Switched Mode Power Conversion
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Lecture - 37
Current Control

Good day to all of you. So, today we will look at the issue of current control in DC DC converters that is the topic of discussion for today. You remember in the last class, we had just began the discussion on current control. Till now we have primarily being using the voltage feedback to compare with a voltage reference and the output, which is the error of the comparator goes to the PI controller, which will ultimately control the duty cycle of the pulse with modulated signal, that is fed to the power semiconductor switch of the DC DC converter, in order to control the output voltage. Now, the problem is to control the output current and as we saw in the last class it has advantages like paralleling multiple converters, and also issues like doing unity power factor converters where you control the input current to the converter. We will of course, have a discussion on that also later on.

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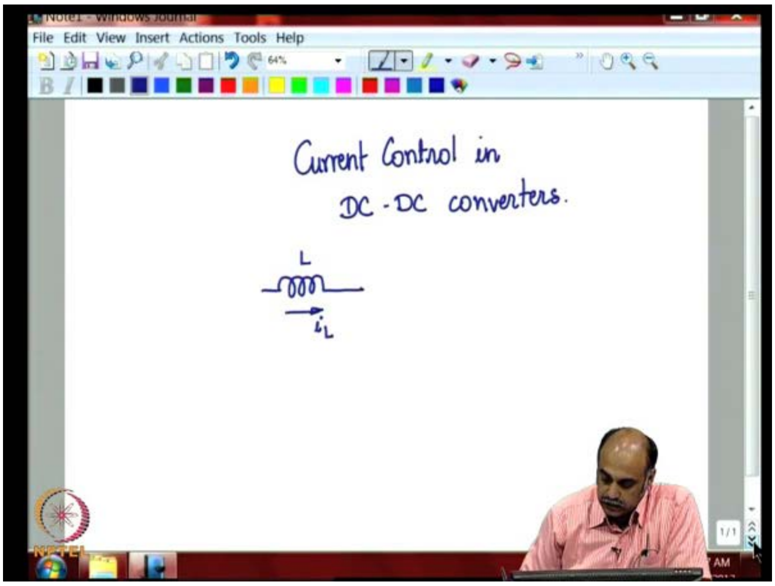

But right now do the concept of current control in DC DC converters, so here the central component is the inductor and we want to control the current through this inductor L. So, this inductor may be on the input side in the case of the boost converter or in the case of the output side, in the case of the buck and buck derived converters, but the objective is to control the inductor current.

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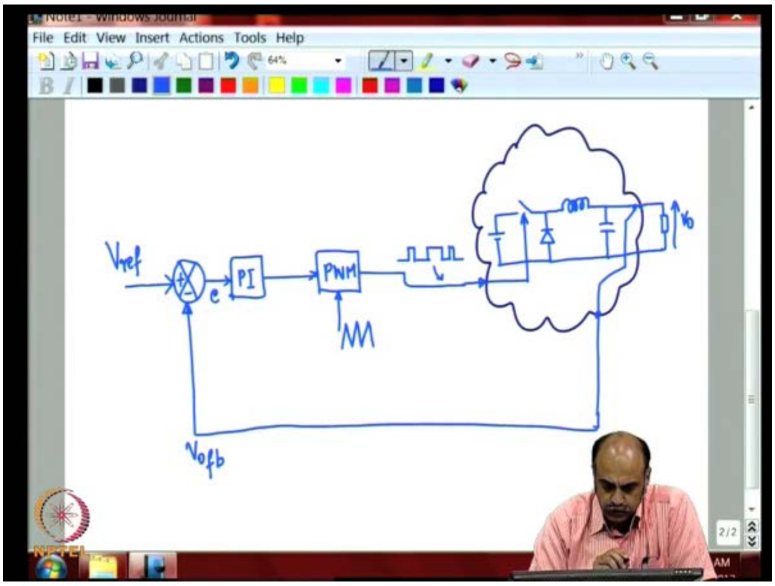

Now, if you look at our control block diagram and let me take the buck converter as an example there is a switch I am showing this as regular relay switch, but actually it is the semiconductor switch we have the inductor and you have a capacitor and a load which is external resistance and this switch semiconductor switch is controlled by the controller which gives a PWM output. We used to have here somewhere a voltage reference and if this is v naught here, v naught is feedback plus and minus.

So, v naught feedback is compared to the reference the error passes through a PI controller and this goes to a PWM modulator which has also the input carrier frequency. This gives an output which is pulse width modulator and that will accordingly control the switch. So, this is the basic control block diagram that we had been using till now. Now, to do in order, to do current control, we need to have one more loop called the current control loop and that should be a fast acting loop should be a high speed.

So, what we do we shall try to modify this control block suitably accordingly and we will have one inner current control loop which will be the fast acting loop. So, for this we need to do one more measurements we need to measure the current. Let us say we want to control the inductor current, so let us measure the current which is flowing through the inductor.

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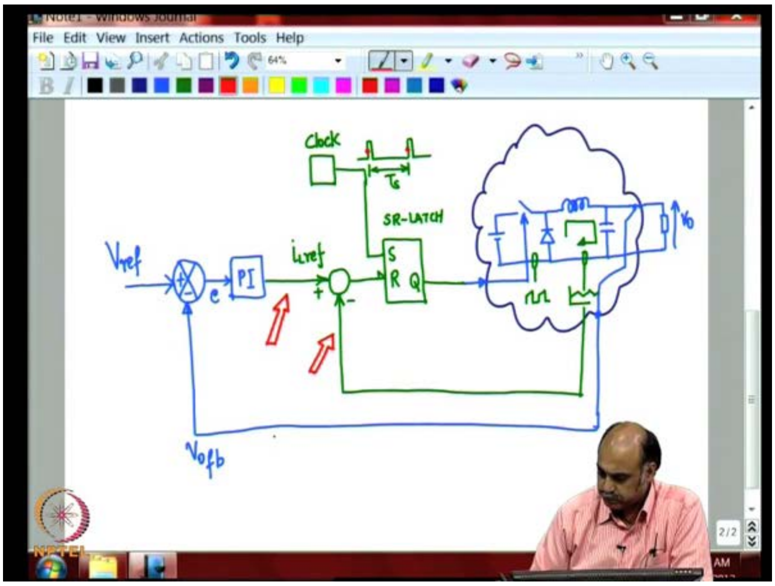

It could be at this point you could measure or you could also measure here, so this current also will basically be a measure of the inductor current. There are few other places also you can take the inductor current you could also measure it here, which will give you an idea of the inductor current. Of course, this will be switched it will be in this fashion, whereas here it will be continuous in this fashion. So, whatever we will take this inductor current measurement and feed it to a comparator block and let us say we get the current reference from the output of the PI controller block or say this is the i l reference.

So, this is plus and minus now the compared output is now given to a flip flop and it is an S R set reset flip flop. Now, let us say that this is the assertion asserted loop and let us say we have Q and the output of that goes to your drive circuit to drive the switch now this is an S R latch. Now, what do you give to the set to the set let us give a clock signal and this clock signal is actually having a period corresponding to the switching period of the switch mode converter. So, this is the switching period and on the positive edge on the positive edge the S R latch is figured.

So, at every positive edge of the clock the S R latch goes output goes high output goes high at every positive edge this switch on the DC DC converter switch the inductor current will start arising charging up. It will be arising charging up that is what is compared here. The moment this current goes above this reference, this becomes negative or goes low and that will reset this S R latch and this goes low. So, this basically is the current loop is the inner fast acting loop it is cycle by cycle control Yagburry switching cycle. This will be active and the power switch will actually turn off once the current in a inductor goes beyond particular reference.

So, this is how the current programming can come into the picture. So, in all current control this would be essentially how the control blocks schematic will look like? There will be a inner current control loop actually being control using a S R latch kind of or equivalent kind of circuit there is a clock, which actually defines the switching period of this power semiconductor switch. Then there is a reference which is actually set by the output of the slower acting slow acting voltage control loop slow, slow acting voltage control loop.

The P I output we will actually define what should be the reference current. Of course, so in practical implementation there are few other modifications that will come in to address some problems in current control we will discuss that is later. Now, let us look at how the waveforms will look like here. Let us look at this waveform and this waveform these two points if you plot versus the time axis.

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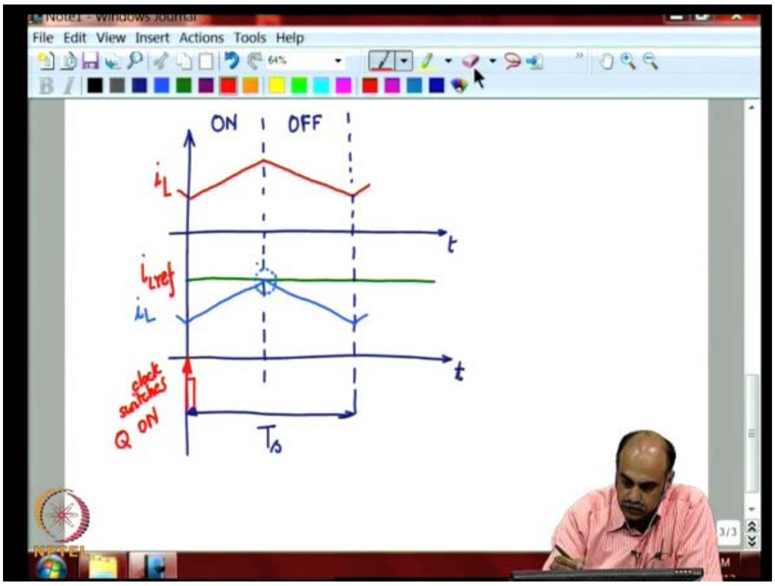

Now, let us consider one switching cycle meaning this is T s area this is the on time and this is the off time of the DC DC converter power semiconductor switch, so during this time the inductor current is rising falling back steady state arising so on. So, this keep repeating and this is the i l the inductor current wave shape and what is i l ref? The reference is the reference is just a DC lines, so basically if I superpose both i l and i l ref, so let us say you have i l ref. Now, i l the same way if I, superpose you will see that the inductor current keeps rising then the moment the inductor current tries to go beyond i l ref the S R latch is switched is switched and the output goes low and the power semiconductor device switches off and from here.

It starts going low and the cycle repeats, so this is the point of comparison for the S R latch at which point it go slow and switches off the device. So, at every cycle if you see at this point the clock rising edge of the clock switches the transistor Q on and what is transistor Q. This is our transistor Q the power semiconductor switch, so every cycle the clock appears here, so the clock is an i pulse. Then once the latch is s r latch is switched, so let me let me erase this portion.

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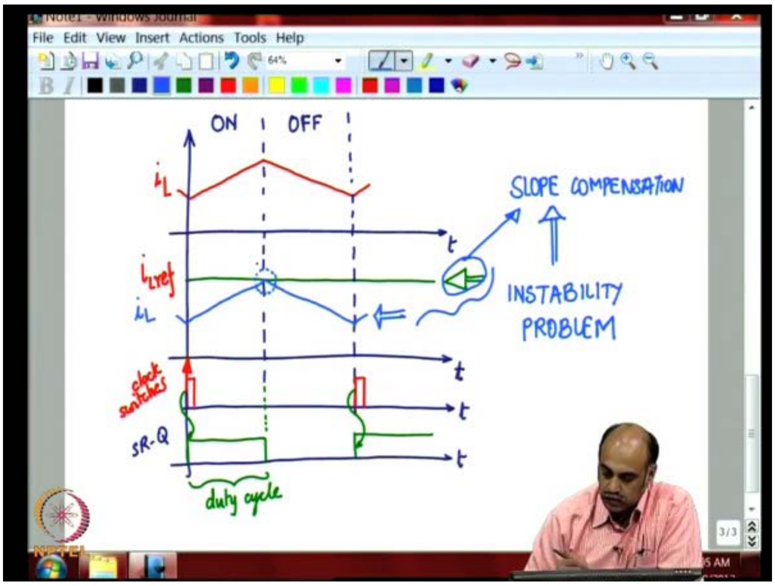

Let us have two more axis here, t now this is the S R latches Q output the clock is going to appear every cycle at this time. What happens to the S R latch at this rising edge? This will go high at the rising edge this will go high. Now, as the inductor current is rising at this point inductor current goes more than the reference. The latch switches of the exact plane on this point and so on it repeats every cycle. So, this actually is the duty cycle modulation that occurs in the current control period cycle by cycle.

If all else is working fine this would give you a very nice current control. However, there is a problem in current control which we will just now start to discuss in a short time.

That is related to this constant reference and also through the inductor current wave shape. So, these two give rise to an instability problem, which needs to be compensated for and this can be avoided. If we do slope compensation for the reference, so let us first see what is issue of instability?

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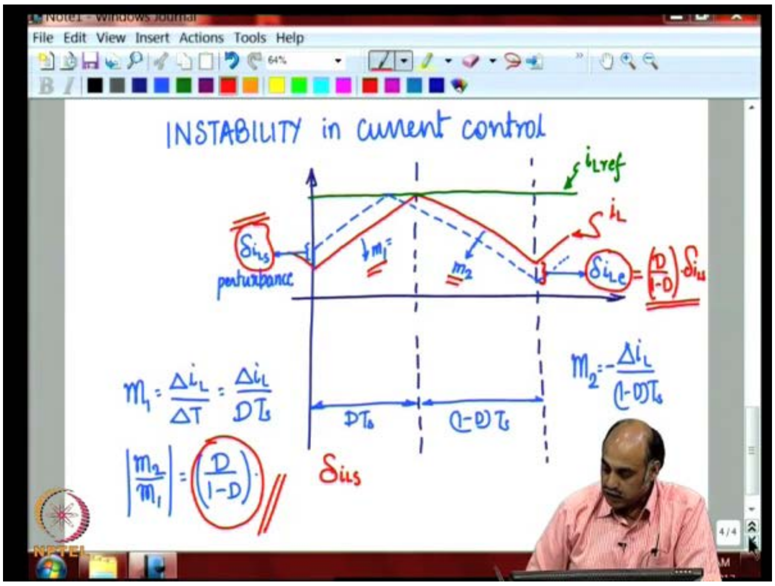

Instability is in current control consider one period consider just one period, let me zoom it, so that it is clear. This is one period, now in this period the inductor current is drawn in this fashion and then it starts repeating every cycle and this is the reference current. So, this is i l reference and this is i l, okay? Now, let us let us bring in some perturbation, now let us say something happens due to so many uncertainties some anything can happen the inductor current instead of starting from here.

It has jumped some perturbation, it came as jumped and its starts moving like this parallelly. From here it hits the reference and therefore, the S R script log switches off. Then starts moving parallelly here keeps coming down till this point when S R script log on switches on output goes high because the clock sets the flip flop and so on keeps going in this fashion. So, if there is a perturbance, so I will call this perturbance as delta i l.

Now, this is a perturbance and which is very very likely in a particle circuit these perturbance could come, due to so many reasons. There could be a spike in the input voltage, which could perturb the i l or a short moment. Then that could carry on from there or there could be a change in a input voltage, which could probably change the slope. So, many of these issues can happen and because of that what we expect the red coloured waveform could actually become the dotted blue coloured waveform.

Now, when the perturbance occurs and after the perturbance is removed, it is natural to expect that it should come back to the original red coloured waveform. Does that happen? Now, that is what we need to look at if it comes back to the original expected red coloured steady state wave shape. Then you know that the perturbance has been rejected and it is in a stable state

Now, let us look at two points now in this one cycle. If there is a perturbance at the input the difference between the steady state expected inductance current and the perturbed inductance current at the end of the cycle is this much. So, let us call that one as let us call that as delta i l at the output and delta i l at the input of the period at the start of the period. We shall probably change the delta i i l at the start of the period and delta i l at the end of the period.

So, we know the slope here. Now, let us say this slope is m one and that is equal to m one slope we know is equal to delta i l the inductor current by delta t. That is nothing but delta i l by d T s. Now, this is the d T s period and this is 1 minus d T s portion of the period and then what is m 2? So, this is m 2 and what is m 2? m two is delta i l, it comes down by the same amount m 2. Let us take the steady state waveform divided by delta t, which is 1 minus d T s. Of course, there is one other term which will come in which is the negative sign because this is the following slope.

Now, if we take the ratio of m 2 to m 1 and take the absolute value modulus, so that the negative sign does not come to the picture, you have d by 1 minus t. So, what it would also mean is if I am having a perturbance delta i l delta i l at the start of the period, then at the end of the period here, what would you get? This would be the slope, because there are two slopes coming to the picture m 2 by m 1 d divided by 1 minus d into delta i l s. So, what our perturbation occur at the start of the period goes through the whole period with these two different slopes and occurs at the output as a perturbation here, which is changed in amplitude respect to the one at the start of the period by this factor d by 1 minus d, which is basically related to the slope.

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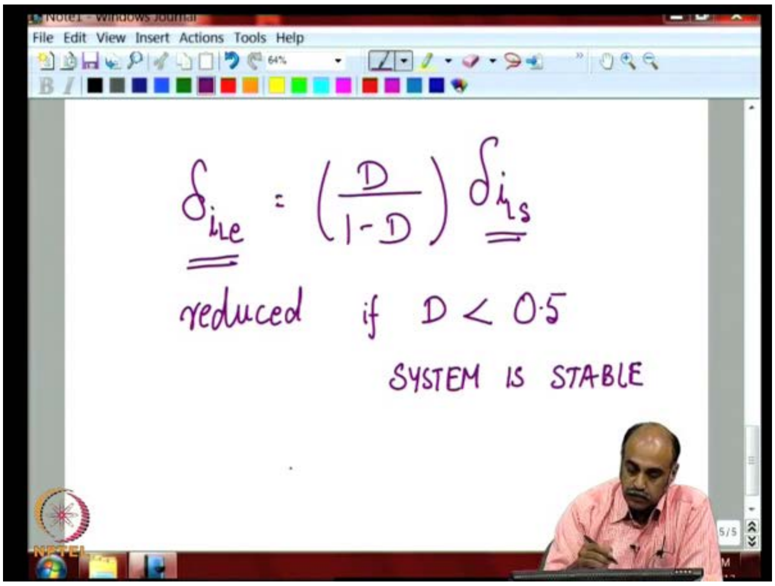

So, now what happens delta i l at the end of the period is equal to D by 1 minus d delta i l at the start of the period. This is the perturbance at the end of the period so the perturbance of the start of the period. We multiply by D by 1 minus D will actually decrease if d is less than 0.5. So, for less than 50 percent duty cycle any perturbance here actually gets scaled down attenuated and the perturbance at the end of the period is reduced.

So, this is reduced if d is less than 0.5, so this becomes the perturbance for the start of the next period, which will further reduce the following period and so on. It will asymptotically reduce till the perturbance becomes is rejected. Therefore, we say for all duty cycles less than 0.5 the system is stable. So, if you take for example, the same problem of the inductor current.

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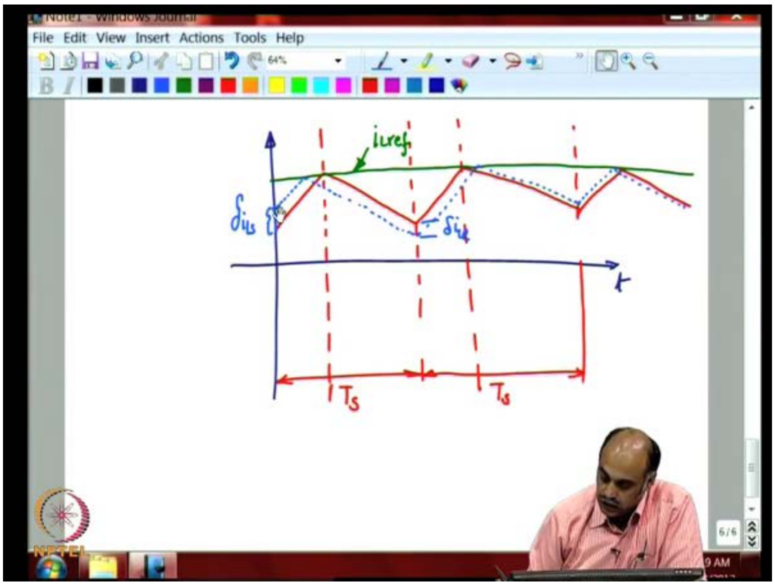

So, let us say the inductor current we will take few more cycles to show two cycle also three cycle. Now, this is slightly 50 percent duty cycle, so to see the affect let us make the duty cycle less than 50 percent, which basically means I will make the off time more go up and more of off time and go up and so on. Now, in this time if you take this two cycle period this is one T s this is another T s. Now, let us say the reference is cycle like this i l reference and now by some reason for some reason the perturbation has occurred, yes.

So, it is start moving like that and start moving like this start moving like that and so on. You will see that the perturbation will start decreasing this would be delta i l e, which will be this magnitude will be this magnitude will be less than this magnitude, because the duty cycle is less than 0.5. Then perturbation here this magnitude will be less than this magnitude, because duty cycle is still less than 0.5 and so on. The magnitudes, so are so every succeeding period starts reducing and the disturbance is ultimately rejected.

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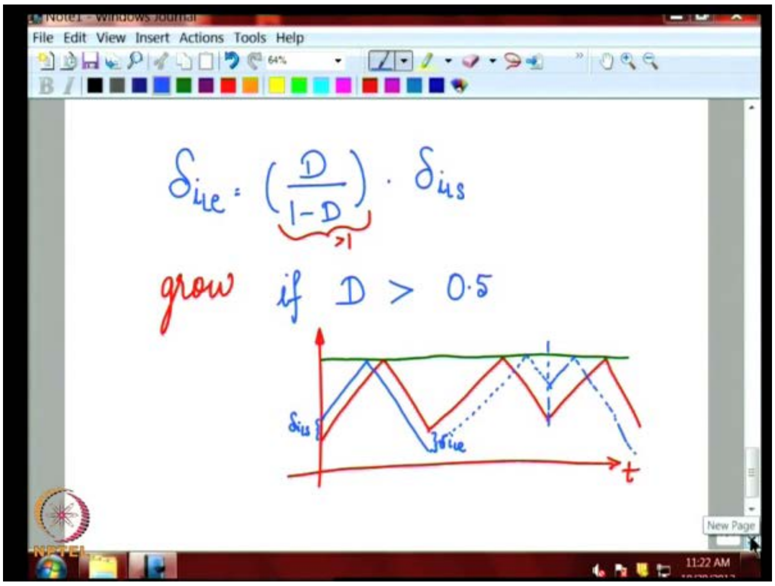

Now, let us take the case when the duty cycle is greater than 0.5, so if duty cycle is greater than 0.5, then what happens? This factor is a number, which is greater than 1, so any perturbance at the start of the cycle start of the period would actually get amplified and appear at the end of the cycle and so on and succeeding cycles. Therefore, it will go into an unstable situation and the perturbances never rejected, even after the removal of the perturbance.

So, this will grow now this is the dangerous situation. Therefore, this is something that is not desirable, so let me quickly draw the wave shape here t. So, this is our inductor current I am trying to show the duty cycle is greater than 0.5. This is the current reference and now we have the perturbance, which will so this perturbance will be greater in amplitude than this. This will further increase at the start of an x cycle and so on this will keep increasing and keep growing.

As a result you will see the wave shape current wave shape is in this fashion you can recognize that, this is an unstable situation which will lead to pulse missing and incorrect inductor current wave shape and in incorrect current programming. Therefore, we need to make correction which will try to make the system stable, even if the duty cycle is greater than zero point five so what is that we try to do.

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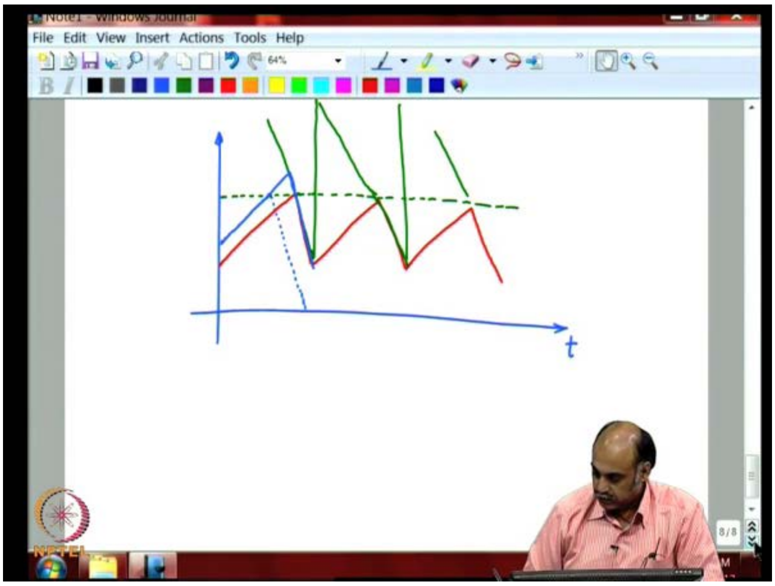

We try to attack the problem in this fashion. Let us say we have this greater than 0.5 duty cycle, I am showing a duty cycle which is greater than 0.5 something like that. Now, this was supposed to have be in the reference like this. Now, assume that we have the perturb signal which goes in this fashion. Now, what would happen, if the reference itself was having a slope like this, if the reference is having a slope like this? So, what would have happened? We will see that the perturb current goes on like this and then takes a turn at this point. You see that it is much less than what it was with reference, which is having 0 slope

So, going along in that fashion if I modify the reference such that it is having a slope in line with the falling slope of it has the reference is such that it is having falling slope like that then. So, let us say for example, the reference is in this fashion it goes continuous like that and let us say it goes back then continuous like that in some fashion. Let us say the reference goes in this fashion. So, what would happen this would go after this point the inductor current compares with the reference switches off and then the inductor current and the reference both are coming like that.

In one cycle you see that, the correction is happening and the error due to any perturbation at the beginning of the cycle becomes 0. So, this is basically what we will be trying to do. We will be compensating for the slope of the negative slope of the inductor current and applying it to the reference the perturbation is eliminated is rejected in just one cycle.

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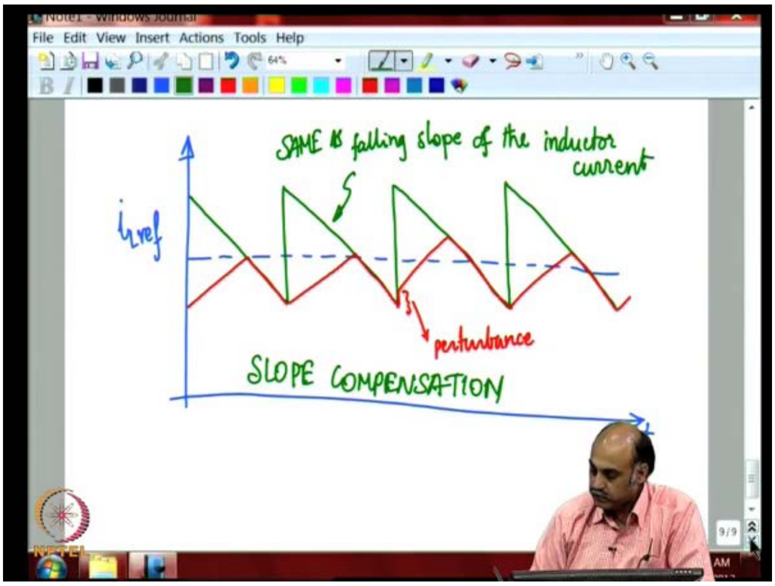

So, therefore, the reference i l reference instead of being just a DC like this, just now modified to be in this fashion, it it is having an inverted saw tooth shape and what is the slope of this? This will be same as the falling slope of the inductor current, it should be same as the falling slope of the inductor current. I will like this same as falling slope of the inductor current. So, which means that if you have an inductor current which rises like that compares at this point switches off the switch. Then falls like this and then the inductor current compares falls.

Let us say there is a disturbance it will go like that and then falls like that and then gets. So, whatever may be the duty cycle this will be a stable solution and the disturbances rejected within a cycle this is the disturbance perturbance. So, giving this kind of a compensated reference reference, which is changed in slope the slope same as the falling slope the inductor current is called slope compensation. So, giving a reference like this is called the slope compensation and it is essential for all current control application where the duty cycle can go greater than 0.5.

If the duty cycle is less than 0.5, you do not need slope compensation, because any way d by 1 minus d is going to be less than 1. It will any way attenuate all the perturb and then reject it eventually. But to be on the safer side giving the slope compensation in this manner is very essential and recommended. So, let us see how the control block diagram looks like.

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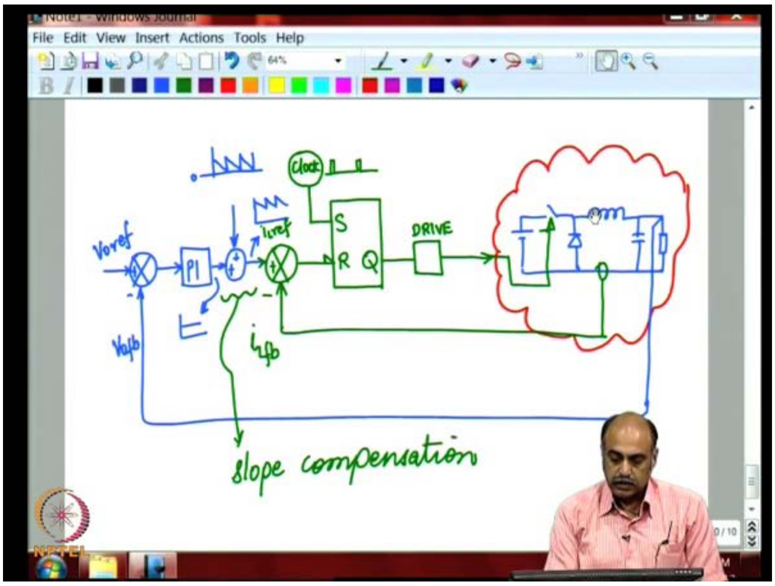

Now, complete we had initially v naught reference have v naught feedback goes through a PI controller. This will give the current reference i l reference and this is pass through the comparator plus and minus. We shall compare with i l feedback and the output of this pass through upper triggers is given to a set reset flip flop set reset flip flop the output Q now at the set point we are giving a clock, which actually tries to set the S R latch every cycle. This course to the drive and then into the plant which is composed of some DC DC converter.

Let us say we have the buck converter or now could be boost converter or any isolated converter in this fashion, where this switch is controlled here. You have the inductor current being sensed and you have the output voltage, which is sensed passes through the sensing circuitry and comes in. So, this would be the total schematic, but now here we are making that modification or giving slope compensation. So, let us say the i l reference is getting changed slightly we shall put one block this before and then add. So, this is plus and this is also plus, so to this let us add an inverted saw tooth 0 and this is a DC.

Here you will have a DC plus that inverter saw tooth, which actually goes like this which is level translated and this forms the reference, which is actually compared with this one.

So, this would be i l ref, which will be compared with the inductor current to get the slope compensated. So, this portion what we are doing is slope compensation and this is the slope compensated current control DC DC converter which has a inner fast acting current control loop and outer slow acting voltage control loop. There is slope compensation here, this can be applied for any DC DC converter without loss of generality.

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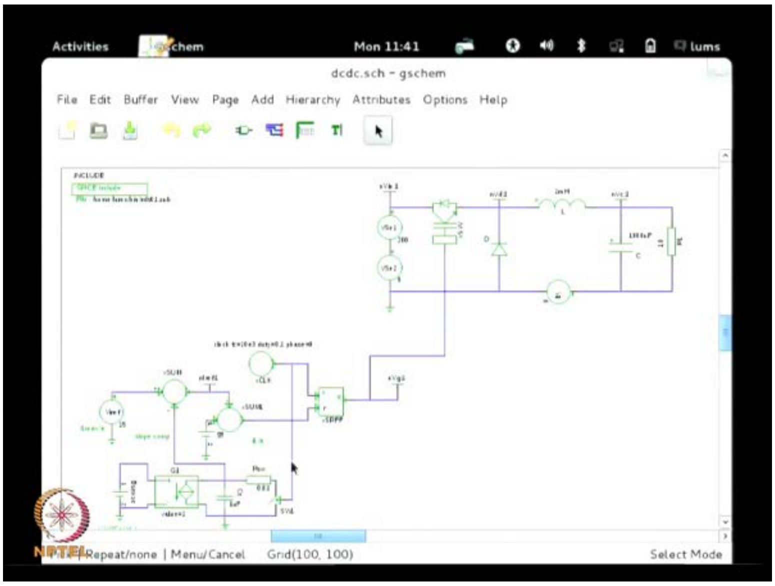

Now, let me just show implementation of the simulation for the case of a buck converter how it is simulated. So, knew this simulation DC, which is basically showing the schematic on gschem g a d, gschem. Observe here this is nothing but a buck converter. I am having two sources here; one both one source is the DC source up around 200 volts and you have a power switch semi conductor switch. This is the buck converter cycloid, there is a 0 voltage source which value 0, which is used as current sense this is the output mode and v.

See this is the node just before the inductor the voltage across the inductor is nothing but when the switch is on v in minus v naught. When the switch is off this 0 minus v naught, now this is the regular buck converter. Now, this switch is controlled from this controller. Now, I am using just only the inner current control the outer voltage control loop is not there.

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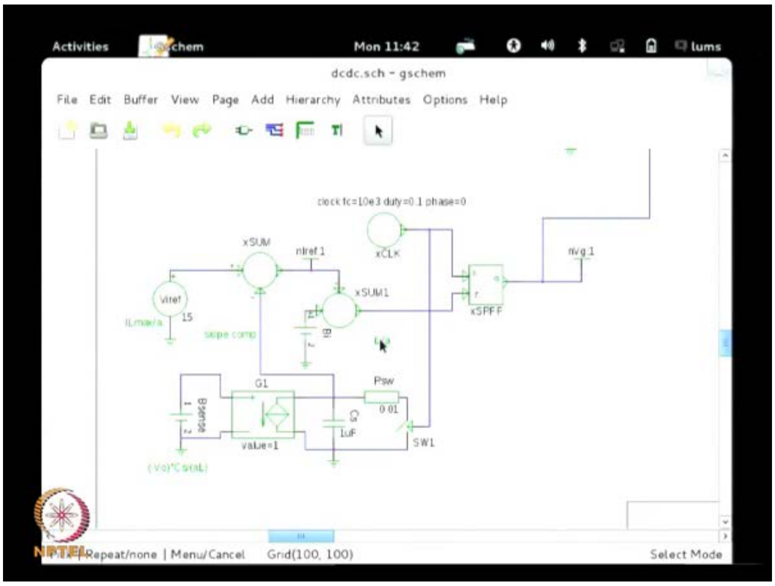

So, if you look at this. Let us zoom in you see that there is a S R flip flop the output of which is go going to the a drive of the switch buck converter switch there is a clock which has 10 kilo hurts setting duty ratio of 0.1 10 percent very small duty ratio. This is used only for triggering the phase of 0 triggering this S R flop every cycle. Now, to the reset pin is connected the comparator output from these two points. This is basically the measurement from the current, which is fed back from the inductor. This is actually a be source wherein you can put an equation. You see the equation here is a voltage, which is proportional to the inductor current v i l source and what is that v i l source?

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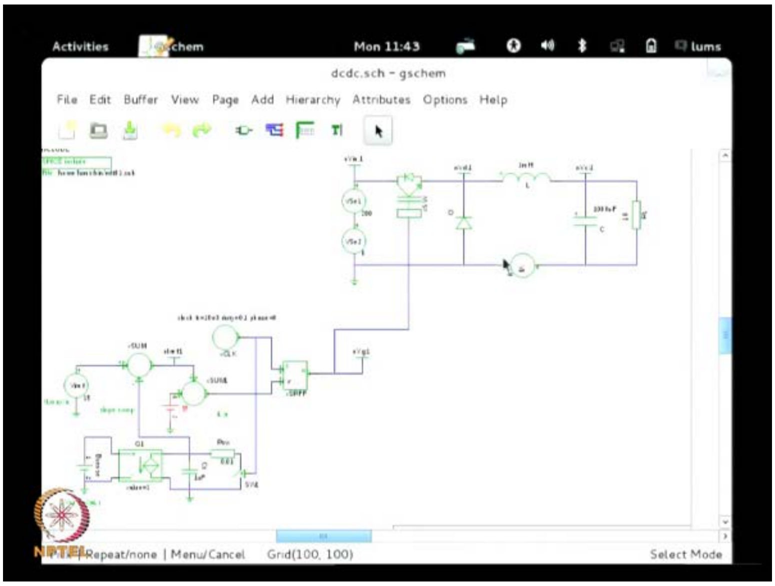

It is it is something like this. This is the v i l source. So, a voltage which is proportional to the current that is flowing through this now it is acting like a current sensor. Now, coming back to this control block diagram here, so this is actually a feedback current i l. This point is actually be slope compensated current reference, so you have a constant current reference here and based on the slope of a current which is proportional to the negative slope.

The inductor current v naught by l is fed through this current controlled source c c c s and the current through this is used to charge a flow capacitance So, the voltage here is exactly same as the current, which is proportional to the negative slope of the inductive current and that is actually subtracted from this DC. So, that you have a falling slope and every time the clock resets sets this S R flip flop. It also switches on the switch, which will discharge the capacitance. So, that you get sawtooth inverted sawtooth kind of a thing, so this is the slope compensated reference. That is used to obtain the comparison with we measured waveform measured inductor waveform. So, this is the entire buck convertor current control circuit with only inner current control. Let me execute that using n g spice.

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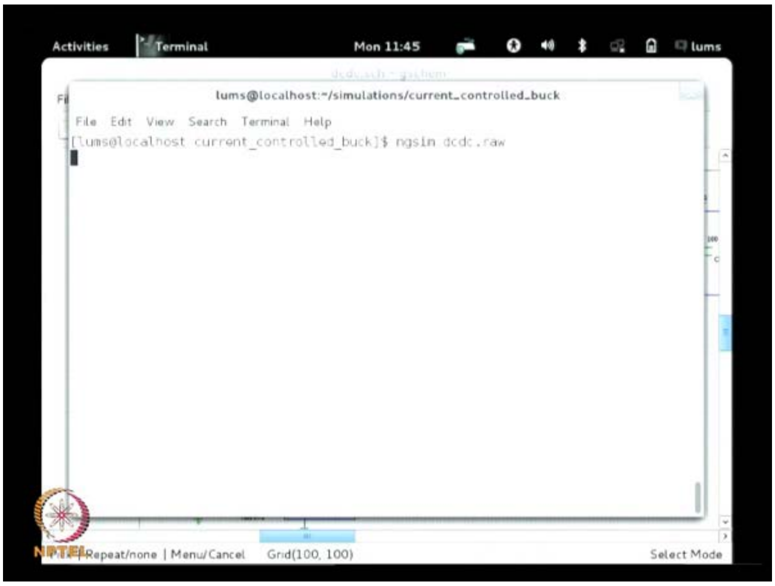

So, I will run the simulation it will be quick, so I am running the simulation.

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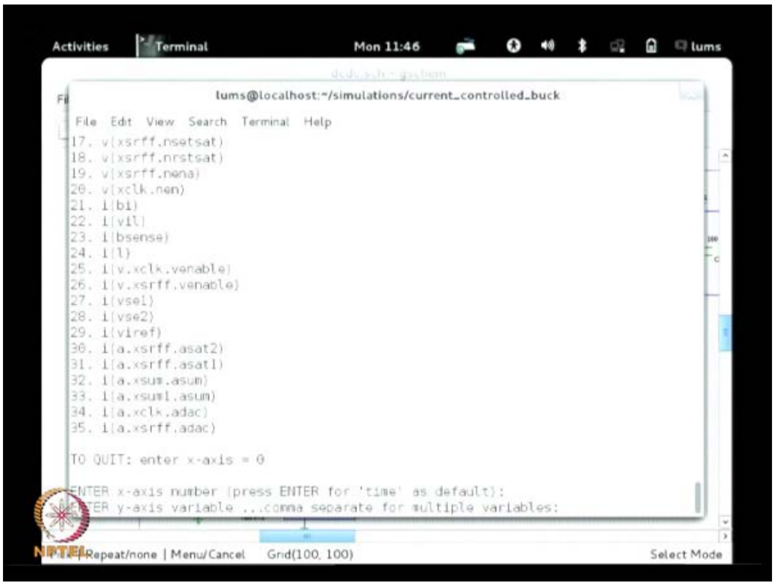

Now, we can look at two waveforms first the voltage the output voltage.

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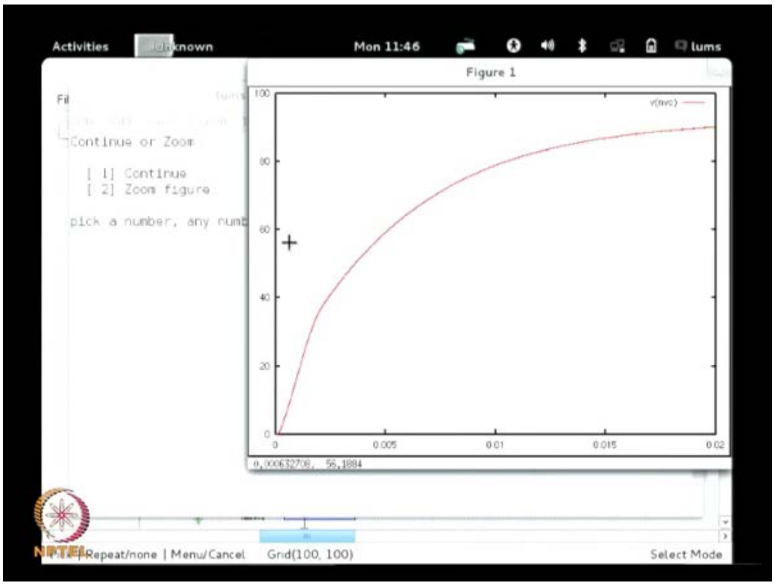

So, the output voltage is building up to something like that around 80, 80 to 89 volts. What we are really interested is in the current control action is it really doing the current control. So, let us look at two important wave forms, the ref the current reference and the inductor current itself.

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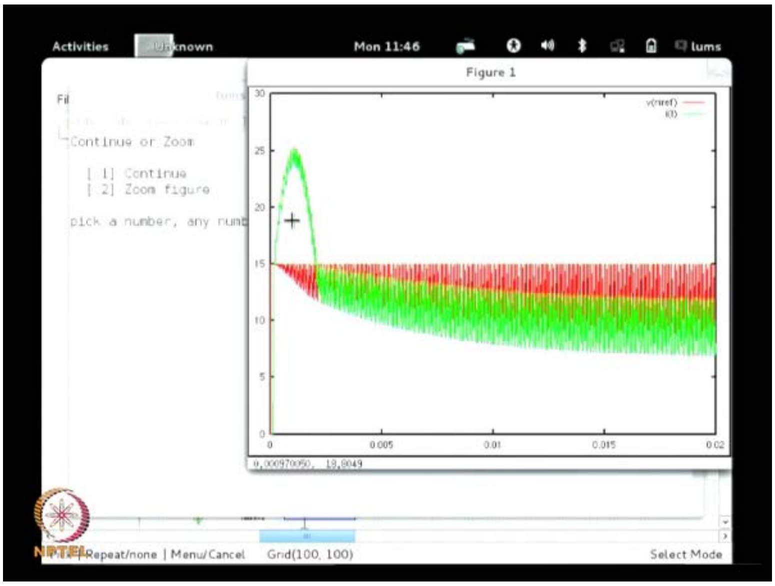

So, you see away from like this let me come to this portion later. Let us look at the steady state portion, so you see that somewhere here we have the steady state let me zoom that.

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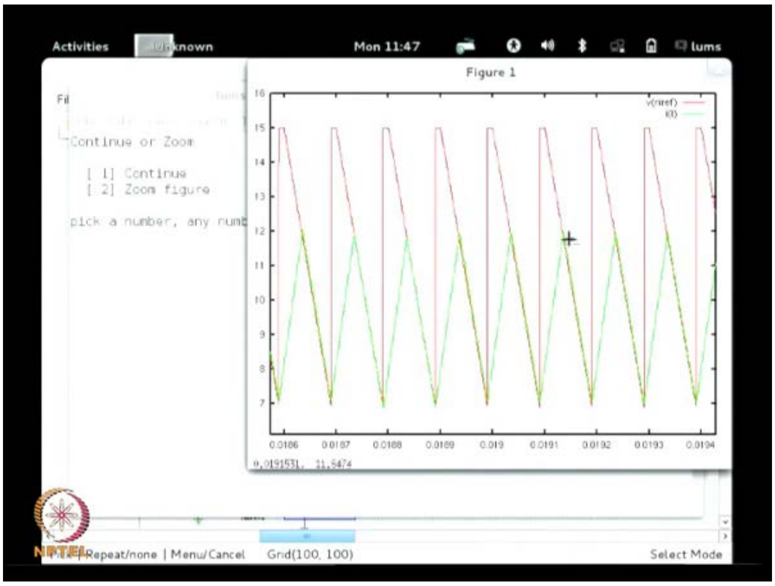

Look at this waveform this is the red one is the voltage which is proportional to your i l reference, which is something like an inverted sawtooth. Look at the reference it is a fifteen amp reference from 15 amp and this flat portion, which you are seeing here is due to the pulse width of the clock for the amount of the pulse width of the clock. The capacitor is discharged and you see the falling ram and when the inductor current rises and meets with the following ram the S R flip flop is switched of and the inductor current starts falling down back back.

So, that is the issue if you look at the initial response during this period. See that we have provided a 10 percent duty ratio for the clock. So, the inductor current will rise for the 10 percent time, then fall. So, one keeps rising till it overcomes the transitions and then starts going to the steady state. This can also be controlled by make giving a soft start or decreasing the clock duty ratio to much smaller like one person, because it is only the positive edge that is needed to trigger the S R flip flop.

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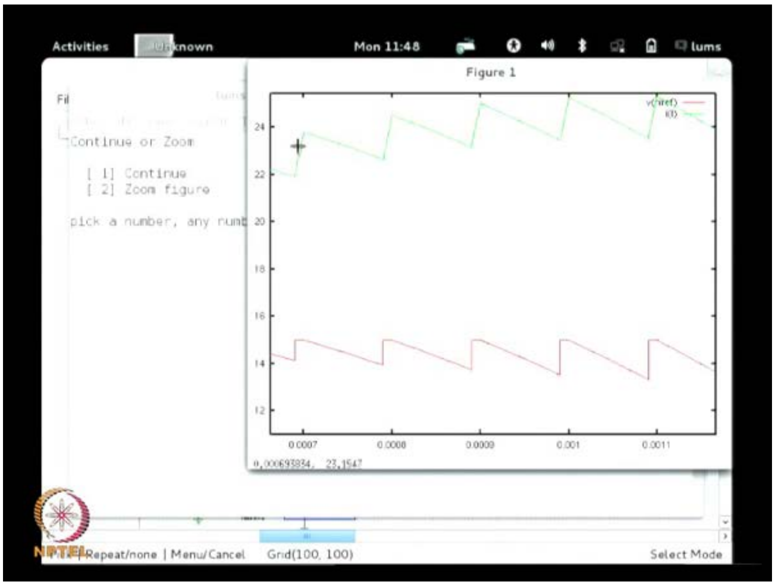

So, you can see that this this portion the current rises the inductor current rises only during only during…

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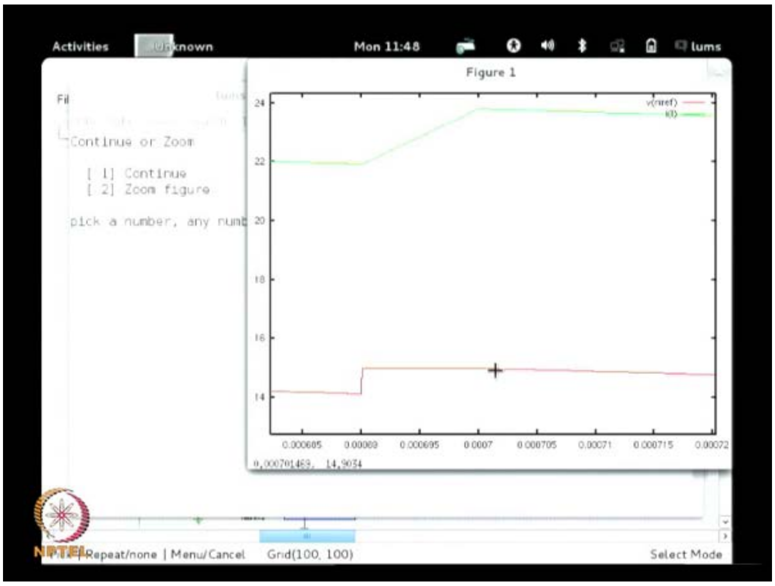

The portion of only during the portion when the clock is in existence and then after the clock goes off, because the current is higher than the reference current this will start decaying immediately. So, this way you can achieve current control and then with an outer voltage control loop. You can get both the current and the voltage control with with this, we shall conclude and in the next class we shall use this principle of current control to look at power factor improvement.

Thank you.