Control and Tuning Methods in Switched Mode Power Converters
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Module - 01
Switched Mode Power Converters and Simulation
Lecture - 04
Model Development for MATLAB Simulation

Welcome back and today is the 4th lecture. Here in today's lecture, we are going to talk about Model Development for MATLAB Simulation.

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So, that the topics covered in today's lecture are models of a series RL circuit and block diagram for simulation. Then modeling of series parallel RLC circuit along with some parasitic; that means, initially we will consider an ideal series-parallel circuit, then we will consider practical parallel circuit with parasitic.

Modeling of parallel RLC circuit with parasitic component, then modeling of conventional and synchronous buck converter; that means dc-dc converter that we have discussed in the previous lecture and we want to build a model for MATLAB simulation and then modeling of a boost converter and model generalization.

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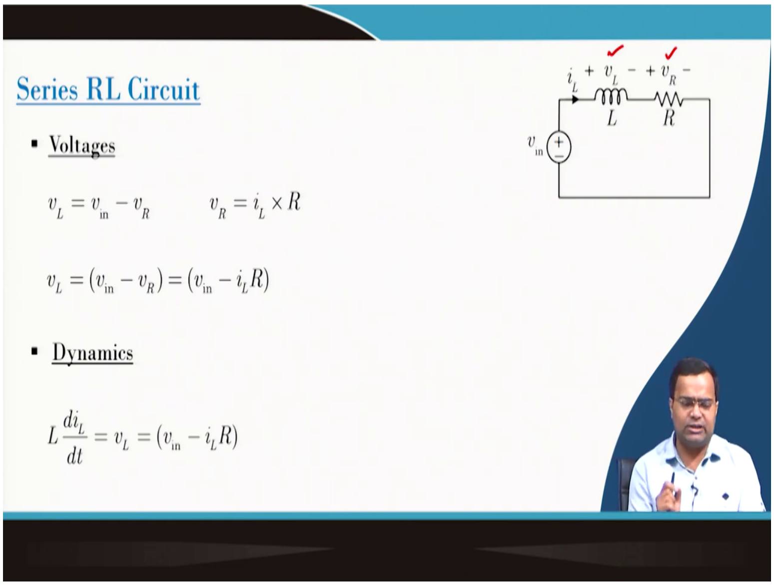

So, the series RLC circuit is a very simple well-known circuit and you know it is shown here. Here we are considering one input voltage v in which can be dc voltage which can be pulse setting voltage which can be AC voltage, it just a source and the voltage across inductor is v L which is shown here and voltage across resistance is v R and with their polarity shown here. And because of the series circuit here, the inductor, the current i_L is common for both inductive element and a resistive element.

So, we can write the voltages equation, equation of the voltages like v_L, which is the inductive voltage, which is v in minus v R where v R is nothing. But the drop across the resistance and we can write now v L which is v in minus i L R. Now these are the equation of voltages and since it has one storing element.

So, naturally it will have dynamics and it will have of first order. It is a first order system; that means, a first-order differential equation which is L d i d t d i L d t that is nothing, but the v L voltage across inductor that is nothing, but input voltage minus voltage drop across resistance.

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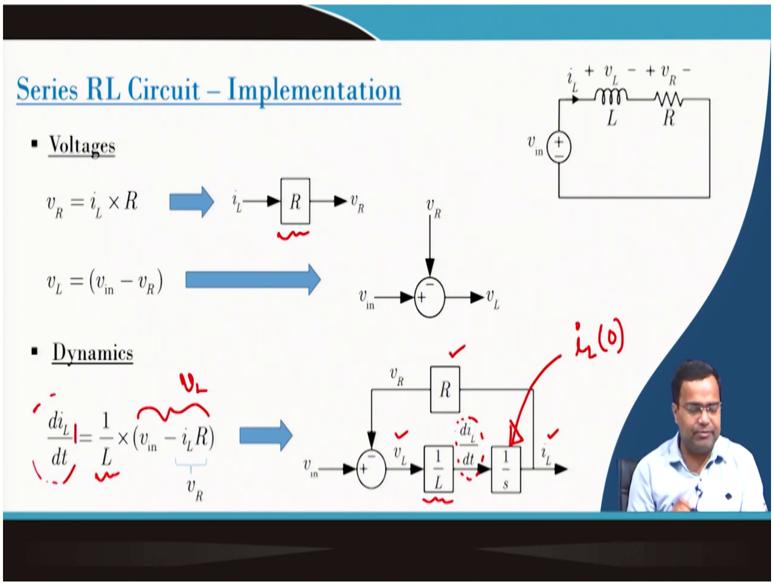

Now, we want to implement in the building block and this implementation is quite similar to what we are will implement using MATLAB Simulink.

So, voltage v R since we are using a resistance and this resistance is like a constant block and the constant multiplied by current will be the voltage and when we will implementing using Simulink, we will use this symbol R rather than putting a value so, that all these parameters that we are plugging to the Simulink model. We can define separately using a dot m file in the MATLAB that we will discuss and then, once we set this parameter value then we can actually run the simulation Simulink model and accordingly we can simulate any circuit.

Now, we you know the voltage across inductor v in minus v R, it can be used. You know, using a summing block, it can be realized, and that is also available in MATLAB. So, all these building blocks are designed keeping in mind the available blocks in Simulink. Now again, the dynamics means di_L/d_t it is 1 by L into this is your v L. This is my inductor voltage across the inductor which is nothing, but v_in minus i L into R.

So, if we want to plug in this block, it is like a feedback block where this is our d i L d t and if we integrate, then we will get inductor current and here we can set the initial condition of the inductor current. Again, if you plug in if you go inside the block whenever we will simulate in MATLAB Simulink, we will open this block we can write symbolically i L 0 and we can define this i L 0 at the beginning is in a dot m file.

So, that you do not have to change you know manually every initial condition that will be even confusing. Then this is a load resistance, this an inductance voltage which is nothing but the inductor voltage into 1 by L.

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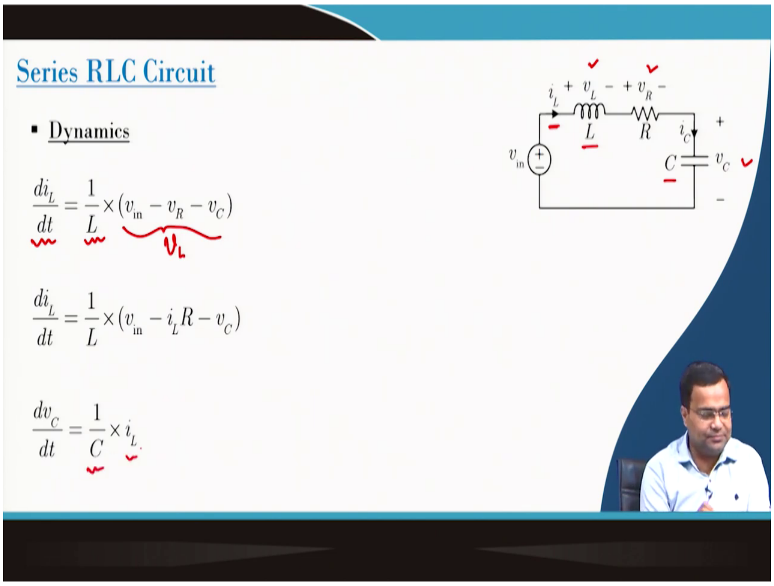

Now, going for the series RLC circuit. In the series RLC circuit, all inductor resistance capacitors are connected in series, we can take output either across capacitor, you can take output across resistance, but there this RLC circuit is in a series combination and it is supplied by a source v in.

For a for this series circuit the inductor current i L or this series current i L is common through inductance, capacitance and resistance and I have denoted the voltage across individual element like for inductor v L for resistance v R and for capacitance v C ok. Now, dynamics of this system. So, we have two energy storing element one is resistance another is that capacitance.

So, these two are the energy storing element. So, we can expect for each energy storing element there will be one first order equation. The overall system can be a couple second order equation or two decouple first order equation depending upon how we are writing I mean, of course, they will not be decouple couple, but you can write either two first order equation in this format like in state space or you can write completely using a second-order differential equation.

So, the first part we are talking about inductance, the dynamics of the inductor current or basically that current going through inductance. Here it is the series current. So, d i L d t is 1 by L that is the and this part is our v L, this part is our inductance voltage. So, v d i L d t is equal to 1 by L multiplied by what is v L?

It is nothing but the input voltage minus a drop across a resistance minus the capacitor voltage. What is the equation of the capacitor voltage? It is d v C d t it is nothing, but i C by C i C the capacitor current c is the capacitors value capacitance value. In this case, the capacitor current is same as the inductor current. So, it is simply i C into i L.

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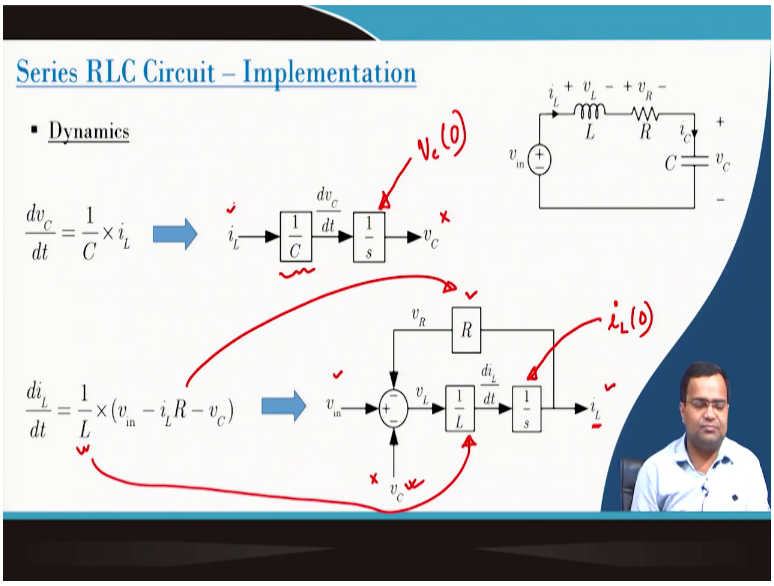

Now the dynamics we are writing d v C d t equal to i C into i L that can be implemented by this block where 1 by C is the constant where we can plug in the capacitance value and in the Simulink when we will implement we will use a parameter C. So, that we can define the parameter value in the dot m file. Similarly, we can define the initial condition of the capacitor voltage in this inside this integrator.

This is an integrator inside the integrator. We can plug in the symbolically we can plug in v c 0 and we can define outside. If we consider inductor current dynamics, then we can actually draw the block diagram because the resistance is constant, and it has 1 by L which is nothing, but it is shown here you can see it is here and this resistance is shown here ok and we can implement the whole circuit and this is our capacitor voltage. This is our input voltage and this is our inductor current.

And here we can actually again set the initial value of the inductor current alright. Next part of the series RLC circuit, whatever we have shown the implementation of two separate like a d i L d t and d v c d t we got i L and v c. Once we got it then we have to replace this v c with I mean we are getting v c from here and that we have to replace here. We are getting i L here and we have to replace i L here.

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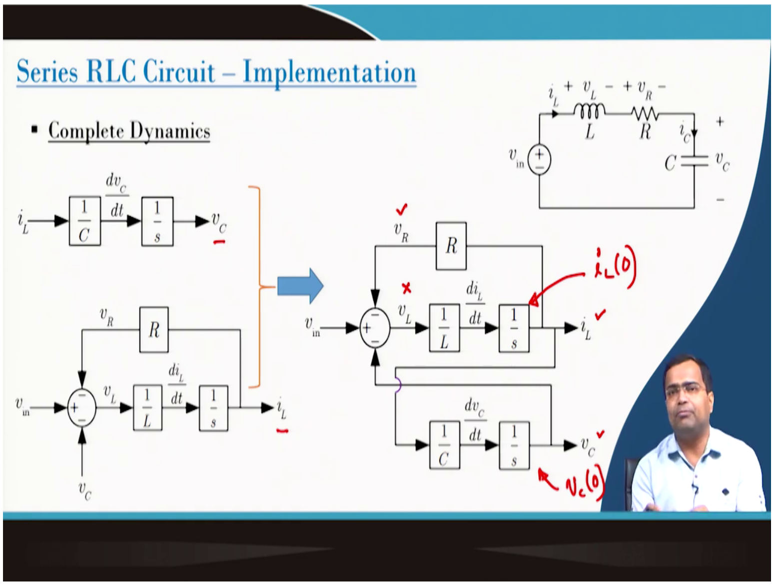

So, the next block we are going to merge. So, we have inductor current dynamics. I mean the capacitor voltage is coming output from here. Another we are getting inductor current and we need to combine to get the complete circuit. So, this complete circuit, since it is linked with the inductor current, we can set inductor current initial value here and it is linked with the capacitor voltage.

So, we can link capacitor voltage here initial condition? This shows the complete circuit where you can get inductor current out and capacitor voltage output. We can if we want to simulate this circuit, we can show the profile of the inductor current for an input voltage profile and you can also show the capacitor voltage profile.

If you want to show the resistance voltage across resistance, you can tap this point. We can show the voltage across the inductance from this point.

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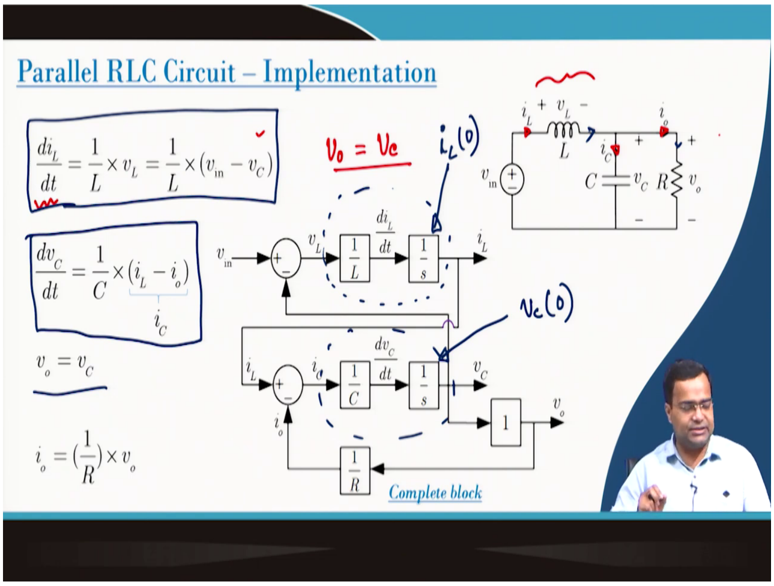

Now we want to move to a parallel RLC circuit. In the parallel RLC circuit, here we are considering the capacitor and the resistance are in parallel and here we may consider this resistance to be a load resistance where it can change that load resistance can change and this is a just a circuit, we can use it in different purpose. But unlike in the series circuit, the current passing through resistance and capacitance, they are different from the series current i L.

So, now we have defined individual current like i L which is the current going through the inductor. i C is the current going through the capacitor and i 0 is the current going through the load resistance. We are specifically showing the current i C which is going in and it is going inside if it is going in to the capacitor through the positive terminal.

So, this current direction is used for charging the capacitor. I mean the notation is used for that purpose. So, we can write the inductor current dynamics d i L d t like we already know it is v L by L and in this case v L is nothing, but the voltage inductor is input voltage minus this load voltage; that means, we are talking about the voltage across this. So, left side is the input voltage and the right side is the output voltage.

So, here v c and v 0 are same. So, here v 0 is equal to v c in this case. So, they are same. So, you can use either v c or v 0 does not matter. Similarly, we can write the differential equation corresponding to the capacitor voltage and what we get? d v c d t is this is my i C this is my i C.

So, it is already shown here. So, I can erase this part ok. So, this is my i C yeah this is my i C by C is my rate of change of capacitor voltage and i C is nothing about i L this current minus load current that is your i C and as I said v 0 equal to v C here and what is i 0?

Since it is a resistive path i 0 is nothing about v 0 by R. Now this shows the complete dynamics because we know how to plug in this equation, we saw in the previous example we know how to plug in this block in the previous example. So, this block corresponds to you know implementation of the inductor dynamics. This is linked with the capacitor dynamics and then we can combine to get the complete block.

Here we can set i L 0 the initial current and here we can set the v c 0 is the initial value of the capacitor. So, we can implement parallel RLC circuit using Simulink using this block diagram representation.

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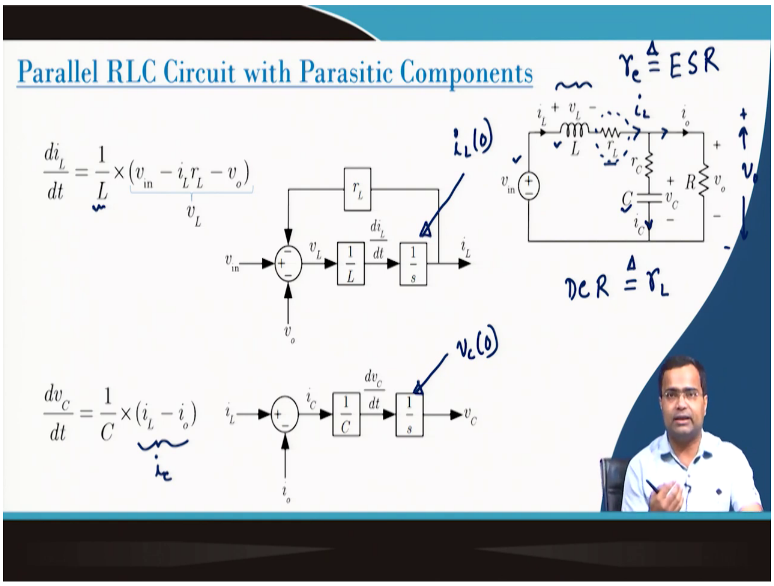

Now, whatever we discuss, we have used ideal inductance capacitance and resistive component,, but now we want to consider practical parasitic. For example, if you take an ideal inductor, the inductor will have some terminal lid where there will be parasitic resistance. So; that means, we need to consider the resistance of the inductor and this resistance will have an effect at low frequency like particularly for dc.

Similarly, inductance you know when we connect in a circuit it has two pins like you know if we use a SMD inductor or through hole inductor like a through hole where now soldering between two points. So, these two point soldering point can behave like a two conducting plates and where air is a dielectric. So, it can also have parasitic capacitors effect.

Similarly, if you consider capacitance, an ideal capacitance will have in a practical capacitance is not an ideal one. This means, it will also have some leakage effect and leakage effect means. If you keep the capacitor for long time, there will be self discharge. I mean it will discharge by itself and the process can be very slow. In order to emulate this discharge process, we can connect a parallel resistance with a large resistance value. So, the process of discharge will very slow.

So, you can consider a parallel resistance also the capacitor lid where we connect in the circuit that will have parasitic resistance that will have like a trace resistance that will also have trace inductance. So, if you connect all this parasitic then we can actually write in terms of impedance form after simplification of the real part and imaginary part, it turns out to be all this real parts can be combined together to get what is called equivalence series resistance (ESR) of the capacitor.

It is not a physical resistance; it is not a pure resistance because this resistance are equivalent resistance, which is also a function of frequency. Because if we actually start from the basic practical capacitor as I told if you consider the leakage resistance parasitic inductance like a trace inductance, trace resistance and if you write the whole complex equation. If you separate out the real part which represents which is represented by r_c there will be a frequency dependent term. It also depends on that resistance which also depends on the trace inductance trace resistance so many other factors.

This is also depends on temperature; that means, if the capacitance is operated at different ambient temperature, this resistance can also vary, but we generally write as an equivalent resistance, which is equivalent series resistance. Similarly, for the inductor, as I said we can have a parasitic resistance which can be a stress resistance and this is also called in many cases is called DCR d c equivalent resistance and that is denoted as r L of the inductor DCR.

Now we still have two energy storing element inductor and capacitor. The ideal part of the practical inductor and we can write d i L d t the current the rate of change of current through the inductor which is again 1 by L into v L, v L is the voltage across inductor I am talking about this voltage and this voltage what will be this voltage.

This voltage is v in like this voltage minus this drop act on this resistance minus the terminal voltage, which is v 0; that means, we are talking about v 0 this terminal voltage. So, this represents v L and we can implement this circuit because you already know how to you know plug in this first-order differential equation and here we can set the initial value of the inductor current.

We want to realize the dynamics of the capacitor. Here we are talking about the voltage across the ideal counterpart of the practical capacitor. The derivative of the voltage d v C d t is 1 by C into i C which is nothing, but this is my i C which is nothing, but in this case i L this current is i L and this current is i 0 and this capacitor current is i L minus i 0.

So, we can also plug in this equation into a block diagram and here we can set the initial voltage of the capacitor ok. So, we have implemented the dynamics separately by inductor current dynamics as well as the capacitor voltage dynamics. Now we need to get the block diagram of the complete parallel RLC circuit with the parasitic component.

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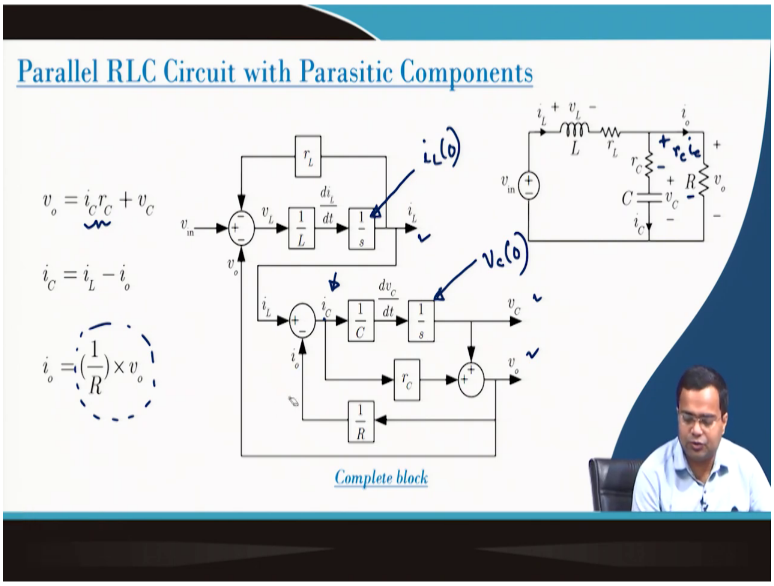

So, voltage across resistance is not in this case is now is not equal to the capacitor voltage because we have another voltage coming in that is the voltage across this part and what is this? This is nothing, but r c into i c. So, this drop will also be there. So, this is the component plus v c which is the capacitor voltage and the sum is now output voltage.

But the capacitor current is still remains that it is the subtraction of the inductor current minus load current and the load current which is going to the load resistance. In this case this is a load resistance. So, if we use a resistive load then we can get the current simply by dividing output voltage by resistance; that means v 0 by r.

Now it is not necessarily the load has to be always resistive, we can we can consider it combined load comprising a resistive load plus constant current load even we can consider constant power load. So, different type of loads are possible. So, you need to know the load current how is it a function of output voltage.

In case of a constant load current, we can simply use a constant value; that means, we can replace the resistance with their with the current sink because it is going out. In case of a constant power load, the i 0 will be power magnitude by v 0. So, because the product of i 0 into v 0 is p 0 constant power which is constant.

So, by that way we can consider a different type of load and the complete block diagram is shown here. We know this block is corresponding to the inductor, and this is the initial value of the inductor current. This will correspond to the initial value of the capacitor voltage and by this block we can get easily the output voltage inductor current capacitor voltage everything we can get.

Even if we want to tap the capacitor current, we can simply take from this point this current and capacitor current multiplied by r c is my v 0. Similarly, i 0 we are getting v 0 multiplied by 1 by R because voltage by resistance is a current. So, if you want to consider the load current with the combination of resistive load and current load. So, you can put an adder block. Also here, we can put adder block here that current because of the resistive load plus we can put a another constant current load right.

So, these are all possible. So, that the net load current which is going out of the you know the current like a r L branch is it comprise resistance other thing, but here since we are talking about parallel RLC circuit. So, it is a purely you know there is no constant current load in this case, but whenever we will show converter there, the load need not to be always resistive load ok.

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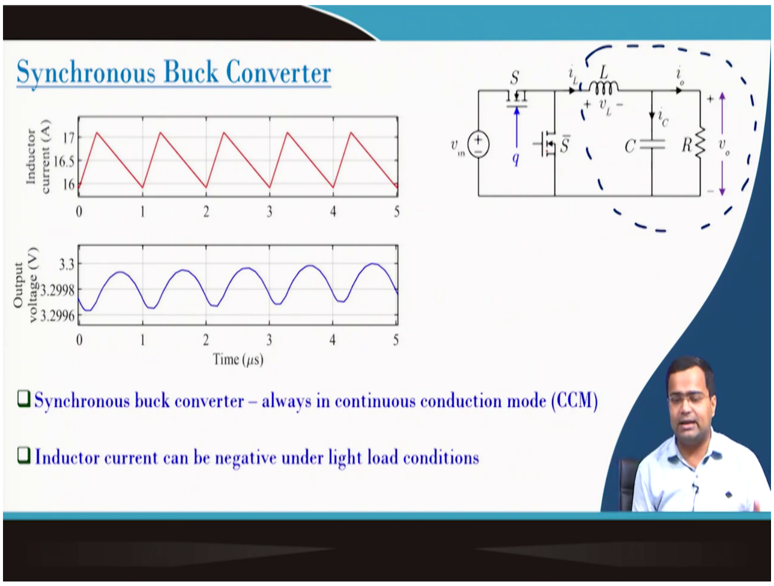

Now, we learn about parallel RLC circuit with practical parasitic and I will show you how nicely we can connect this with a switching converter. If you take a buck converter, you will see this RLC branch will look like a parallel RLC band branch was there in the earlier example we saw and this all RLC be particularly L and C. We can replace with their practical parasitic. And the switches in this case actually these switches are not ideal switches.

So, this is I am just showing a simulation result where this is an ideal switch and it shows the q when the q is 1 the current rises because I am talking about this part the q is 1 and again it goes like this. So, this is my q. When the q is on the switch is on when the q is 0 the switch is off ok.

So, you can accordingly draw the waveform ok. Now this switches then we sync. This is called synchronous buck converter, since we are using two MOSFET and they operate in a complementary fashion that we discussed earlier; that means we can achieve negative current because MOSFET also allows the current in the other direction.

So, this converter always operates in continuous conduction mode even under no load condition. If the load resistance is removed, it will still operate. In that case, there will be back-and-forth power flow; that means, when the current is positive, the current will come out from the source when the current is negative; that means, you are going you are giving the charge back to the source. So, inductor current can be negative under light load condition.

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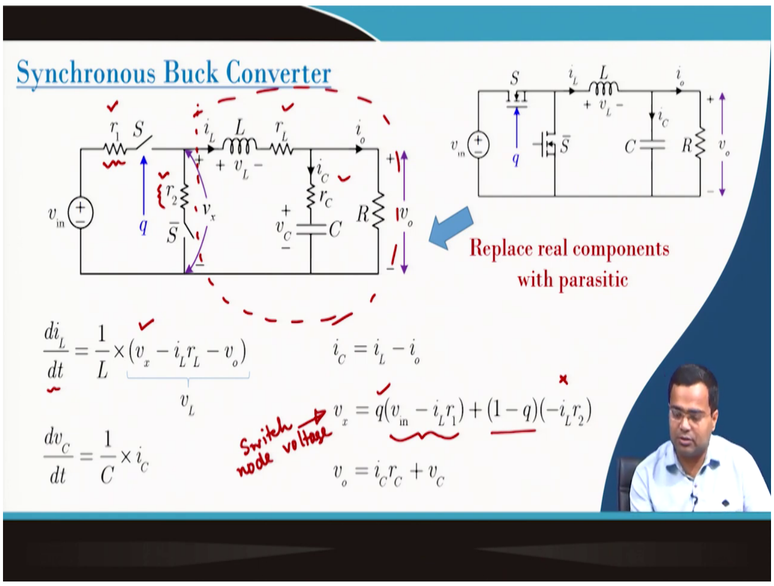

So, in this synchronous buck converter, if we want to replace all these component including switches with their practical parasitic, we already know about this r L r C. But now for switches we are considering ideal switching; that means we are not considering here turn on turn off practical process, but that can also be included if we can include the switch models.

But here we are only considering the dc resistant on time resistance of the MOSFET r 1 and r 2 are the on time resistance of switch a and s bar and if you consider v x. If you just look at this circuit, you see for this RLC parallel circuit, we already have implemented the block diagram.

Only difference in the earlier circuit we have an input voltage v in, but nowhere voltage is v x and in this case this voltage is called switch node voltage. This voltage is not a fixed voltage, it is a pulse setting voltage. So, we can again write all the differential equations. This is bar v L the inductor current dynamics. We can write capacitor voltage dynamics. We know the capacitor current, but here instead of input voltage now you have a switch node voltage.

So, this voltage is switch node voltage, and this is what we call it as a switch node voltage switch node voltage, but this voltage is a pulse setting voltage. When q is on 1; that means, switch is on it takes v in minus r L sorry, v in minus r 1 into i L because the drop this represents the drop across this resistance.

When the switch is off; that means, s bar is on then it takes minus r 2 into i L; that means, the drop across this part and 1 minus q means when q is 1 this part does not come does not arise when the q is 0 then this part arises. So, depending upon the q configuration. So, it is a pulse setting voltage.

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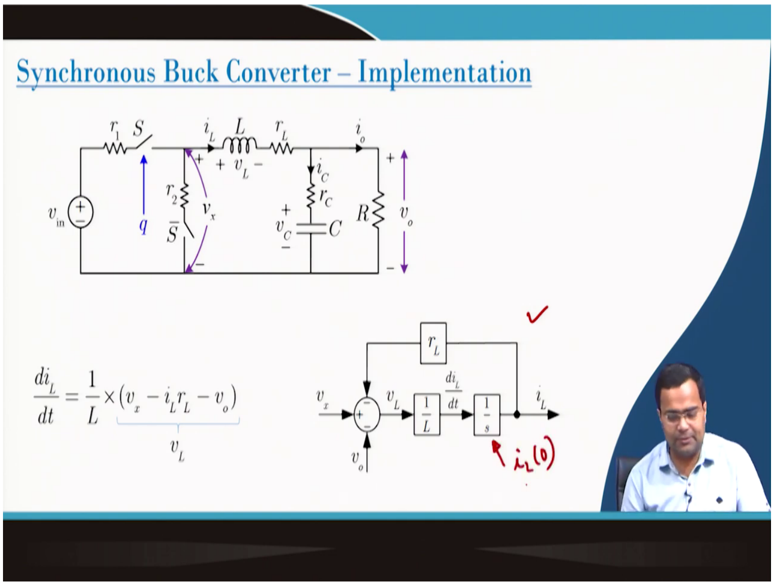

So, now again we can write down this equation and we can this part. We already know how to implement and we can plug in this i L initial condition.

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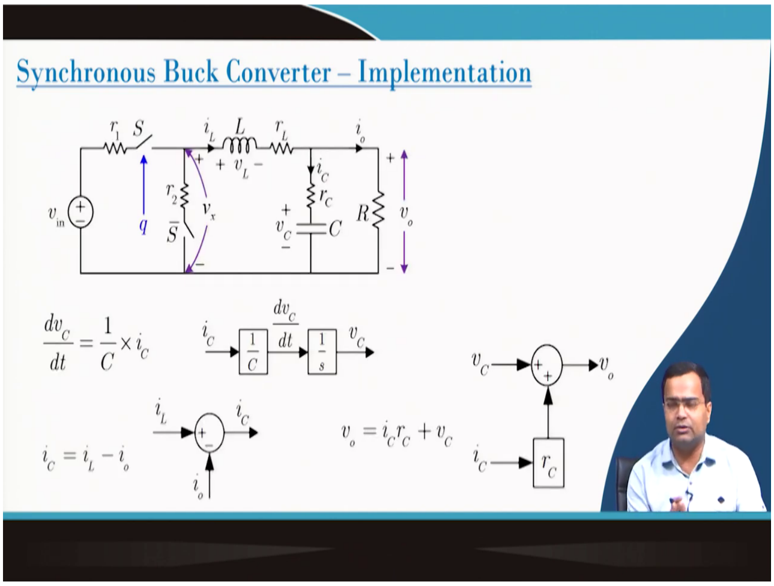

We can also plug in the capacitor voltage. There is no problem, we already did it. But these parts are well known we have already shown, but what is interesting here we need to derive the switch node voltage.

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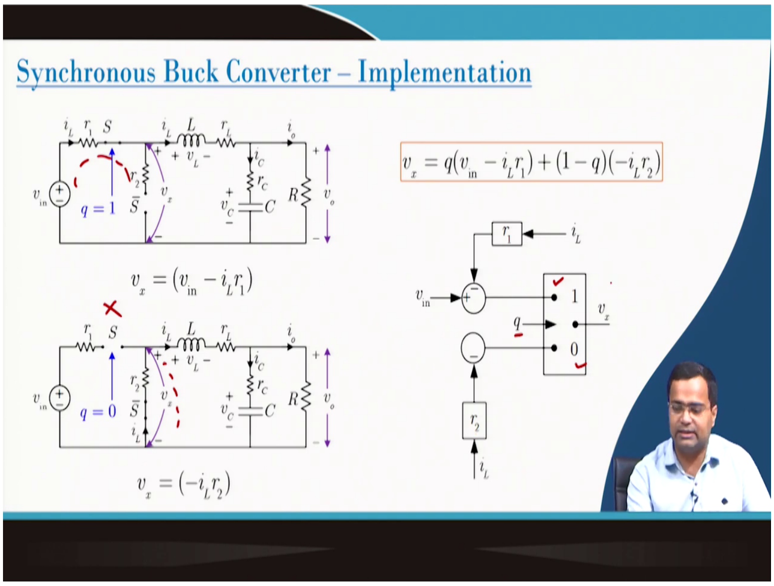

So, this switch node voltage when the q is on this is v in minus i L r 1; that means, we are talking about this part of this circuit. When the switch is off we are talking about this part of the circuit. This part is disconnected.

So, it will be minus i L r 2. So, we can plug in this and we can simulate using a switch in the MATLAB Simulink. This switch represents when q 1 q is 1 it will take the first input, input 1 this is the first input point when q is 0 it will take the second input which is minus r 2 into i L and that is why by that way we can generate the switch node voltage.

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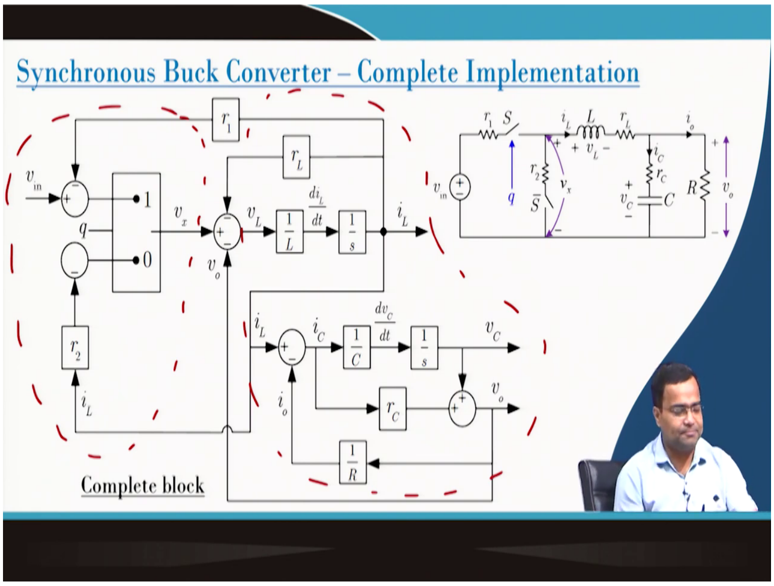

Now, we can combine this whole thing to get the complete representation of the synchronous buck converter. These parts this whole part is well known to us because we did it for our parallel RLC circuit with parasitic, this is a new additional block which is coming due to the switching configuration of the switch node voltage, because it is not a fixed voltage.

This is you know you can. You can think that in a parallel RLC circuit, we can also apply a pulse setting voltage. So, similarly, we are generating the pulse setting voltage from here.

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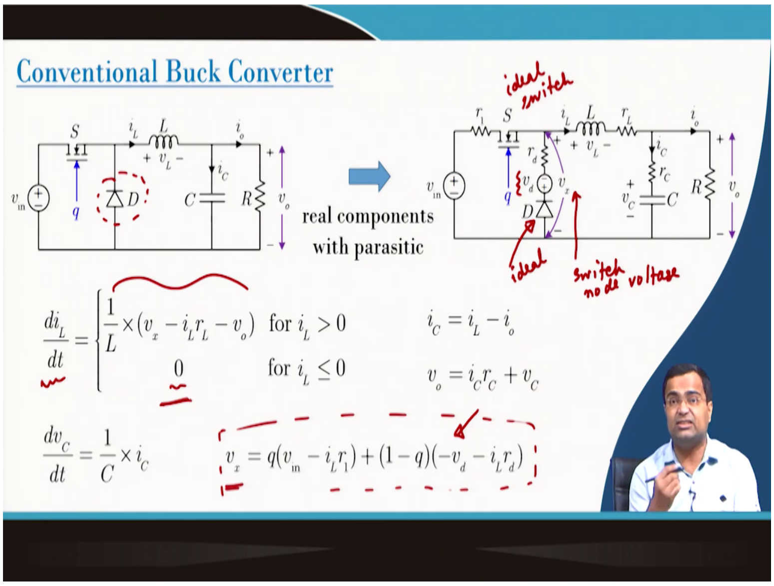

But now if we consider a conventional buck converter, where the low side MOSFET is replaced by a diode. Now this is the diode we have replaced the low side MOSFET. If we want to represent this circuit using their practical parasitic can be a real component, then this MOSFET actually this should be an ideal switch this will become an ideal switch and it is basically a single pole single through switch with a series resistance of r 1 that is a on time resistance.

The diode will be replaced by and this is an ideal diode, this is ideal, this is ideal along with the practical parasitic. What are the parasitic in a diode? We can consider the resistance of the diode like a r d resistance drop series resistance of the diode or it is called forward resistance and also the forward voltage drop, which is v d v d here.

Now, like a similar to the earlier, we can also denote this as a switch node voltage. This is my switch node voltage switch node voltage ok. What is the difference in this case compared to earlier? Earlier case, it was low side we have a MOSFET which can carry current in the negative direction, but now we have a diode. So, diode cannot carry current in a negative direction.

So, whenever the inductor current become 0 or it try to go negative direction, then this part during the off time because when the switch is off I am talking about the scenario when the switch is off the current is falling when the current hit the 0 current then the diode is reverse biased. So, it cannot carry current in that case the voltage across inductor or basically d i L d t a rate of change of current should be 0 and current also is 0.

So, now d i L d t earlier was a single equation, which was this one, but now we have an additional logic due to the 0 current of the diode. So, we can again write the capacitor equation, we can write output voltage equation, we can write the switch node voltage equation all this we can write. So, we can derive the switch node voltage and along with that.

So, this is somewhat similar to the earlier synchronous buck converter only addition is that you have a diode forward voltage drop and the resistance of the forward resistance of the diode you can think like analogous to the on resistance of the MOSFET.

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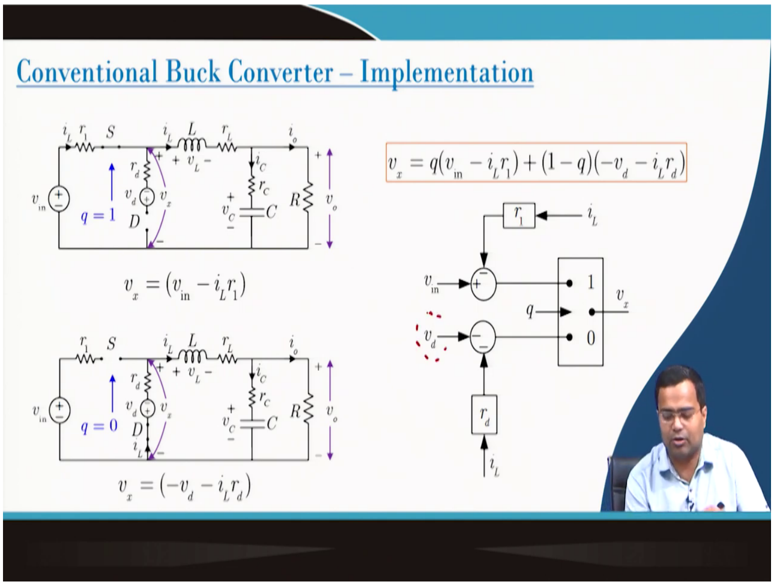

But because of this zero current logic, which is a discontinuous conduction mode, we need to do a little different thing. We know when the switch is on this is a condition when the switch is off this is a condition and along with diode reverse this is without 0 current is a straightforward when the current is positive this is simply enough and we already have this for the synchronous buck converter only we are adding this particular block.

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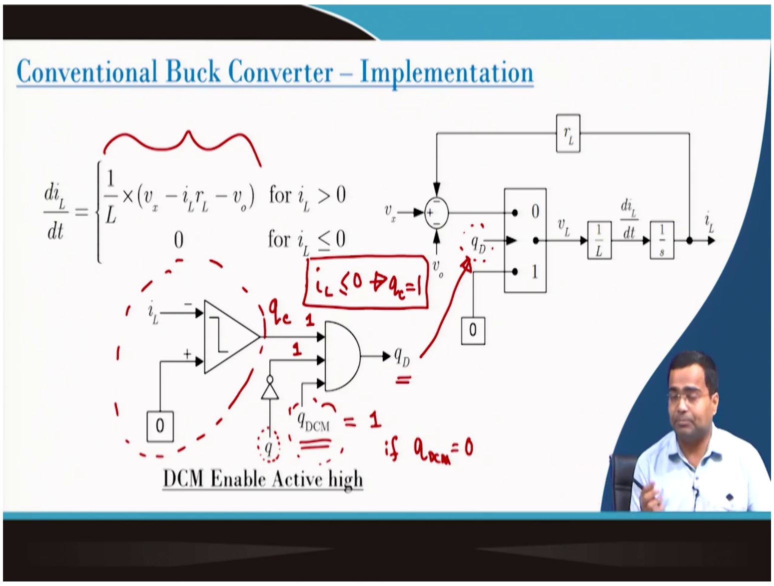

But what happens when this zero current logics comes in. So, how can you realize? So, we can realize you can say we are generating a q D block, which corresponds to a switching signal when the DCM condition is hit; that means, 0 current is hit. So, this signal is used when q D equal to 1. This means that the DCM logic is hit, then the v L the voltage across the inductor is 0 if the voltage across the inductor is 0 d i L d t is 0.

So, whenever it hit 0 current, we are keeping the derivative of the inductor current 0. As a result, inductor current is 0 and it is derivative is 0. So, it will remain at 0. When the q D is 0; that means, off it takes the earlier value; that means, this one this is the value, and this is a realization.

So, this can be realized by a DCM enable active high where you say this block actually detect the zero current using a comparator. So, if the inductor current is compared with a zero current and whenever inductor current try to go beyond below zero current then this comparator output this comparator output becomes high.

If the comparator output becomes high; that means, I am talking about the i L is less than equal to 0 this give rise to q c equal to 1. When q c equal to 1 this signal is high now and we are talking about the scenario when output the q switch is off; that means, if we do this thing like a current is already at 0 and switch is turn on, then if we continue these logics the inductor current can never rise.

So, in order to avoid that we are talking about, we are also checking the status of the switch; that means, the control switch of the high side MOSFET if that switch is 0; that means that switch is off; that means, diode is carrying. W e are talking about the turn off condition. If it is in the turn off condition, this logic is also 1 now, we are giving an additional enable logic.

Do you really want enable DCM or not? If DCM is not enabled, then as if it is like a synchronous buck converter, there is no discontinuous conduction mode. This block is particularly used because you know integrator circuit you know instead of using a pure diode they use a MOSFET in the low side and they also use an emulated diode that they emulate a diode using transistor.

So, whenever you want to achieve first step down transient that we will discuss later we allow the current to go to negative direction for some time so, that the capacitor can be quickly discharged and then when the current again comes close to 0 then we enable the DCM operation.

So, by that way this q DCM can be configured in the run time ok. If q DCM is set to 1 then only DCM operation is possible, but if it is set to 0 if q DCM is set to 0 set to 0 whatever DCM condition is detected, you will not enable a DCM operation; that means, it is now we are using a MOSFET ok.

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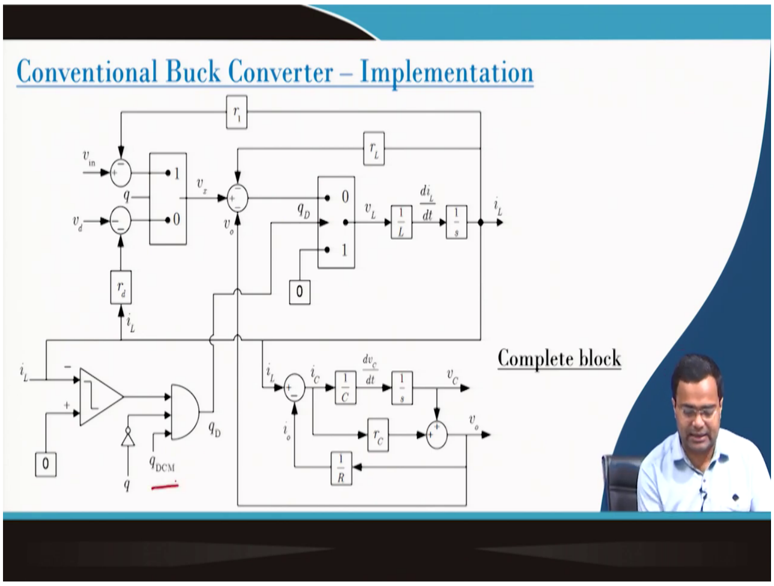

So, with this block, how can we generate this q DCM q D now. So, this is this block is generating q D which is used for this purpose this purpose. That means, when the q D is 1; that means, if DCM is detected and it is enabled, then d i L d t will be 0 and inductor will remain at 0 current.

When this block will be 0, then it will take the regular operation when the inductor current will rise or fall depending upon the switch condition. This is particularly when the current is above 0.

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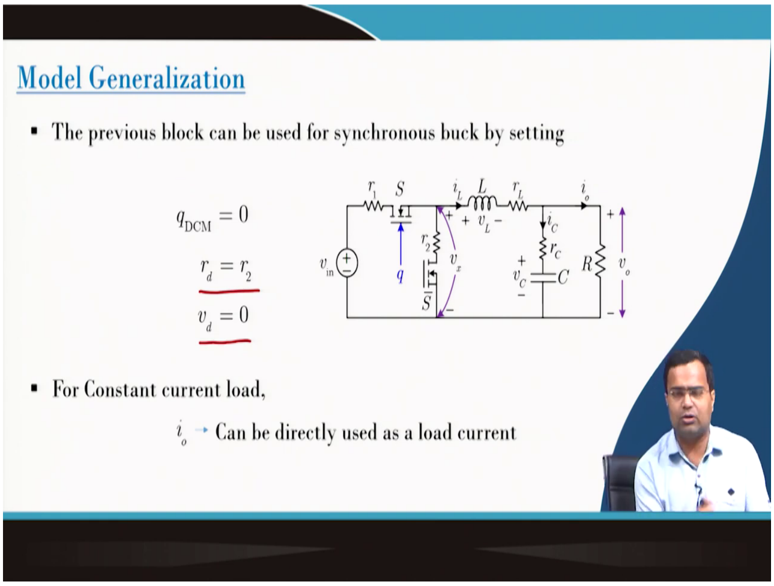

So, now, we can implement the complete buck converter circuit, including this DCM enable block. This model can be generalized. If we set q DCM to be 0, then as if we do not want a conventional buck converter. This can be configured to a synchronous buck converter where we can simply set that diode drop to be 0 and this r d is now replaced with the off time like on time resistance of the low side MOSFET.

So, now this can be a synchronous buck converter can be derived or the model can be implemented using conventional one by setting this parameter. So, the load current can be directly used as a load current or it can resistive load, it can be constant current load, it can be constant power load, and accordingly the load current should be generated.

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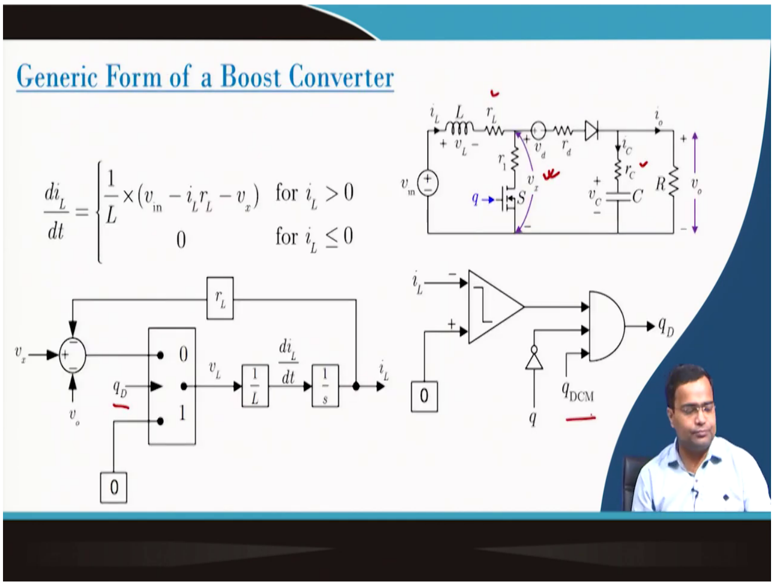

Now, if you take a generic form of a boost converter. So, boost converter inductor is sitting here and again we have a switch node voltage this is my switch node voltage and again we can consider the diode drop if we consider a conventional boost converter, ESR of the capacitor, DCR of the resistance we can write the derivative of the inductor current. Again, if we enable DCM operation, we need to check whether inductor current is going below 0 when you need to stop the current or you need to keep the current at 0 condition.

Again, this block can be realized the similar way to a discontinuous signal; that means, this q D and the q D can be generated by a DCM_enable that we discussed earlier.

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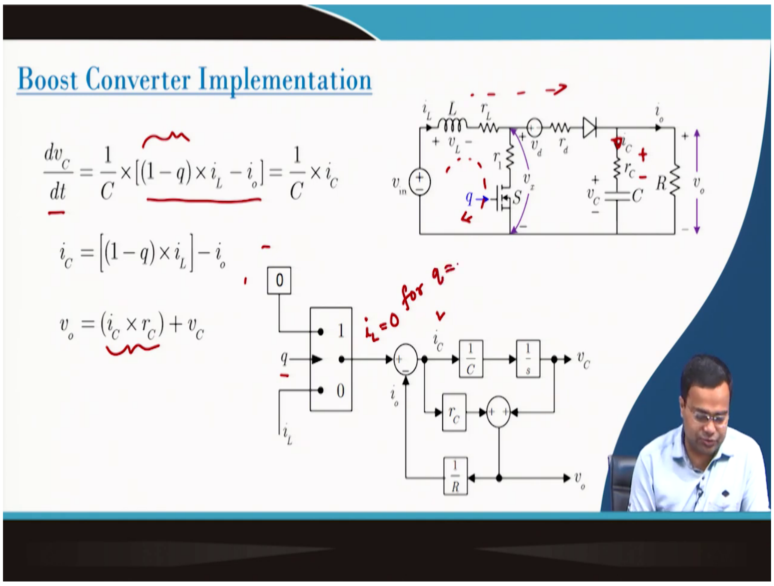

Now the boost converter dynamical equation of the output voltage can be realized. This means that you can see the capacitor current for the boost converter here. It actually becomes whenever the switch S is on, when q is high. Then inductor current actually flows through this path flows through this path, and the capacitor current is nothing, but minus load current and this is this can be shown from here.

But when the switch is off, then it is going through this path. In that case, the capacitor current is nothing, but inductor current minus load current. So, you can put you can write in terms of a switching signal 1 minus q ok. Then output voltage is nothing but capacitor voltage plus the drop across this ESR; ESR drop and which is nothing but this drop.

So, you can implement the output voltage equation. Here we have to consider the capacitor current is discontinuous and that can be realized by putting a switch block when the switch is on it will take 0 current; that means, i L equal to 0 when the switch is on for q equal to not i L equal to 0 I will say sorry this current this is not i L; that means, this current is 0.

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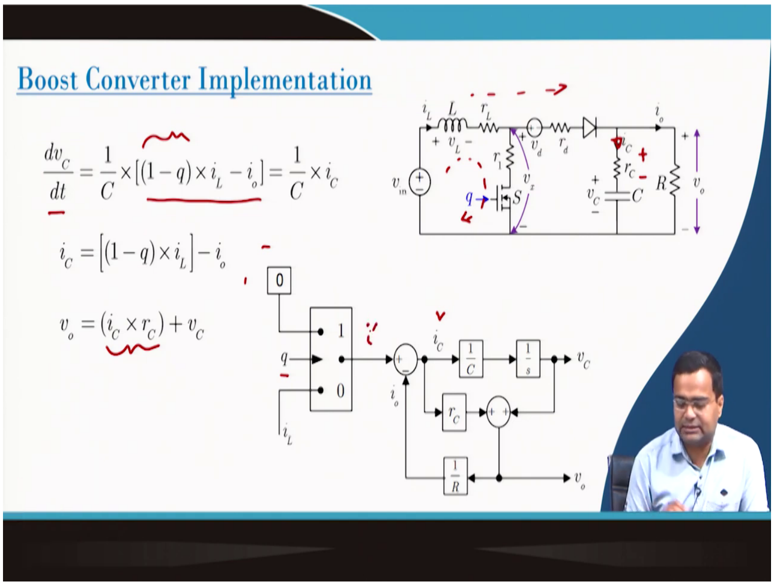

This particular current let us say i_dash it is 0 when switch is on when the switch is off it is nothing, but the inductor current.

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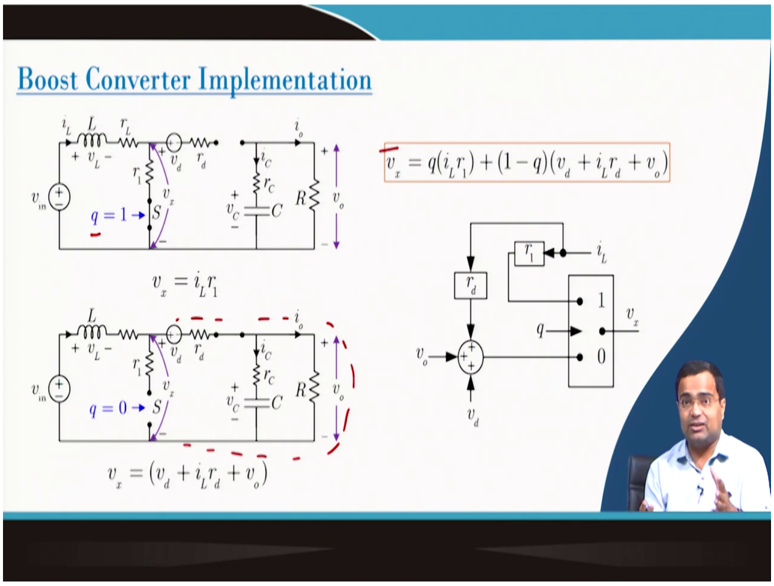

So, the complete diagram of the inductor boost converter is shown. The switch node voltage is equal to i L into r 1 when the q 1 is on and this is equal to v d d plus i L r d plus v 0 from looking at this terminal this side, we are talking about this side when the switch is off. So, you can plug in this switch node voltage and that can be realized using this switch block in the Simulink.

So, we can now implement the boost converter again if you want if you do not want a DCM operation; that means, if you do not instead of a diode if you replace with a switch synchronous boost, then we can disable the DCM operation also using q DCM block that we discuss earlier. That means, we can you know what we discussed earlier, the q DCM block we can set to 0.

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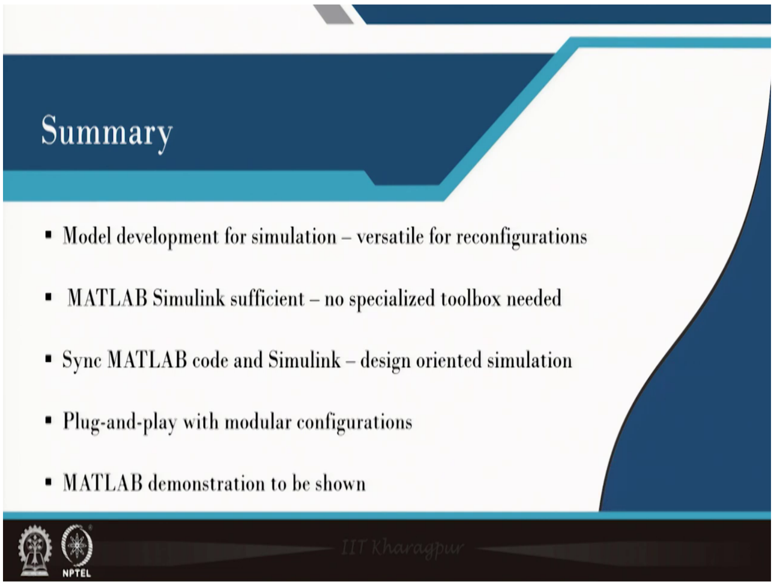

And this will show in the MATLAB simulation how to enable and disable DCM operation. In summary, we have discussed model development for simulation and these models are versatile for reconfiguration. In fact we can plug and play type blocks, we can if we want to implement multiple converter, we can plug on this block we can create subsystem.

If we want to realize a more complex converter comprising more energy storing element we know how to implement individual storing element differential equations into the Simulink block. Then you can simply keep on adding this block. The MATLAB simulation Simulink is sufficient. We do not need you know specific like a specialized tool box like a sim power system and other tool box.

So, this custom blocks enable you to better understand the converter, and you can realize many effect in Simulink block itself. We can sync the MATLAB code with a Simulink file you know and that the design we can simulate design oriented case study and these blocks are plug and play and their modularity like we can make the design modular and MATLAB demonstration to be shown at the next presentation.

Thank you very much for today.