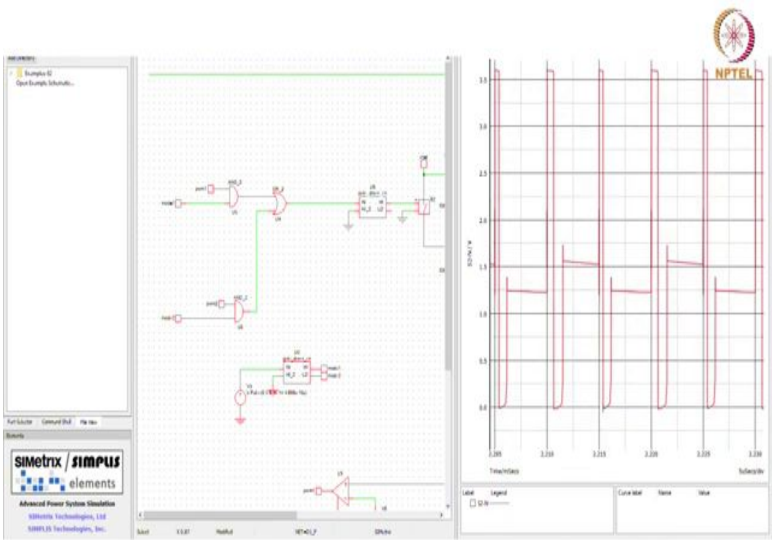

You can see the on time is different compare to this one ok and you can still I mean, you have a see during this portion inductors is still resting. So, you can insert one more output here or increase the load current basically. So, this will automatically increase so it will reduce the high Z time ok. So, this you can do with boost also with boost is even simpler because you the boost switch is at the output. So, you just connect one more switch in parallel you are done.

So, number of switches required in the boost will be less compared to what you need in the buck where each output requires a switch there in any case you have one switch at the output. So, that will we go to and in parallel with that connect another switch take another output. So, all the switches will be connected in the parallel and one switch for the charging the inductor which connects the inductor to ground that will be common to all ok.

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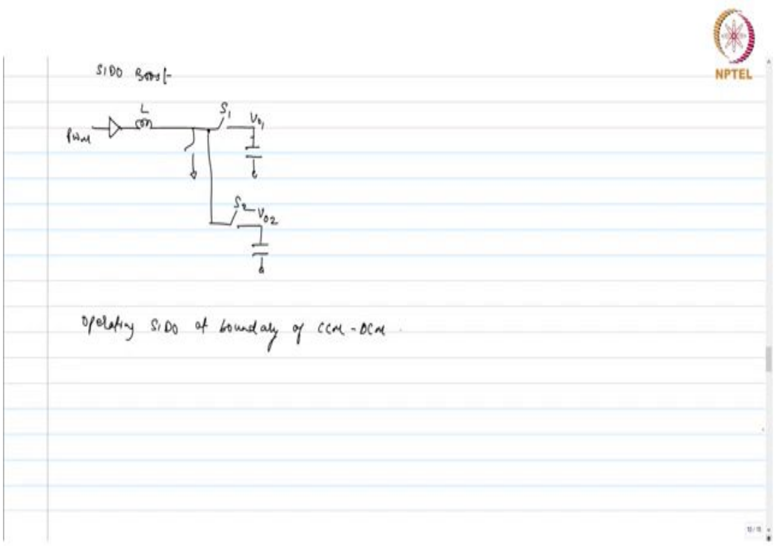

So, for the boost it will be like let’s say SIDO boost; so, this is your single output all I need to do. So, this is your PWM1 V_o1 that is it; so this will charge and supply current to S1 and second cycle will diverge the charge ok; any questions?

Sorry.

Student: CCM.

Yeah.

Student: We have two outputs.

Yes.

Student: How one cycle inductor in one two first PWM and vice versa. So, won't the other switch will go completely unregulated for one cycle.

it won't go unregulated your duty cycle will modify accordingly actually the switch time I mean it won't what do you are doing actually. In that case that is why I said it is then you are in the CCM this SIDO or SIMO operation is not easy actually when I say cross regulation that is what it mean cross regulation means one output rise to disturb the other output and it will never regulate actually it will go out of regulation.

So, you have to take care of and that is taken care by usually making sure that whatever current is supplied here you have to supply that and here. So, I mean that balance you have to maintain if there is extra current you have to throw by adding a freewheeling switch here actually ok. So, discontinuity is always there you cannot say there V_out equal to D minus V_in formula is gone here completely because of these switches.

So, now you have to just maintain the that the inductor average inductor current in each phase is same what is required by the load and if that is getting disturbed then extra current you have to throw out by adding a freewheeling switch here. So, that is why you need another third control or third time duration which will avoid the cross regulation and you short the inductor and basically intentionally making the inductor current 0 during that time in that case.

So, if it does not balanced out if balance out then you are fine, but if that won't be in all the cases there might be cases there it may not balanced out. So, the control is not simple there cross regulation is the main problem with that and that is why it is not very successfully in CCM in DCM it was very simple because you know you are not disturbing because inductor current is goes 0 only then you operate the other output. So, they will not disturb each other and another possibility could be operating at a boundary of CCM, DCM

So, in that case inductor current is continuous you can say. So, what do you do you trigger the other phase only when inductor goes to 0; so, SIDO at boundary of CCM, DCM.

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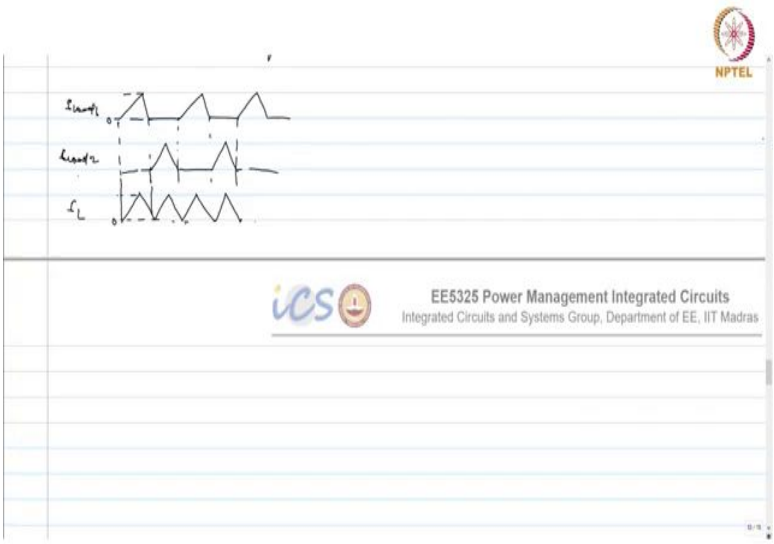

So, this is your I_L is going like this you wait until it goes 0. So, this is 0 and that is some load current peak depending upon the load and this is not I that I_load1 I_load2 see if I ensured that my I_load2 always starts when this goes to 0 and remains until here could.

So now, the inductor current will be simply I_load1 plus I_load2. So, what you can see something like this I mean the shape may not be perfect, but which is get an idea that it will go to 0 and it will be whatever the peak current. So, there is there is no time during which you have a high Z region so, inductor is not resting; so, as soon as inductor reaches 0, it trigger the other phase, but the problem with this is frequency will vary when the load current changes. So, the slope with basically I mean when input output is changing your slope will change; so, it may reach the 0 point at different time or if your load current changing the same may also happen.

So, in order to maintain this continuity you have to change the frequency. So, if you are not concerned about the switching frequency then it is fine and you can always keep inductor current continuous ok. So, it is similar to like you can say controlled on time or like constant on time we are talking about.

So, as soon as it goes 0, you trigger the next phase and that will be coming from your control the on time will be decided by your V_ctrl say you comparing ramp with the V_ctrl that we generate the ON time. So, that ON time will vary, but it will get basically triggered always at a 0 current information that is it.

And since this 0 is current information will be different I mean will be coming at a different time depending upon input output and load current. So, your ON time will get adjusted according to that that’s it your f requency will vary ok.