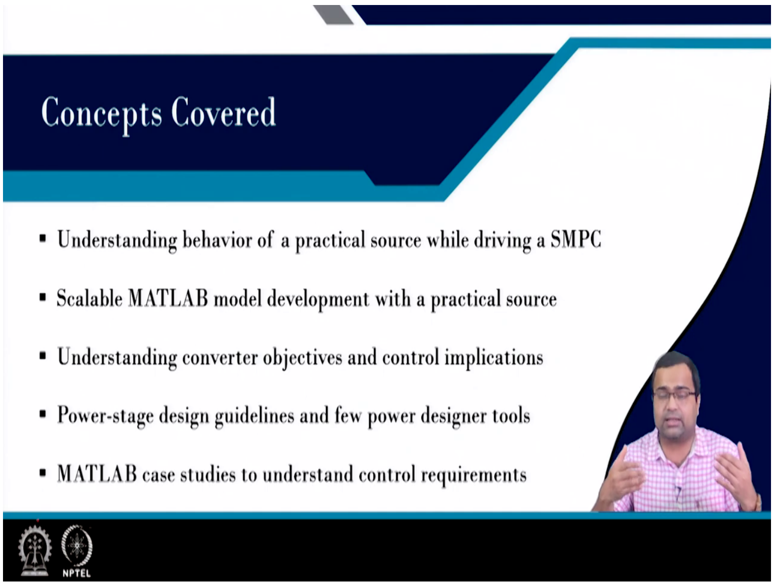
Control and Tuning Methods in Switched Mode Power Converters
Prof. Santanu Kapat
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

Module - 03
Fixed Frequency Control Methods
Lecture - 13
Converter's Objectives and Control Implications using MATLAB Models

Welcome. This is lecture number 13. In this lecture, we are going to talk about Converter's Objective and Control Implication using MATLAB Models.

(Refer Slide Time: 00:39)



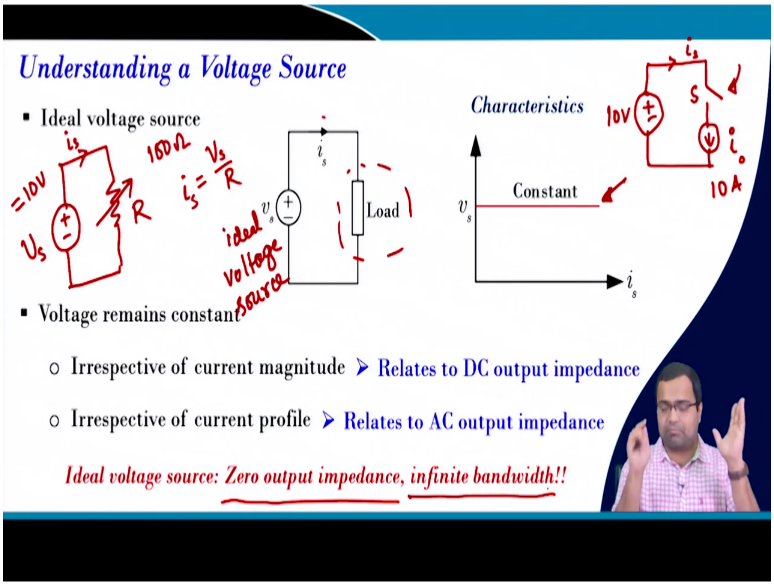
So, in this lecture, we are going to first talk about the understanding of behavior of a practical voltage source, while driving a switch mode power converter. Then, we want to also discuss the development of MATLAB model.

So, in this lecture, I am also going to talk about the models are scalable. Because we talked about that you know we created one subsystem for a converter and I will show you that if you develop the subsystem of a filter or a source, you can simply plug and play, attach that block to another converter and so on.

So, that also with a practical source, we want to develop a scalable MATLAB model. Then, we want to understand what are the converter objectives and control implication implications. So, before that, we want to create a few motivating MATLAB test cases, to show why do we need like a various static dynamic and you know other objectives and then, what is the need for control.

Then, we also we will talk about some power stage design guideline and few power stage designer tools. And finally, the MATLAB case study will be you know in this lecture. We will also show MATLAB case study to understand the control requirement.

(Refer Slide Time: 02:07)



So, first, we will talk about a voltage source. When we talk about voltage, source the first thing that comes to our mind is an ideal voltage source and here, I am talking about an ideal voltage source. So, this is an ideal voltage source; ideal voltage source. So, in this source, we have connected a load.

So, this load can be a resistive load, this load can be a constant current load. So, it can be a different type of load. But the objective in this particular talk what I am going to talk about, what is the current and voltage characteristic of an ideal voltage source.

And in various textbooks from our undergraduate, we have studied that if you draw current; but yes, generally, we do not talk about the limit of the current. But suppose if the source current has a certain limit, within the limit, if we draw within the limit or in fact, you know the ideal definition is the there is no limit on the current.

So, if you draw current from the source, any amount of current, the voltage should remain constant. That is the basic definition of an ideal voltage source and it is shown here. So, that means, your current your drawing current, but the voltage remains constant.

You can see this is a constant voltage. That means, the voltage remains constant irrespective of current magnitude; that means, there are two ways of looking into this problem. The one way we suppose we take a resistive load, suppose you know we are talking about a voltage source and we are let us say connect we have connected a resistance ok.

This is a variable resistance, and this is a source. Now, but we have to keep in mind because if we vary the resistance, suppose we decrease the resistance. Let us say we start with the voltage source is of 10 volt and we start with a resistance of let us say 100 Ohm. Now, we slowly decrease the resistance value. So, if you decrease the resistance value, naturally, what is the current flowing through this resistance?

The current will be simply v s by R; that means, if we reduce the value of the resistance, the current will increase. But we need to keep in mind that this resistance power rating should be such that it can withstand that heat generated. Because i square R loss that will introduce that will actually lead to you know heating effect because the Joules law; it comes from the Joules law.

So, that means, if we reduce, if we keep on decreasing the resistance slowly by using a potentiometer, then the current will increase and you can actually create this condition and you will see the voltage should remain constant, if it is an ideal voltage source. But when we are talking about slowly varying resistance, in fact manually varying, then it relates to the very slow characteristic, and that is nothing but the DC output impedance.

That means we are talking about the output impedance of this source is 0. There is no output impedance; that means, there is zero output impedance, there is no drop. Now, we can also talk about suppose we create a transient case study; that means, another case study, where suppose this is my voltage source. Again, it is a 10 volt. Suppose I apply a switch and this is my constant current and it can be resistive load. This is my i 0 and this is my source current.

So, if I turn on and off this switch S, this is my switch S periodically; that means, when you turn on the switch, suddenly and let us say this i 0 is let us say we are drawing some maybe 10 Ampere current; may be let us say we are drawing 10 Ampere current, 10 ampere.

So, when you connect the switch, suddenly we draw 10 A. When you disconnect the switch, then we are totally disconnected. That means the source is now unloaded; that means there is no load and when we connect, it is fully loaded, that is 10 A.

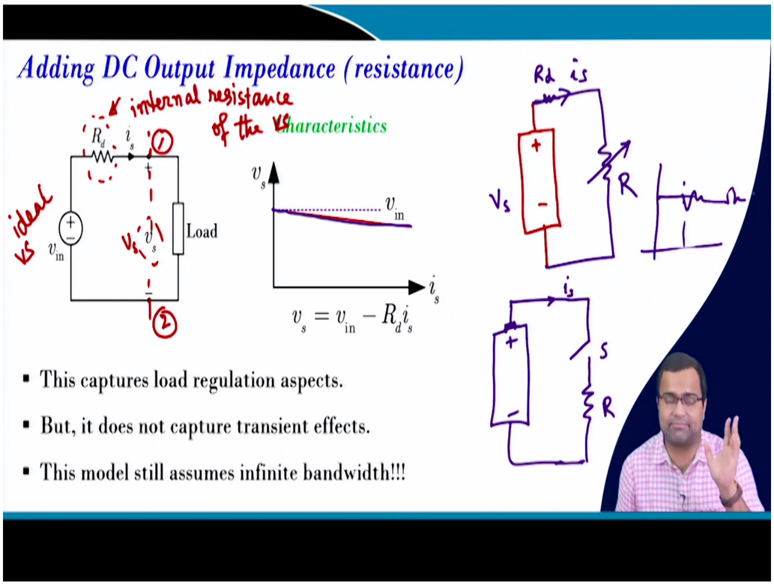
So, this is another current profile, where we will talk about the transient current ok. So, earlier, the current was continuously changing, but it was a very slow process. So, we are talking about the DC output impedance.

Here, we are talking about the current is repeatedly connected and disconnected or you can create a pulsating current by means of a current source. But remember, this slew rate of this current has to be much faster. This relates to the AC output impedance.

So, if there is no change in the output source voltage, even after applying the transient current. Then that means, then we talk about two thing; the one thing is a zero output impedance that is a DC characteristic and the third second one is an infinite bandwidth; that means it has no undershoot overshoot in the voltage irrespective of the transient current ok.

So, the ideal voltage source has two characteristic; in the DC characteristic, we talk about zero output impedance and the AC characteristic; we talk about infinite bandwidth. That means, there is no frequency dependent term, it will respond to any transient current.

(Refer Slide Time: 07:42)



But we want to we know that ideal voltage source does not exist in reality. So, all voltage source are practical and when we start our undergraduate first year or second year, the first thing we have taught that if we want to convert an ideal voltage source into a practical voltage source, the first thing we do we add a series resistance. So, this is a series resistant to R.

This resistance is a part of the source because it is an internal resistance of the source as this is an ideal voltage source. This is our internal resistance we can talk about; this is our internal resistance, our internal resistance, internal resistance of the voltage source, it is a part of this.

That means, what is accessible to us is the two terminals; terminal 1 and terminal 2. So, this is our actual source voltage. That means, this is our v_s. In this case, if we draw the current and voltage characteristic of the ideal voltage source, sorry the practical voltage source. What we can will find?

In fact, if you take a battery, suppose, for example, you take a battery ok and battery positive and negative terminal and if you connect; I mean this you can try it out; you connect a variable resistance like a pot. It is a battery and you decrease the value of the resistance, you will find the battery voltage is decreasing; it is like something like this.

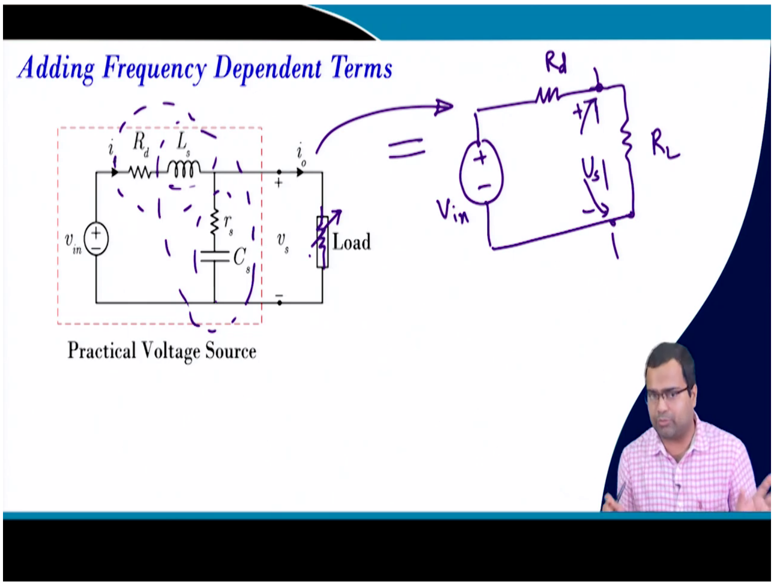
That means, when the battery voltage is decreasing, when you are trying to increase current; that means, you are drawing more current from the battery. This is the source current. Now, here battery is the voltage source. Then, the voltage is slightly slowly decreasing and this can be modeled or this can be characterized by adding this resistance and that is why, in the ideal source, there will be a series resistance here that is our R d ok. As if this is an ideal voltage source.

But this captures the load regulation aspect; that means, all voltage source has some finite DC output impedance, the DC characteristics; but it does not capture the transient. Because still if we apply a transient current. Suppose you again take a battery and you know again you we take a battery and now, we apply a switch and again; we apply a resistance here. Now, we turn on and off this switch in a periodic manner.

Now, you will no longer find that it only. So, there will be some effect of the battery; that means, battery voltage if you draw, we will soon see that battery voltage was clean, when you start drawing current, there will be some kind of effect will be there. Again, you leave like this.

So, we will see some transient effect, but this only adding resistance is not enough to capture this behavior because all voltage sources, practical voltage source has finite output impedance as well as it has finite bandwidth ok. But this model still captures what we learnt, the basic practical voltage source that model does not capture the bandwidth effect I mean effect, but as if it assumes that it has an infinite bandwidth.

(Refer Slide Time: 11:25)

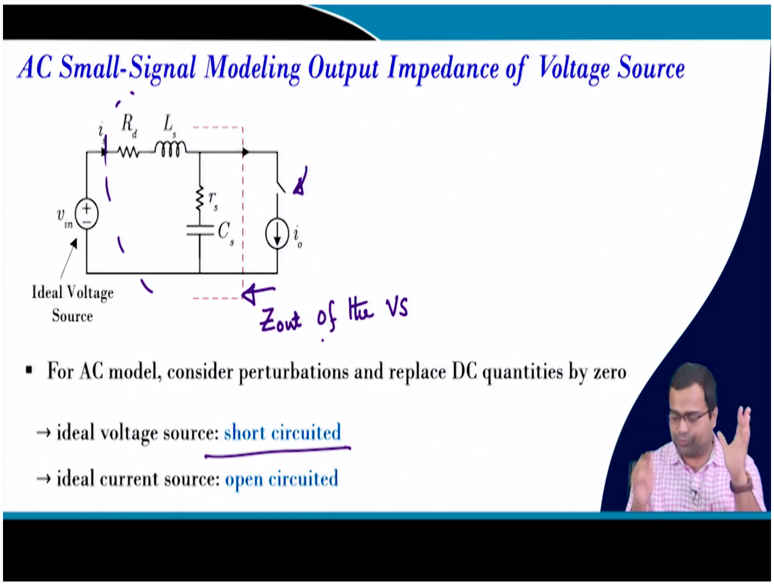


Now, we want to add frequency dependent term. So, we want to model a more realistic voltage source and this can be modeled by introducing some effect of L C circuit and because this is even if you consider a DC-DC converter which is the major theme of this course, almost the whole course is based on the control of DC-DC converter. The DC-DC converter itself we want to regulate the output voltage; that means, we want to achieve a regulated output voltage, which means we want to achieve a voltage source.

That also we will see that you know the DC-DC converter, we generally connect an output filter. So, that filter will have some finite output impedance as well as finite bandwidth. So, that means there will be some overshoot undershoot and if you take a step down DC-DC converter, buck converter. We know that this L inductor is there on the output side and capacitor is there on the output side.

So, applying that common sense, we can think of an ideal voltage source can have some amount of finite inductive and capacitive effect. But you may model in a more accurate way. But this is one of the simplest way to model, which can capture the transient behavior or the finite bandwidth aspect of the of a voltage source.

(Refer Slide Time: 12:50)



That means this is what we are going to. Now, this voltage source if we do AC model; that means, if we now it is an ideal voltage source and this if you look at the impedance from this side, that means, we are talking about the output impedance of the source of the voltage source. Then, here, we are talking about the AC characteristics that mean there will be a frequency dependent term and that will lead to some overshoot undershoot, when we when you consider a pulsating current; that means, this transient current ok.

And it will also you know it will also capture the DC characteristic that we will see because if you talk about because in the previous consideration, we only took I know a resistance here. This resistance we have considered, that was the DC.

But now, in this AC characteristic, if you want to analyze DC, you are applying a resistive load ok. You are changing the resistance value slowly, that means it is a low frequency effect and in the low frequency, the inductor will behave like a short circuit and capacitor will behave an open circuit.

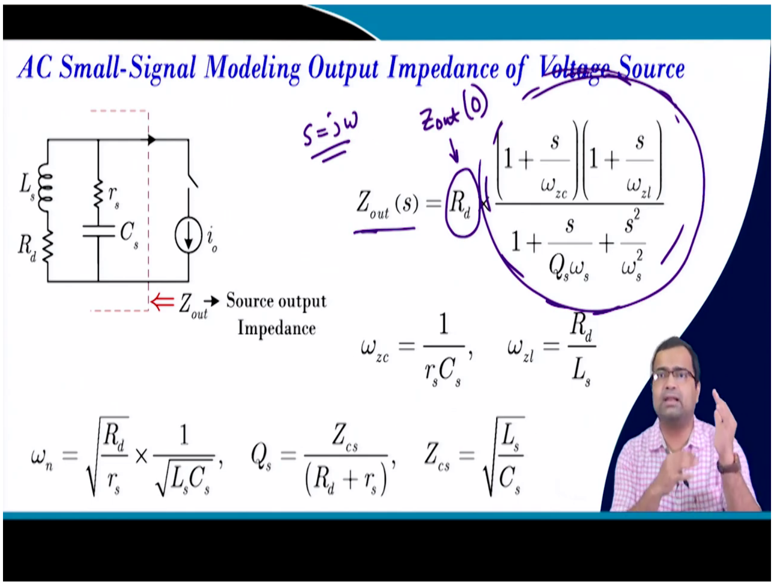
And if it does, then this resistance this will be equivalent to again this voltage source v in R d and then, here we are connecting, this is my load. So, this is my source terminal; that means, this is my actual voltage source terminal. So, this is a low frequency model of this. That means, this is a low frequency model of this, where we are assuming that current is changing very slowly, where this transient effect will not come into the picture because it will be died out it will decay out ok.

Except for the fact that if this L C oscillation may cause some oscillatory problem, if you take you know for a specific choice of L C for some set of L C, you may end up with some oscillator behavior; but we are not talking about that ok. So, output impedance transient behavior, in order to get the output impedance of these characteristics of this source, we need to get the AC equivalent circuit and that can be obtained by considering you know all DC term.

We will learn in the subsequent lectures from the equivalent circuit model that from a given circuit, we can extract the DC equivalent circuit. We can extract AC equivalent circuit. Also, the original model is a large-signal model which considers both DC and AC and in order to extract AC equivalent circuit, we generally keep all the DC quantity is 0.

So, for a voltage source, ideal voltage short should be short circuited and ideal current source should be open circuit because current we want to replace 0.

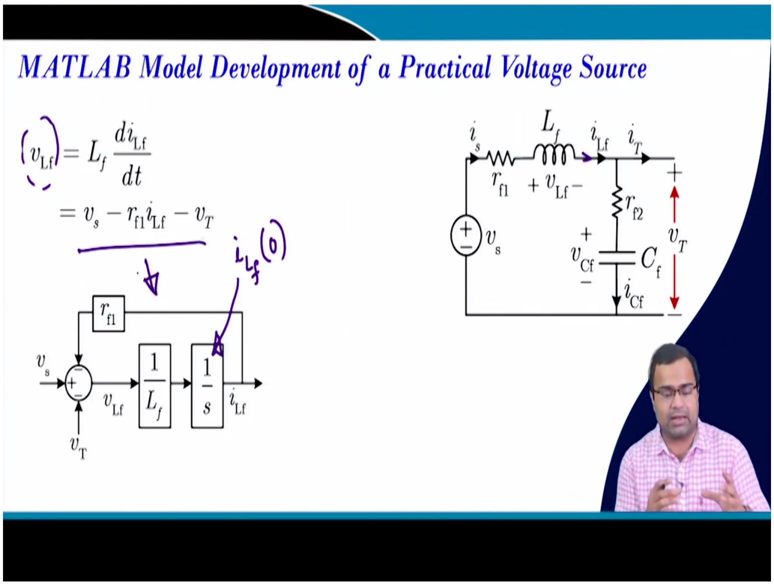
(Refer Slide Time: 15:56)



And then, we can get the AC equivalent model of output impedance of the source like a parallel branch of L C circuit with parasitic resistance. Then, we can write the output impedance of the source and it can be shown that from this model, the parameters are this. In fact, this is quite similar to the output impedance of a buck converter, only the value will be difference that different values.

Now, if we consider this model and if you make that s equal to j omega; that means a frequency response and if you substitute omega tends to 0; that means, at low frequency behavior, all this term will become 1 unity and it will become R d. That means, this is the DC that means this is the output impudence at 0 frequency; that means, it is the DC output impedance and that we have started with the practical voltage source by putting an internal resistance in series.

(Refer Slide Time: 16:58)



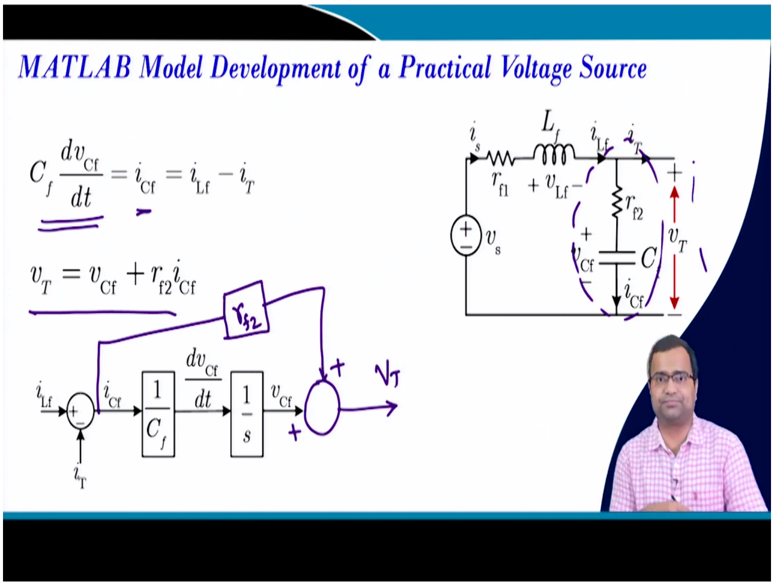
Now, we want to incorporate this ok. Because what we talked so far of a DC-DC converter, we have consider an ideal voltage source drive by just taking a number in the MATLAB; but in reality, the voltage source will be practical and in this course, we want to understand the control objective.

So, we need to know if the converter is connected to a practical voltage source, then what causes that can happen and then, in the control as well as you know the other aspect in the converter design aspect. How can we take care of such a practical aspect?

So, in order to get, we need to develop the MATLAB model of the source and we have already discussed in lecture number 4 how to build you know the model which can be used for simulink simulation and this is a similar approach that is why I am not going detail again and again. Here, you can set the initial value of this filter current which is passing through this inductor, ok.

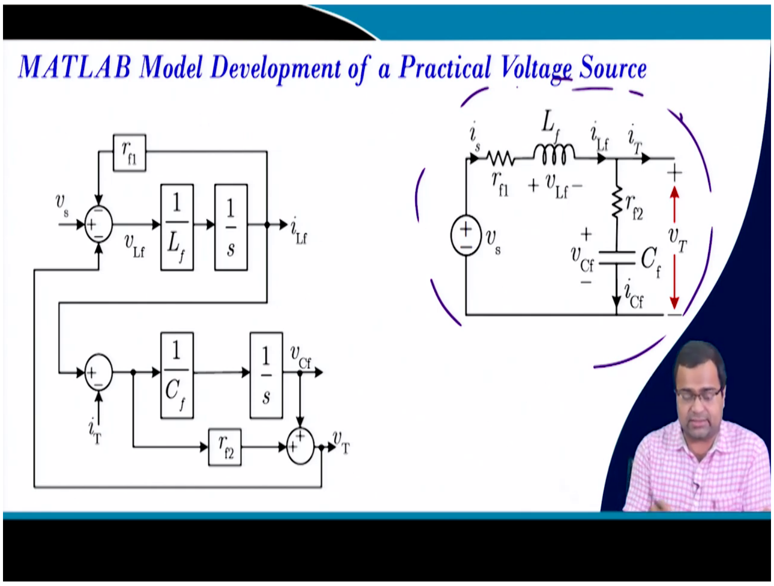
And again, you can write the voltage across the inductor is the differential equation and from this equation, you can get this model; that means, you can realize this equation using this model.

(Refer Slide Time: 18:13)



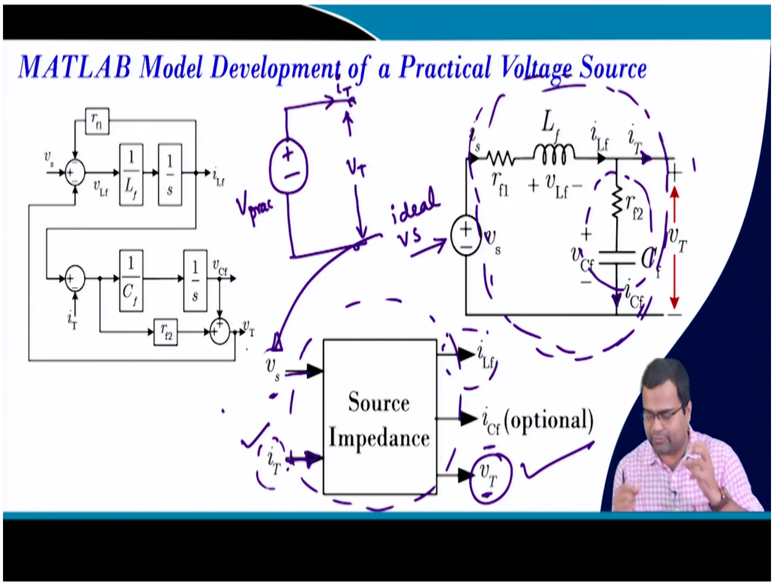
Similarly, you can realize this dynamics of this capacitor because this is a capacitor current, the capacitor current going through this path and then, the terminal voltage of this filter is nothing but the source voltage, which can be obtained by adding this together. That means, here we got v Cf. So, if we add this v Cf plus if you tap this point and if we add this r f 2 and if you add together. Then you will get actually v terminal which is a source voltage ok.

(Refer Slide Time: 18:52)



This is a complete model of this particular filter and this, we can build in MATLAB and I will show you just you know in a few minutes. So, we have this model task.

(Refer Slide Time: 19:04)



And this model, you can make a subsystem and in that subsystem, if you look at this, for this source that means this is the impedance model of the source right, this is the impedance model of the source. For this impedance model, this is an ideal voltage source. So, I mean this is an ideal voltage source which is here; ideal voltage source that is the input to this block.

Another input which the current going out of this block because they are depending upon that how much current the other circuit. Because we need to connect this source to a load, the load can be, in this case is a DC-DC converter. So, DC-DC converter will draw some current. So, that current is the load to this block, input to this block, this simulink block.

Depending upon how much current it is drawing, whether because we told that earlier, if we connect a pulsating load to the source; so that means, depending upon the nature of the load, the amount of you know current it is drawing, the source voltage characteristic will vary. That means the time domain waveform of the source voltage depends on the profile of the current that you are drawing out of this source.

So, that is the input. Then, what is the output? The output to this block is the terminal voltage, which will be connected to the input to the next block, where we are going to drive which one which we are going to drive. We can also optional; it is optional that we can tap this current, we can check though in actual circuit this block is the capacitor.

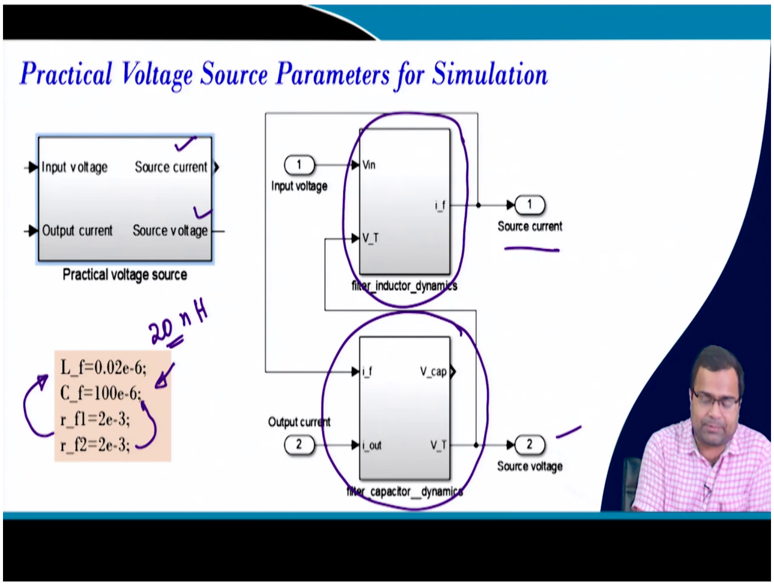
So, it is a ESR of the capacitor which is an integral part of the capacitor. So, we cannot access it. But for simulation, we can check it. We can also access this current of this inductor; but again, these are optional because you know whenever we talk about a practical voltage source, I will say a practical voltage source, so only this terminal voltage is accessible to us; nothing else is accessible.

And what is accessible is the current going out of this terminal; that means this correct which is an input and here for our understanding, we created this model. But when we actually take a source, let us say if you take a power supply of a lab; that means, we generally, use power supply for connecting as the input to the DC-DC converter.

So, now, this power supply can be treated as a practical voltage source in which we can only access the current coming out of that power supply and the voltage terminal voltage of the power supply ok.

So, that means, this is accessible, this is something accessible, and this is accessible which is coming out; the other things are internal. But in this simulation, since we are connecting this is a separate, so we are connecting an ideal voltage source. So, this whole thing is combined as a voltage source.

(Refer Slide Time: 22:04)

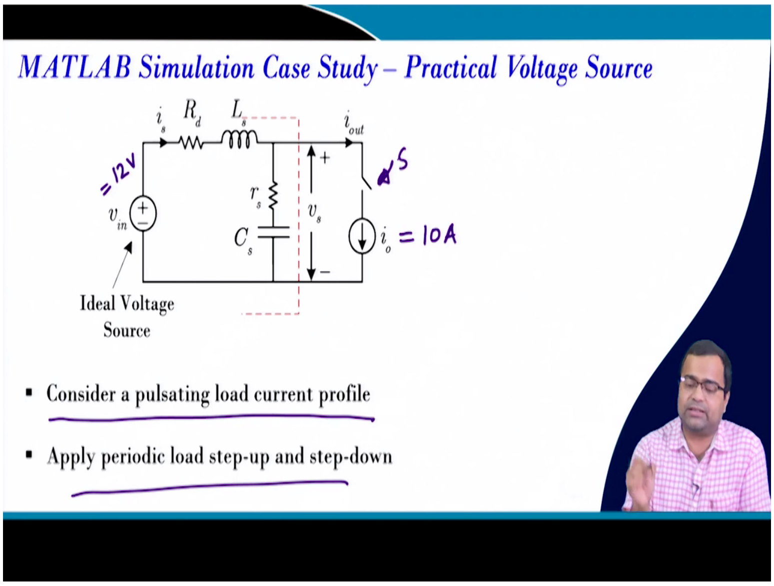


Now, I want to show the performance of a practical voltage source. So, I have created a model, I will go to the model is a simulink block ok. If I go inside the simulink block, it has two subsystems; one is the inductor current dynamics and which we are discussed in the converter model. So, I am not going to do that, but I will show you in the simulink block another dynamical equation is linked with the capacitor current of the filter ok and then these two of the terminal.

So, these are the terminal volt of this block and we have taken for simulation the L f; that means, the inductor of the series path is 0.02 micro Henry that is it is 20 nano Henry. Because this could be traced in that term, as if you know we are putting even it can include the cable resistance, inductor of the cable resistance because we generally connect a cable from the actual power supply to the DC-DC converter.

So, that inductance can be you know you can incorporate that or you can put a large value does not matter, but I am just I want to show you. Then, the capacitor which is in the output side of the source and this is the DCR of this inductor and this is the ESR of this capacitor.

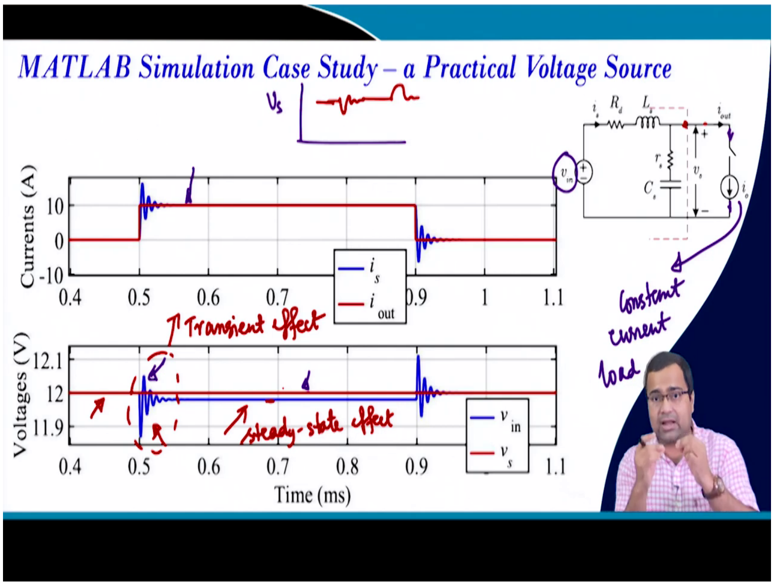
(Refer Slide Time: 23:25)



Now, I want to show a simulation case study because that we have started with the very beginning that if we draw a pulsating current from the source. How does the wave from the source voltage look like ok? So, what I am going to show? I want to consider a pulsating load current profile; that means, periodically, I am connecting and disconnecting the switch.

So, that I am this I am taking as a 100 Ampere current and this I take as a 12 volt source, ok. And then I am applying periodically; that means, this switch, I am turning on and off in a periodic fashion ok.

(Refer Slide Time: 24:03)



So, this is the simulation case study. See here the red trace that is shown here. Red trace is nothing but i out; that means this is because this is nothing but the constant current source that means, this is the constant current load because we are connecting a load. So, that is why irrespective of the supply voltage, you know, because we are talking about a voltage source now.

When you talk about a constant current source a load, that means the current load will behave like an exact ideal current load. So, that is what we have emulated here: the red wave form. Then, the red wave from here is the ideal voltage source that is v in here ok, but what is accessible to us is that source voltage terminal and that is indicated by the blue traces.

So, this is what is accessible because, as if you take a laboratory power supply. If we look at the waveform, that means, if we look at the waveform of the power supply, our v s is the power supply and we want to see what happen suppose if we do not draw any current from this, here it will be. But suddenly, if you put a transient current, then there will be some overshoot effect. Again, if you remove the current, there will be some undershoot effect.

So, this is exactly what is happening here by the blue trace is indicating. That means, there is a transient effect due to the finite bandwidth of the voltage source and voltage source has some. That means, it will respond to the transient current if you apply some step current.

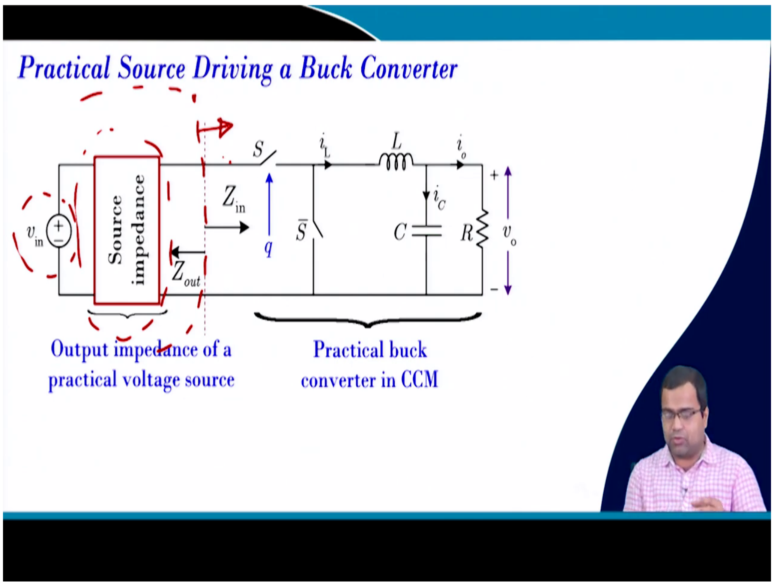
Now, why we are interested in this? Because our DC-DC converter, another point I want to show here, you see here initially these two points are exactly overlapping because there was no we are not drawing any anything out of the source; that means, our both inductor, capacitor, they are all kind of discharged. So, that means, this point will be same as the input voltage, but when we are apply a 10 A current there are two things.

So, this portion is a transient effect. We can see the transient effect is a transient effect. This portion is the steady state effect. So, in the steady state, you see the blue trace voltage is slightly less than the red; that means, it has a drop and that drop can be attributed to suppose if we what is the R d?.

We took R d to be DC r. So, it is 2 milli Ohm. So, 2 milli Ohm into 10 Ampere is how much? It is a 20 milli volt 2 milli 20 milli volt. So, if you measure, it will be something around 20 milli volt difference. So, this drop is due to the resistance in the series path and in DC equivalent circuit, we have seen the inductor can be shorted, capacitor can be open.

So, it will look like an whatever practical voltage source we have learned in our very basic undergraduate course that means, a resistance in series that will be reflected ok.

(Refer Slide Time: 27:25)



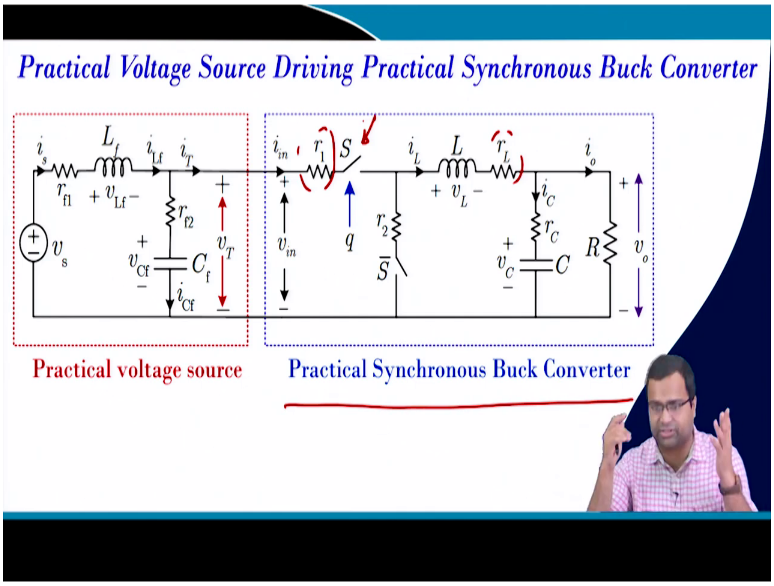
Now, when such a practical source is connected to a buck converter for driving; that means, as if this is my source and this is connected to the DC-DC converter, ok. And the input voltage for sake of modeling, this is our ideal voltage source and in most of the simulation in subsequent, we may not consider this. Because we are assuming that, I mean this effect is negligible; but it may be, may not be negligible.

But I want to show that if you draw because this if you take the buck converter, the buck converter input current is discontinuous. That means it should create a similar transient effect in the source if you repeatedly turn on and turn off this high side switch because it will appear like a pulsating load.

And this pulsating load will create such transient effect and this transient effect will actually cause which is called conducted EMI because it will cause some disturbance in the power supply and that is propagated through this current source correct. This is propagated to the source current, and that is replace that is that can be used to quantify the conductor EMI; that means, if you take the power of this voltage source, not all power will be you know associated or it will be along the DC value.

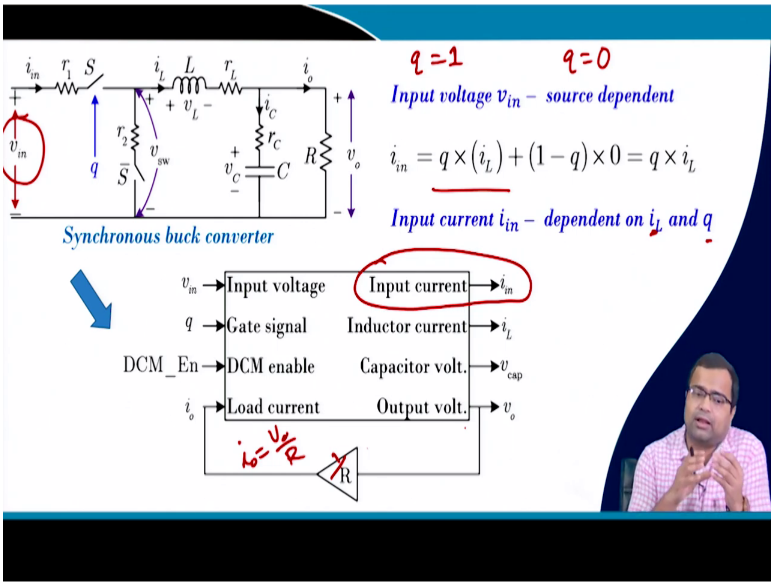
There will be some power which will appear at the damp frequency of this transient behavior, where some power will come and that power can come at very high frequency and that is associated with the EMI effect and if that power amplitude is large, then that power can interfere with different communication devices ok. That means the practical buck converter.

(Refer Slide Time: 29:21)



Now, if you take a practical voltage source and which is driving a synchronous buck converter, a practical buck converter, you see I have taken this parasitic of the switch. Though we have not considered the switching capacitance and other, like you know drain to get to source capacitor, then drain to source capacitance, those can be considered also; but their dynamics are even much faster ok.

(Refer Slide Time: 29:51)



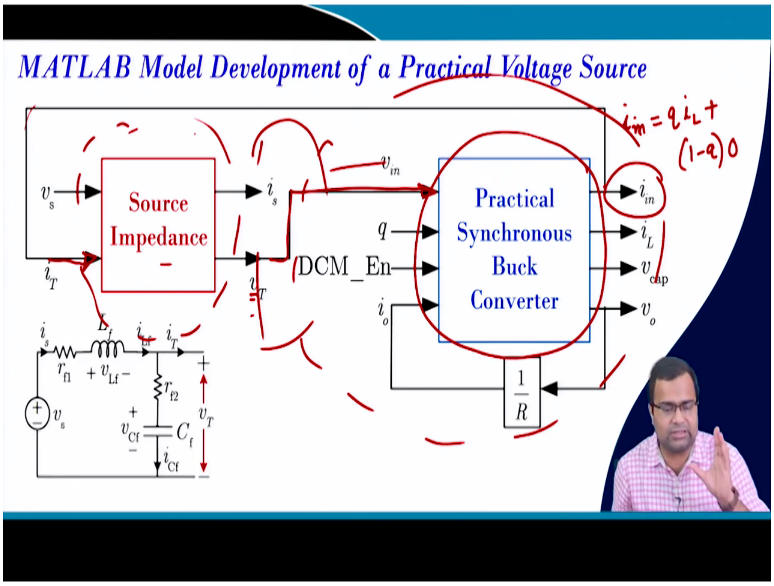
So, now how to build such model like a plug and play, the synchronous buck converter, we so far we have show whatever model we have developed up to lecture number 12, we have not considered the input current in that or in our simulink block. But now, it is very easy because out of this model what is input voltage of this converter is source dependent because you are connecting a practical source here ok.

Earlier, we used just a number. Now, the input current will for the buck converter is same as the inductor current. When the switch is on that means, when your q equal to 1, it is nothing but the inductor current and when the switch is off, it is nothing but that means, q equal to 0, it is simply 0. That means, there is no current ok. That means, input current depends on the inductor current as well as the status of the high side switch ok.

So, we can create now we have earlier model, but we have added this extra terminal because this terminal will be used for building block for adding input filter or a voltage source to the converter ok. Because earlier we have shown the converter simulink model, where we have connected this should be 1 by R; a resistive load because the current is equal to v 0 by R ok.

But now, so that means, you have connected resistive load. Now, we want to connect the filter to the converter. So, my question is that should we need to make a whole subsystem again? I want to tell no.

(Refer Slide Time: 31:32)



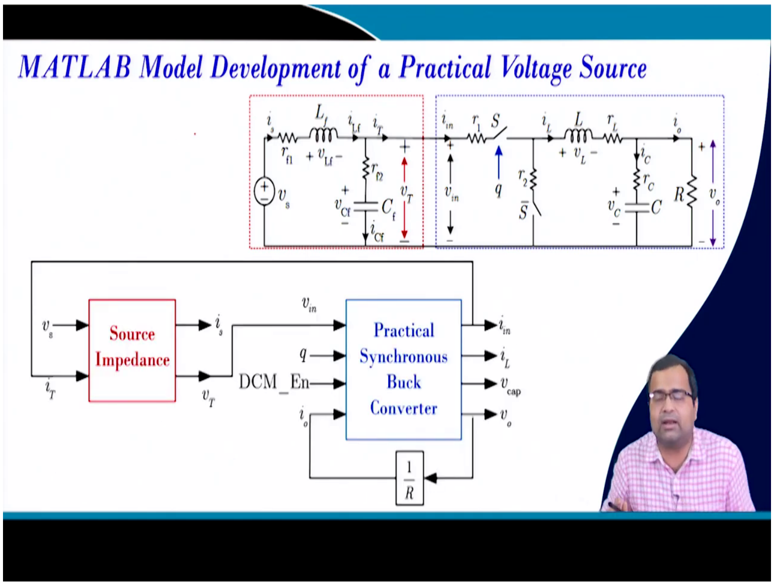
How? That means, our practical synchronous buck converter model we already have, the only thing I have added is the input current I told you which is nothing but what the input current I have developed is q into i L plus 1 minus q into 0 because when the switch is off, it is 0. So, this block, now the input current of the buck converter is nothing but the output current of the source.

So, it is simply connected here and the output voltage of the source terminal voltage is nothing but the input voltage of the converter, ok; that means, if we just connect them, it is like a dragon drop model right. So, as if we have a converter and here, we have model another model; that means, if you want to add another module like input filter, you can just connect in between and it is again dragon drop model.

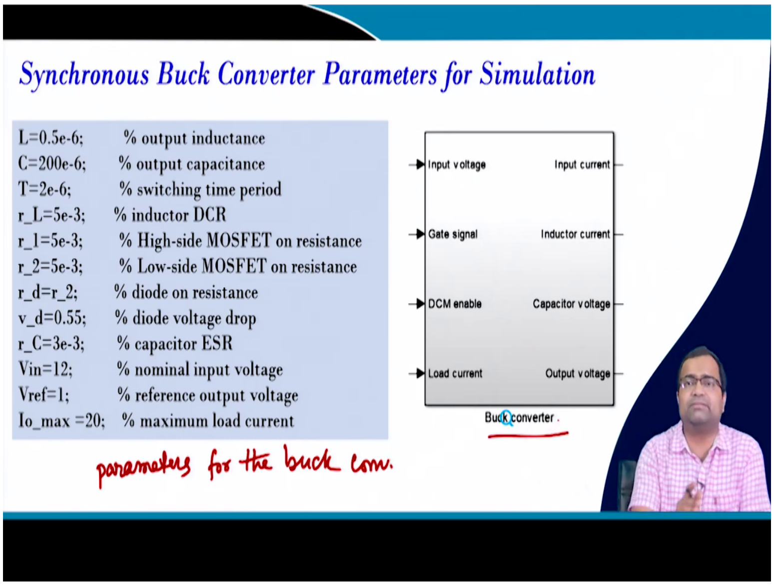
So, this model is plug and play type. You develop one model, but you need to create the terminals such that you can interconnect the source or any other converter. In fact, I will show you in lecture number you know probably in say 16, where we want to show that another converter if you want to create a cascaded DC-DC converter. That means the first stage, second by second stage, then one model just you create copy paste of the other model, change the parameter of the complete model.

Then, output of the first converter will be the input to the second and the input current of the second converter will be the output kind of the first. So, the similar configuration can be created to create a plug and play type module, ok.

(Refer Slide Time: 33:21)

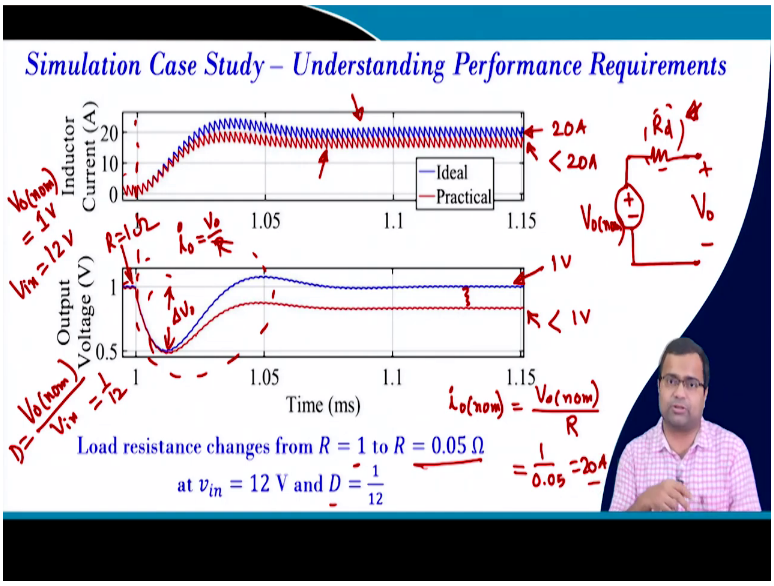


(Refer Slide Time: 33:27)



So, this is the source impedance. Now, we can this is a complete model ok and with this model, we want to create some simulation parameter. So, I have created this parameter for simulation. For the buck converter, it is the same that we have taken earlier. This is I called as a buck converter parameter or you can say it is a buck converter just a minute. So, it is a parameter file. I will show you it is a parameter file; it is a parameter for the buck converter ok. So, this is a model and all the parameters are defined in a separate dot m file.

(Refer Slide Time: 34:08)



Now, I want to show first thing. The first thing is that here we have taken an ideal voltage source, and we have created an open loop case study, where our objective is I want to achieve output voltage nominal value to be 1 volt. That means, this is my reference voltage and my input voltage here I set 12 volt ok. So, if you take open loop DC-DC converter, then what we will do?

And we will simply say D equal to 1 by 12 because D equal to v out nominal, which is the 1 volt divided by v in and this is nothing but 1 by 12 that I have taken. Now, interesting point here, we will see. I have considered two load resistance value; it is an again here we have connected an ideal voltage source because we will see the practical voltage source in the subsequent simulation result.

In the ideal voltage source, but the converter is practical that mean it has parasitics and all, you see when the load resistance was 1 Ohm; that means here R equal to 1 Ohm, then what is load current? Load current, it will be v 0 by R and v 0 is very close to 1. So, load current will be roughly 1 Ampere.

Now, I have taken two cases; one ideal buck converter, which is the blue one, where there are no parasitics and the red one is the practical buck converter, which is they are parasitic. And you see, at 1 Ohm resistance, both are nearly identical in terms of the average current, in terms of the average output voltage; they are almost close to each other.

But when we increase the load resistance from 1 Ohm to 0.05 Ohm; that means, our target load current was 20 Ampere; that means, we wanted to achieve i 0 nominal to be v 0 nominal by R which is nothing but 1 by 0.05 is 20 Ampere is my nominal current. But for the ideal case, you say here we are getting 20 Ampere load current nominal. But in practical case here, it is less than 20 Ampere.

Another point, the output voltage here you can see it is roughly 1 volt; it is 1 volt average, but here, it is much less than 1 volt. Now, the question is why it is happening? That means, this difference between this voltage, which was almost negligible for R equal to 1, now becomes very much prominent and that difference increases when the load current increases or the load resistance decreases.

That means, this can be attributed to our output DC impedance, DC output impedance because we just now talked about a DC voltage source. That means, if you take an ideal buck converter, you can assume that you have a nominal voltage that is our desired value, nominal with some resistance R d and this is my actual output voltage that we are getting and this R d is 0 for an ideal converter.

But in practical converter, when you go for dc equivalent circuit, I will show you this R d primarily depends on the inductor DC resistance of the inductor, on state resistance of the switches and if you have a diode base implementation. This drop can be also part of the diode can contribute to this drop ok.

So, that means, this R d, it shows a practical voltage source, where the voltage drops when the load current increases and which is consistent. Another point, I want to show that I have just shown you, the transient effect because it is an open loop. So, the voltage is not simply; you know changes immediately. So, there are some overshoot and undershoot; whether it is an ideal buck converter or a practical buck converter, the overshoot and undershoots are there.

When there is a step of load transient, there is a voltage undershoot and it is around v 0. So, delta v 0 the voltage undershoot is there ok, and this is quite large around 0.5 volt; that means, the voltage has reduced from 1 volt to 0.5 volt, which is not acceptable ok.

So, that means, here from this waveform of the converter, we can clearly see that where we talked about because this converter is, you know, a voltage source; but since it is not regulated, in an open loop, it has a resistive drop. That means it has a finite DC output impedance, and it also has you know that AC output impedance which contributes to this overshoot undershoot behavior of the system.

Now, this motivates us that if because it is an open loop, we have fixed the duty ratio. So, our one of the objective of the control of this DC-DC converter, the first thing we need to reduce this R d effectively. That means, we need to generate the output voltage of the DC-DC converter in such a way if we draw, let us say the converter is rated for certain current; that means, if it is rated for nominal current or 20 Ampere.

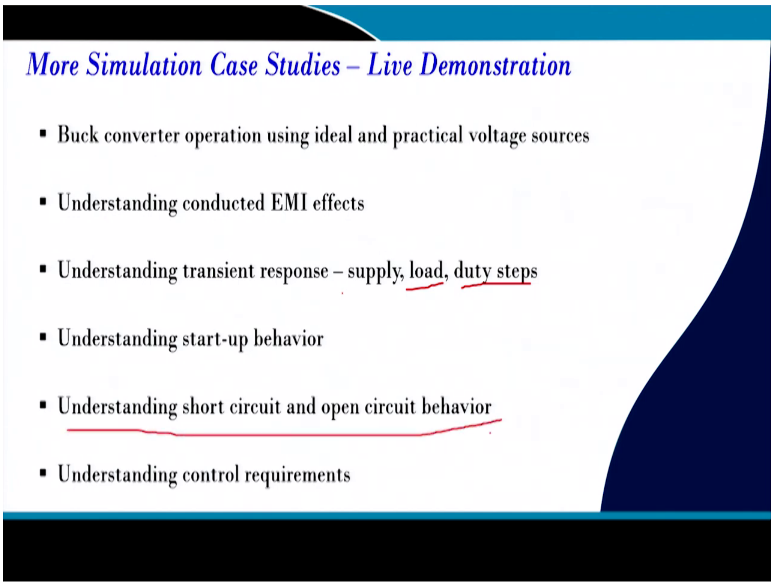
So if you draw from you know 10 milli Ampere or 100 milli Ampere, 220 Ampere throughout the current range, the voltage should be nearly 1 volt; that means, almost constant.

So, that can be achieved by closed loop control and we will see soon in the subsequent lecture. We need an integral action to reach steady state error, but that may take some time. Another thing, we will see the need for control is to this undershoot is not acceptable because you know in the very first lecture, we told that in processor application, where our current repeatedly will change like you know a large step transient happen step up step down.

So, this voltage will supply to a digital processor, where such voltage different can completely lead to a malfunction of the digital circuit because the digital circuit has certain noise margin. It has a certain voltage range for which the logic level will be treated as 1 and if we go beyond that, then the digital circuit will start malfunctioning.

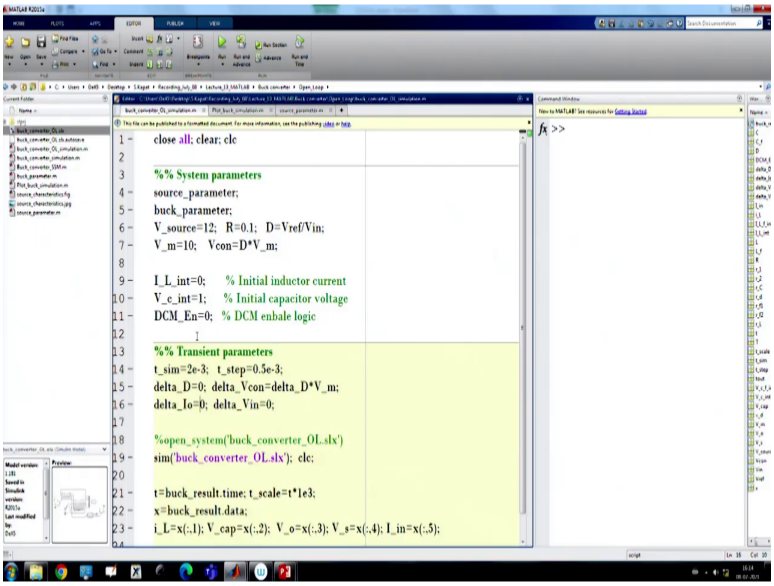
So, the DC-DC converter has to be tightly regulated within the noise margin of the digital circuit. So, we need to apply some control logic such that the undershoot can be substantially reduced so that the whole profile of the voltage can be within the limit of the digital circuit for which we are designing the power supply.

(Refer Slide Time: 41:44)

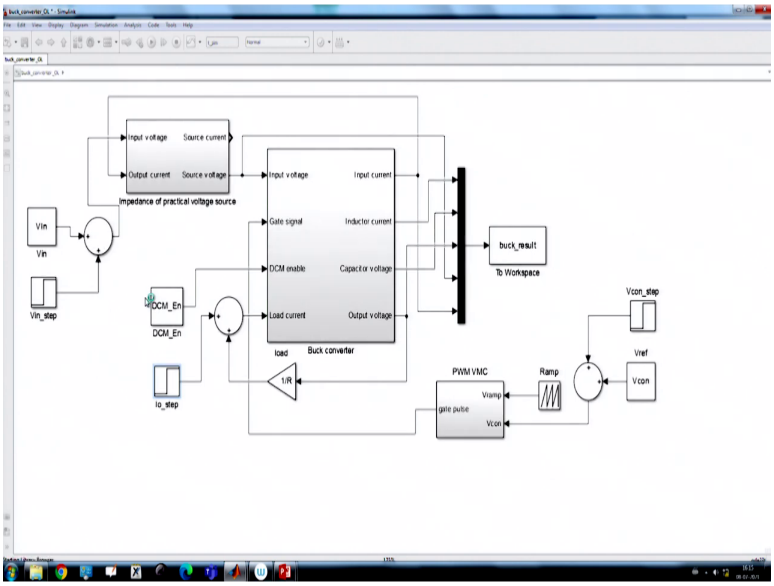


So, that means it motivates us we need to do something with closed loop control. Few more things we want to highlight; the buck converter operating using ideal and practical voltage source. Then, we want to see ok.

(Refer Slide Time: 41:56)



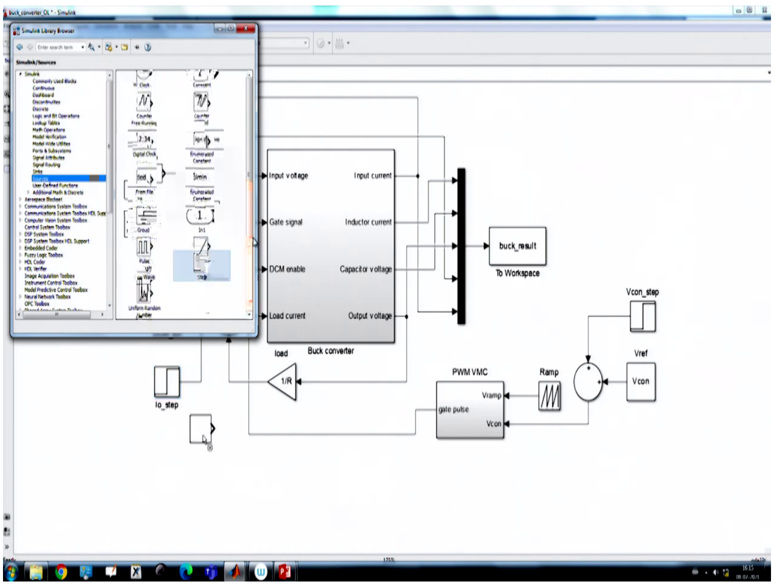
(Refer Slide Time: 42:03)



So, first let us go to the MATLAB, one by one we will check ok. Here, what we are considering? If you go to the simulink model, you can see this is our DC-DC converter, this block. So, this block is DC-DC converter, and this is our actual voltage practical voltage source impedance. I will not say source, the impedance of the practical voltage source; impedance of practical voltage source because ultimately, it requires a supply which is here ok, which is here ok.

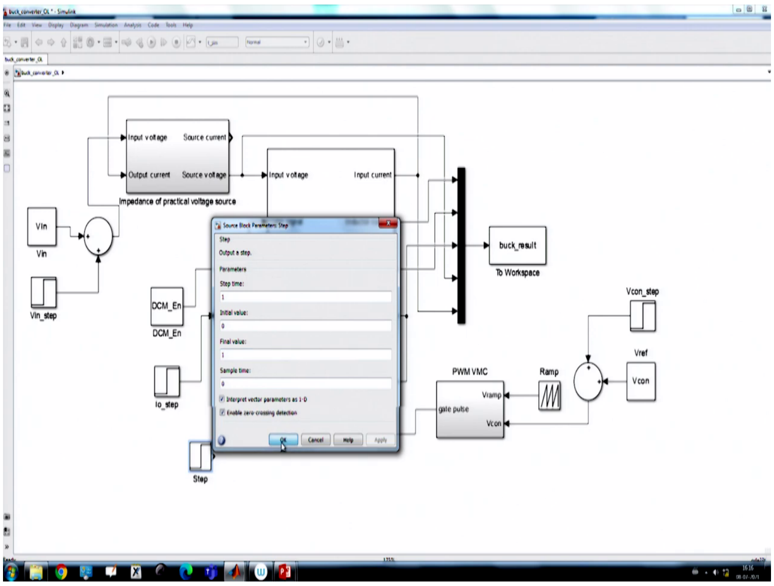
Now, so, what is going to the converter is actually output of this practical voltage source, which is nothing but an ideal voltage source followed by its impedance of the supply ok. Then, the other things are same that we have discussed; that means, you know we have a converter. Here, we want to mention; that means we are applying some step transient, you know this is a resistive load R, which we have also discussed but along with resistive load, we are applying some current step load.

(Refer Slide Time: 43:15)



And here, if we go to the MATLAB simulink block, you know in the source you will find if you go to the library in the source, you will find this step; this step blocks ok.

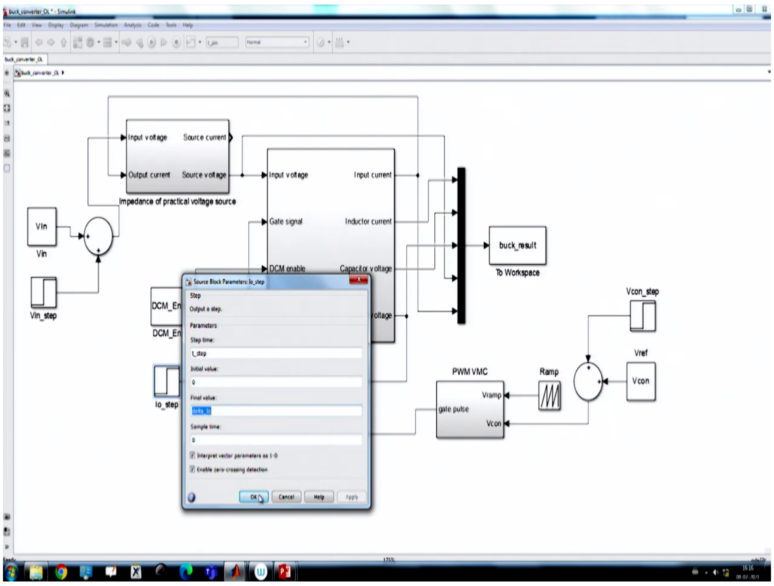
(Refer Slide Time: 43:22)



And if you go inside the step block, it will ask for step time; that means, at what time you want to apply the step transient. That means you may not want to apply the transient at the very beginning. So, you want to apply this step transient after certain time. So, this is called the step time. If you set it 0, then step will appear at the very beginning and we are not going to do that.

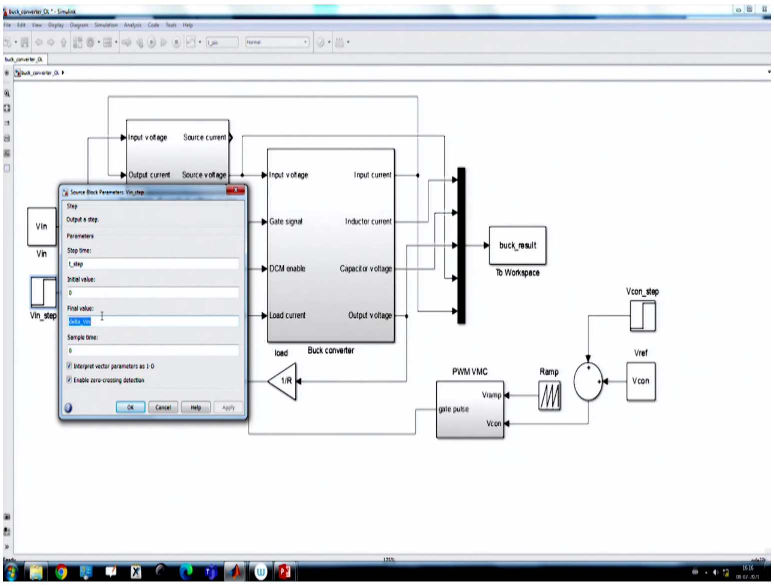
The second thing it will ask for initial value. So, naturally, the initial value is 0 because the step load will appear after the time. Then, the final value, how much value we are going to apply; that means, what is your step size ok.

(Refer Slide Time: 43:59)



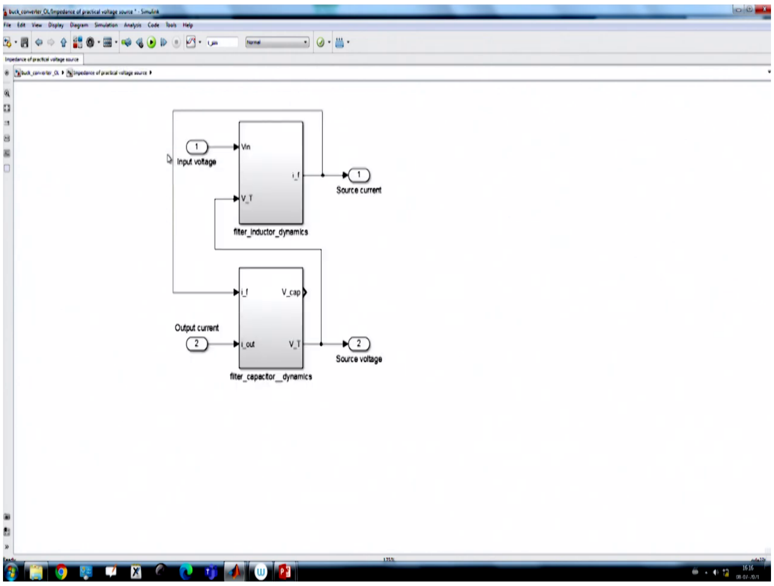
So, for this block, I have defined custom that means, a t-step I am defining in my dot m file and the step size of the load current, I am defining from the dot m file ok.

(Refer Slide Time: 44:12)

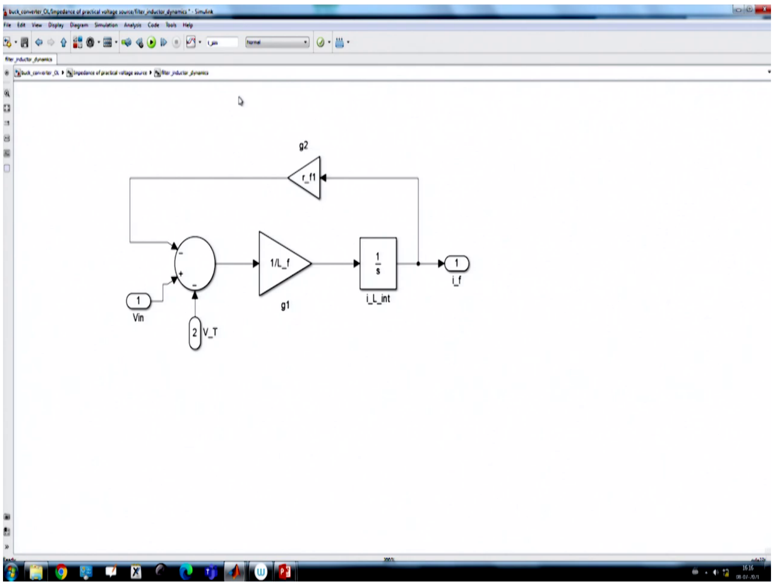


Similarly, for the source also I am defining all these parameters from the dot m file and delta v in that means how much if I want to make a supply transient. Similarly, I can create a step transient in the reference voltage ok.

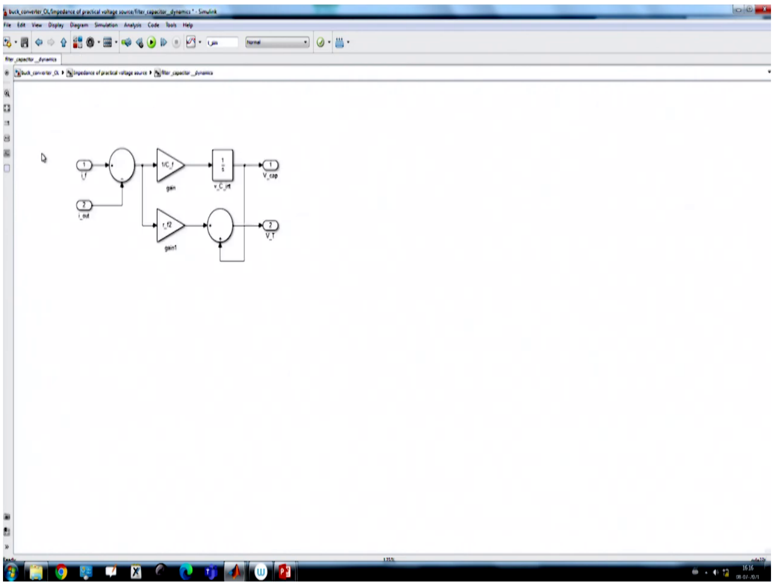
(Refer Slide Time: 44:29)



(Refer Slide Time: 44:32)

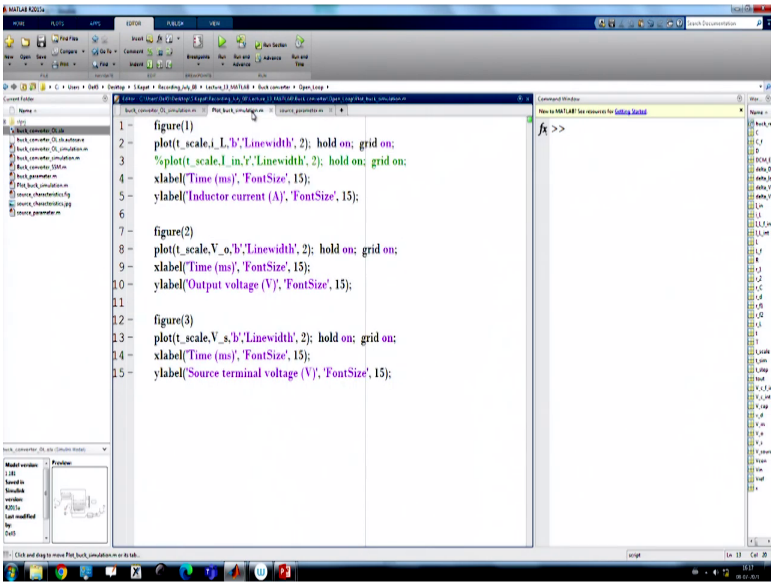


(Refer Slide Time: 44:38)



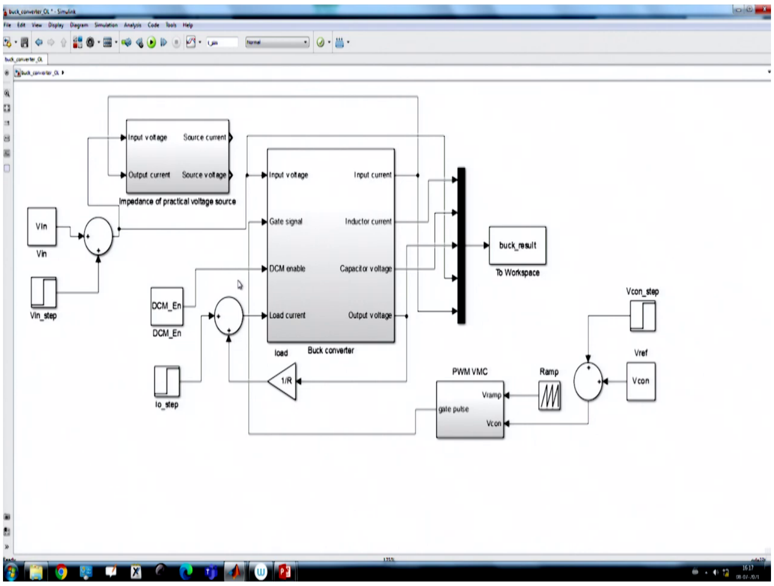
Now, if you go inside this block which I have shown, this block I have already shown. If you go inside, I have implemented this inductor dynamics of the filter source filter. Then the capacitor dynamics of the source impedance and then, this is a converter that we have discussed.

(Refer Slide Time: 44:50)



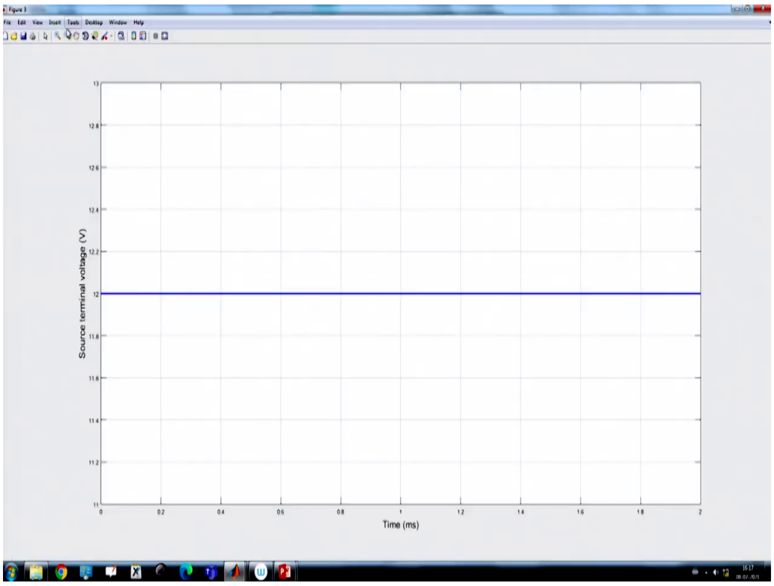
Now, what are we going to do? We are going to create a test case, first thing we want to create; that means, we want to run with a practical voltage source first or let us run with an ideal voltage source, ok.

(Refer Slide Time: 44:59)

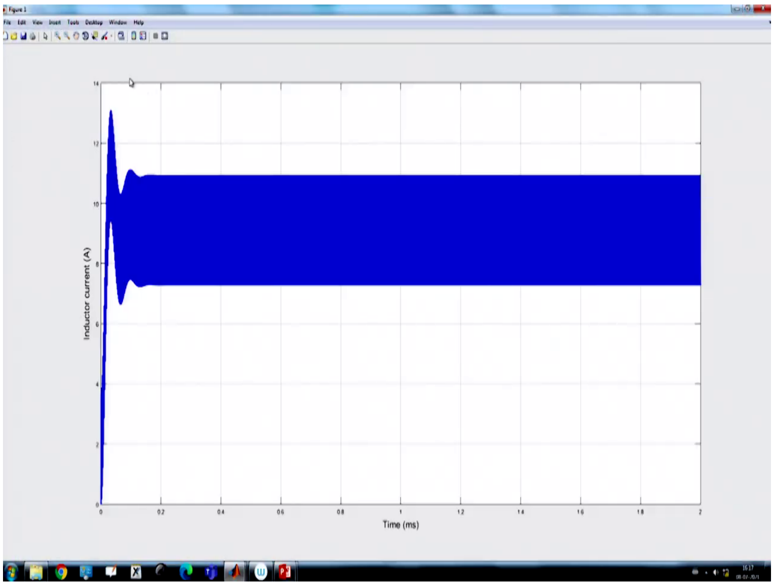


So, if we apply an ideal voltage source ok, let us say we are applying an ideal voltage source that is the fixed value. We are not applying any transient ok. So, we can take the same as this ideal voltage source. Now, this converter is running by an ideal voltage source ok. So, let us run this simulation.

(Refer Slide Time: 45:29)

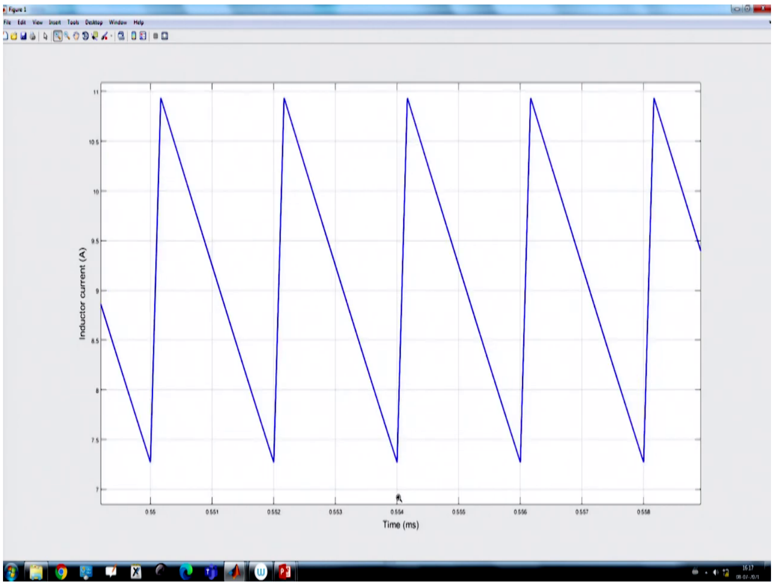


(Refer Slide Time: 45:38)

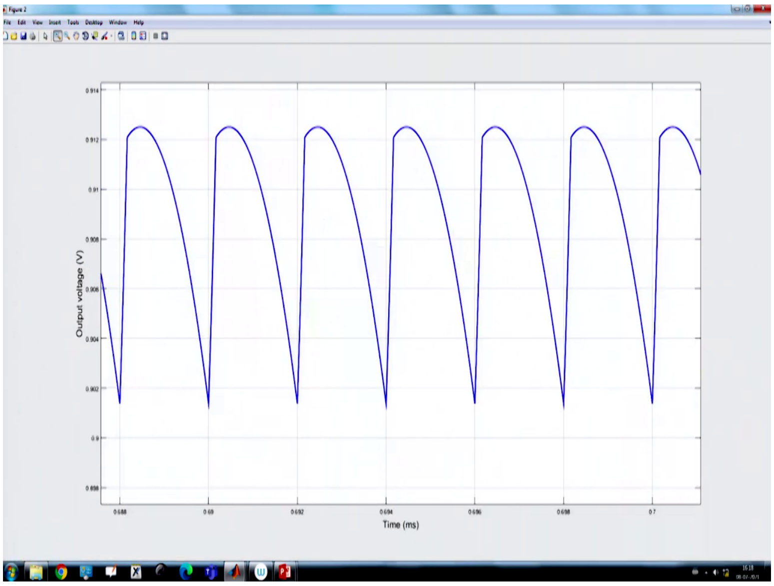


So, in this particular see you can see the source voltage I am drawing, so it is perfectly 12 volt; that means, since it is an ideal voltage source, it is perfectly 12 volt and you can see the converter inductor current wave from ok.

(Refer Slide Time: 45:45)

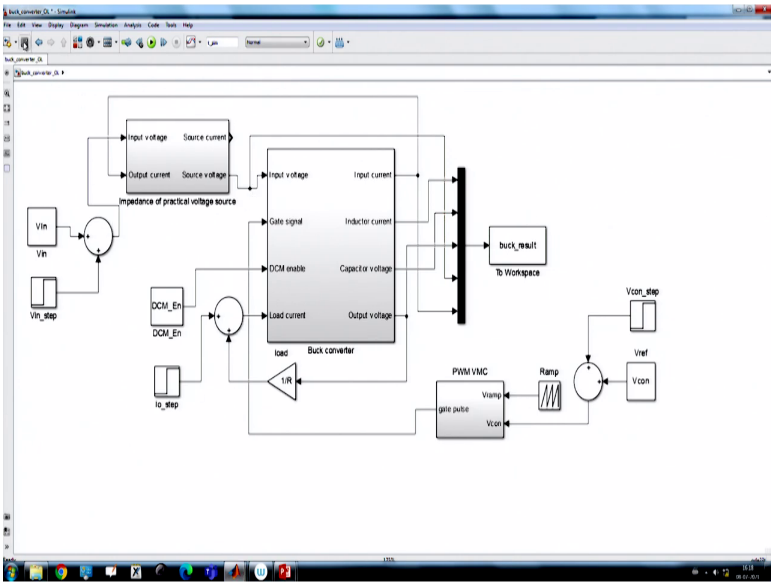


(Refer Slide Time: 45:55)



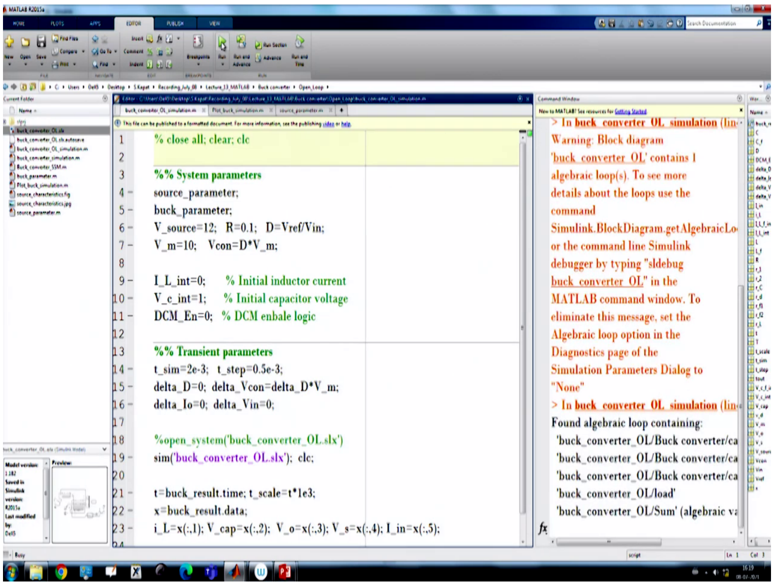
So, this is the inductor current wave from which you have seen earlier and this is the output voltage wave form. We have set a duty ratio 1 by 12. So, there is a drop and that we know we have already seen the drop; but we have not investigated fully the reason. That we will investigate in a subsequent lecture.

(Refer Slide Time: 46:17)

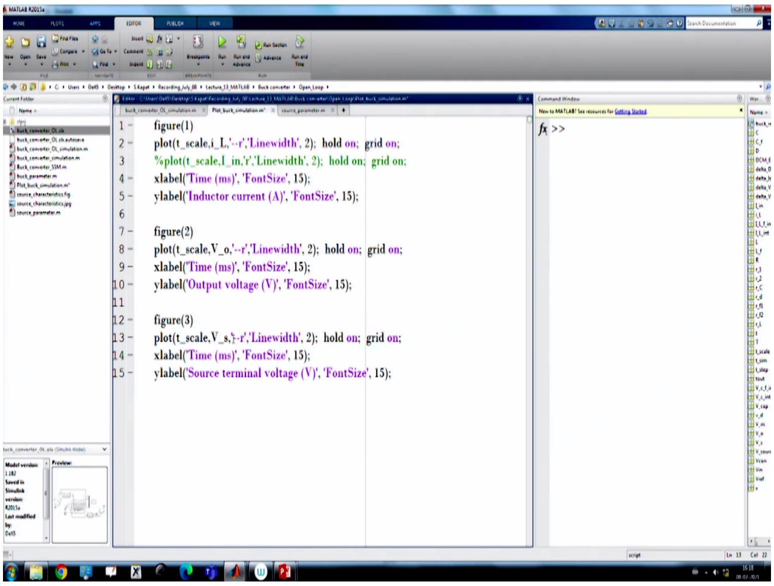


Now, on top of this, that means, we are we can see clean source voltage, if it is an ideal voltage source. Now, I want to show the next case study on top of this. That means, now I want to connect here the practical voltage source; that means, here is a practical voltage source and here, I want to show the practical voltage source ok.

(Refer Slide Time: 46:31)

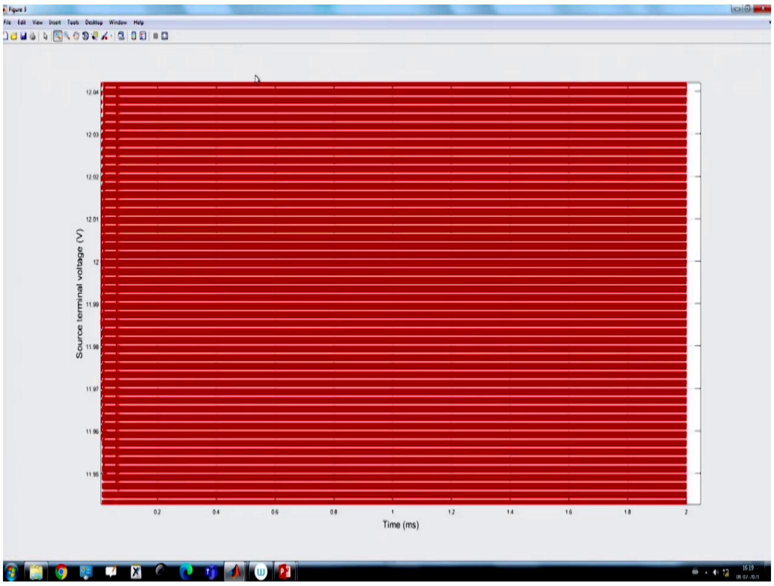


(Refer Slide Time: 46:39)



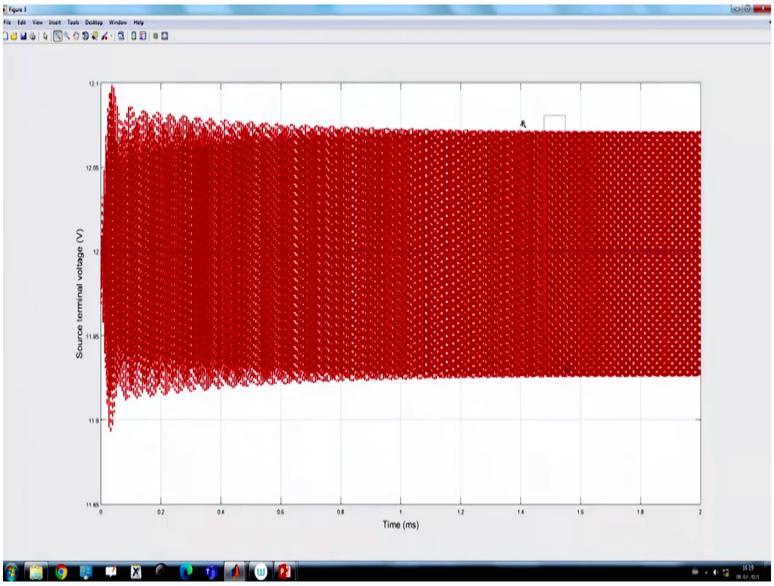
Now, in the case study, I want to repeat overlap this waveform.

(Refer Slide Time: 46:56)

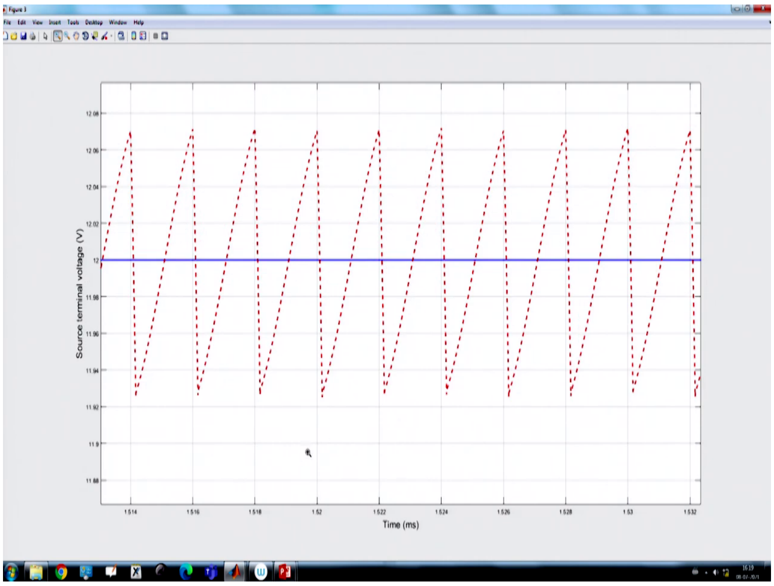


So, let us run it. Now, this is with a practical voltage source; the same DC-DC converter, same duty ratio, but now with a practical voltage source ok.

(Refer Slide Time: 47:02)

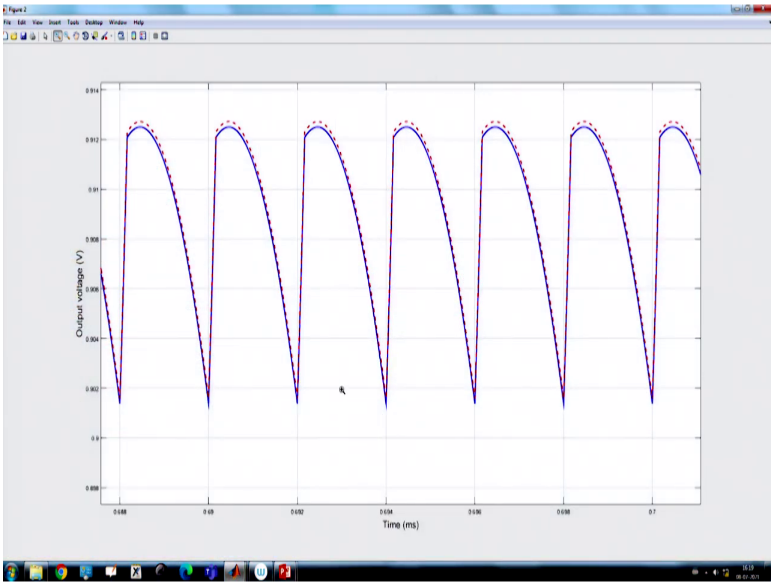


(Refer Slide Time: 47:04)

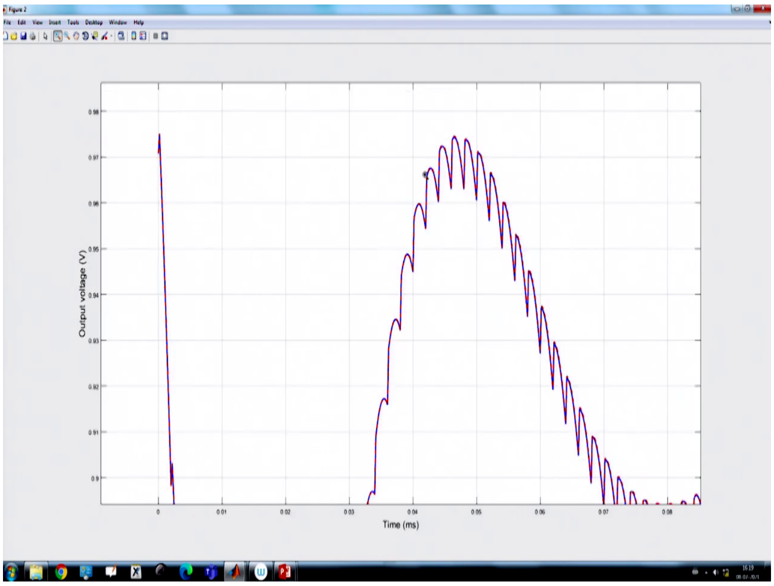


So, let us see what happens? So, if you see here, if you zoom-in, a practical voltage source you see; that means, there is a transient effect because we have put you know transient effect here 12 volt was the one when there was you know ideal voltage source was connected to the DC-DC converter.

(Refer Slide Time: 47:27)

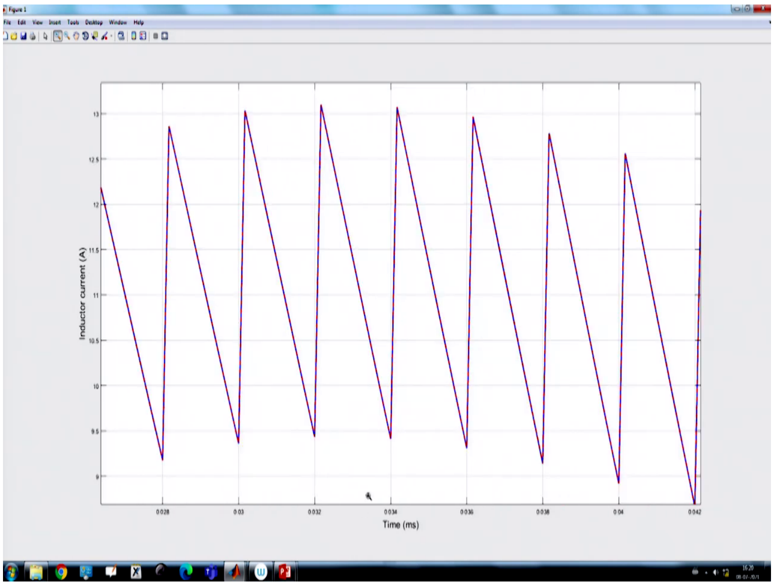


(Refer Slide Time: 47:33)

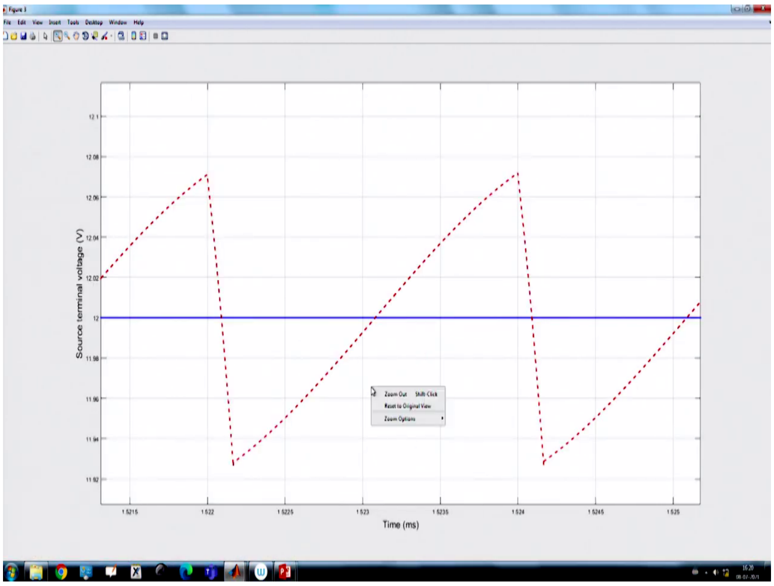


Now, because of switching event of this DC-DC converter, you see the output voltage waveform got change a little bit, you know shape has changed. Because we have overlap, these two waveforms look somewhat very close, ok.

(Refer Slide Time: 47:50)



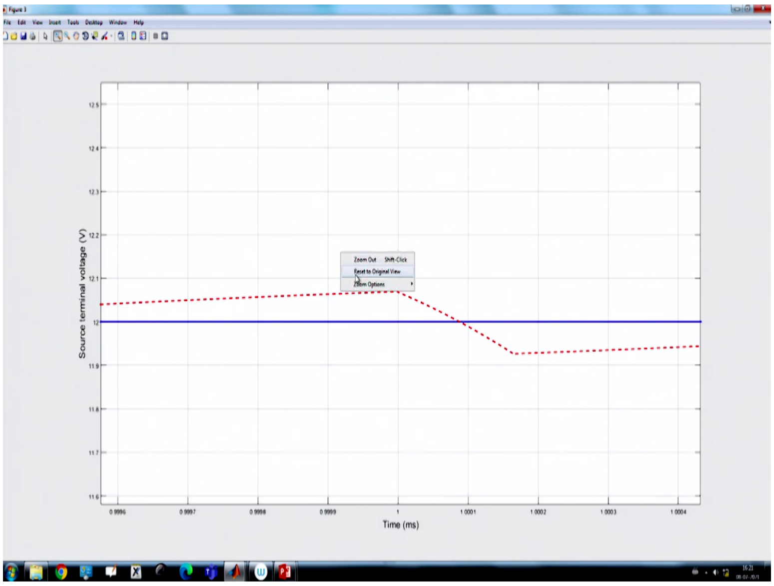
(Refer Slide Time: 47:57)



And if you go to the inductor current waveform, you know they look very similar, identical. That means, if the impedance of the output volt output you know source is you know is not and the effect due to the transient in the source is not very severe because if you see the magnitude, it is varying from 11.92 to 12.06. So, that means, it is roughly around 60 millivolt, which is not very large quantity.

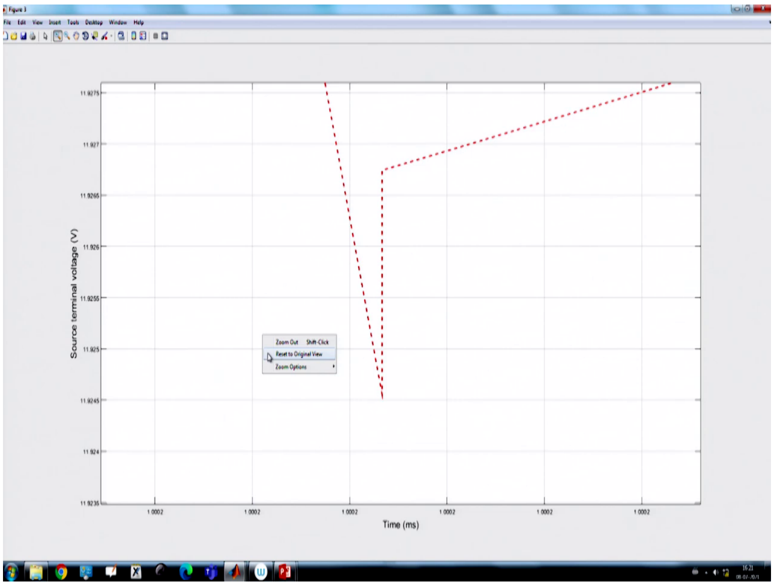
But we can clearly see because our switching frequency is how much? It is 2 microseconds. So, if we extend this, if we go close to this, let us go it is in millisecond. So, we can take from this two waveforms, 1 millisecond you can if you go further, there is a jump, there is a jump because of ESR of the source R C circuit.

(Refer Slide Time: 48:49)



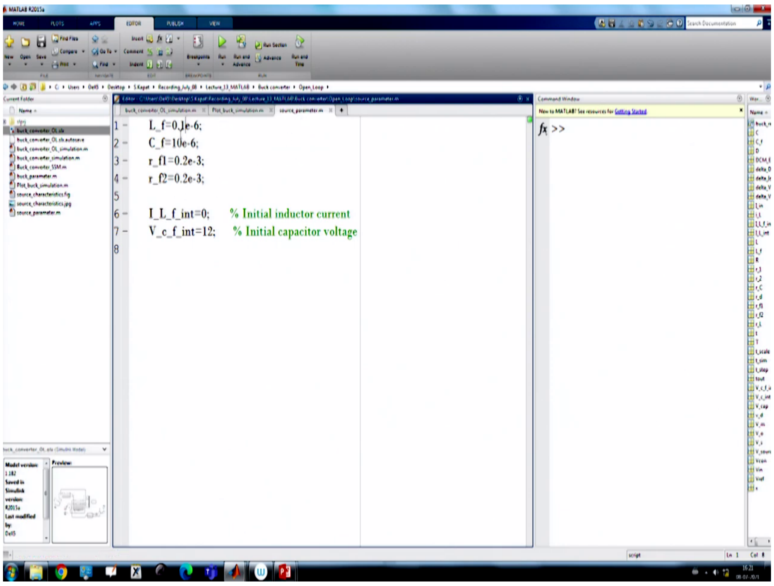
And then, again, if we go here ok; again, if we take up this, so here also we will get 1 jump ok.

(Refer Slide Time: 48:57)



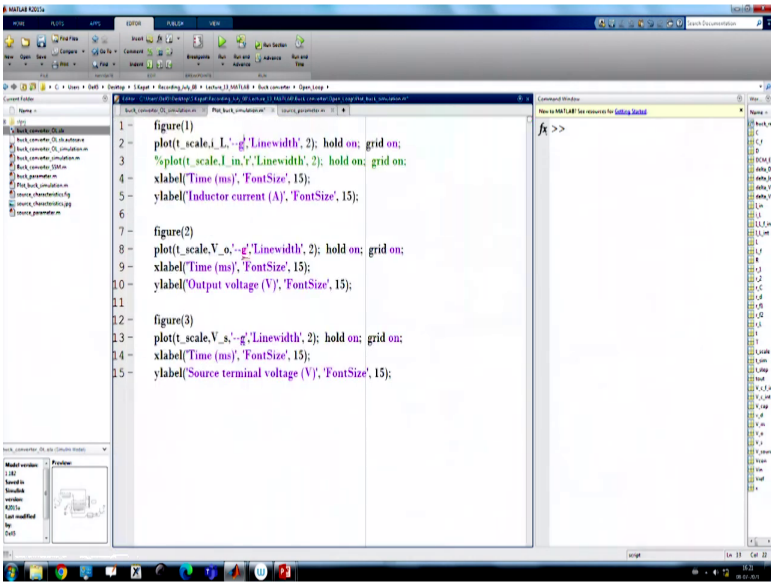
So, this jump phenomena is the because this ESR jump will be direct jump when you suddenly apply a load step and when you suddenly remove. So, here, we are not applying any load step because the buck converter current is discontinuous, and that appears like a load step to the source and that is why it is responding.

(Refer Slide Time: 49:19)



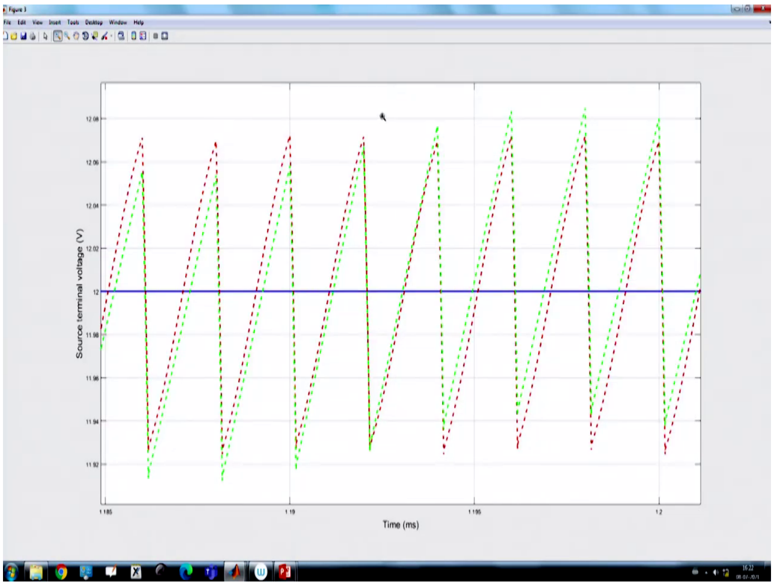
Now, what will happen if the impedance of the source converter; that means, suppose I take 2 micro Henry, suppose you put a thicker wire. That means a long cable wire, where it introduces sufficiently large inductor; 1 micro Henry, earlier it was a 2.2 micro Henry.

(Refer Slide Time: 49:38)

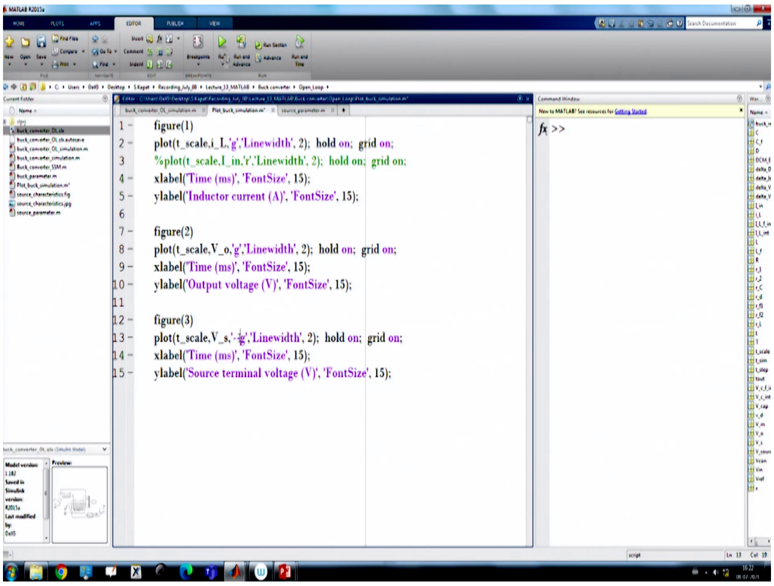


And we want to repeat this simulation and I want to create another color green color ok. I want to see the effect, what will happen if we; that means, I want to say as if the cable impedance the length is increased and we have some inductive effect.

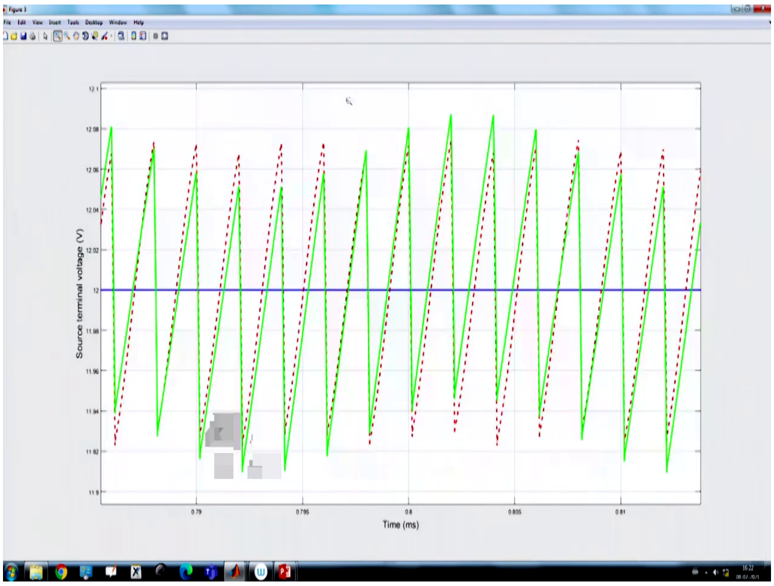
(Refer Slide Time: 49:49)



(Refer Slide Time: 50:10)



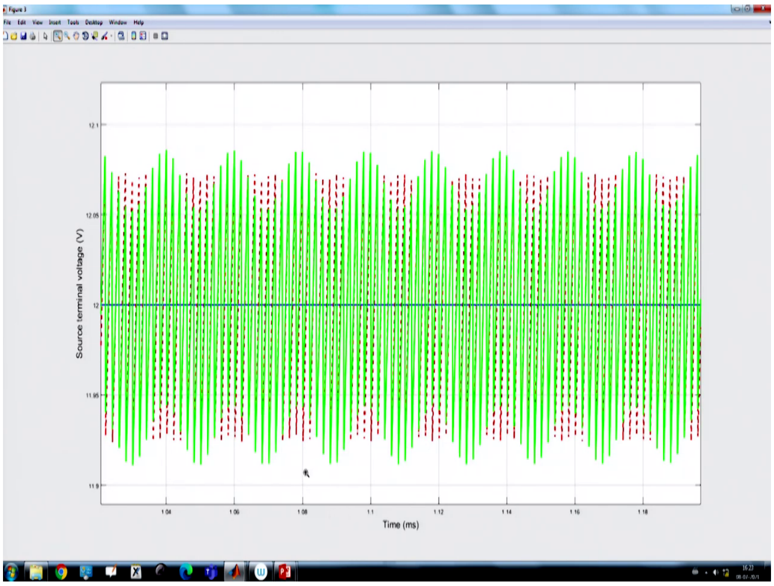
(Refer Slide Time: 50:14)



And you can see now there is the effect is somewhat you know, significant now. It is no longer, you know, I would say. So, let me run it once more. So, if you take the affect, it is no longer negligible.

Because if we take around one particular during the inputs like you know this side, you will see there is also a slow scale oscillation along with the switching event and that oscillation slowly damping out because there is a L C circuit and they are frequency resonating frequency. So, basically L C frequency it is damping out that coming, and that is interfering with this event.

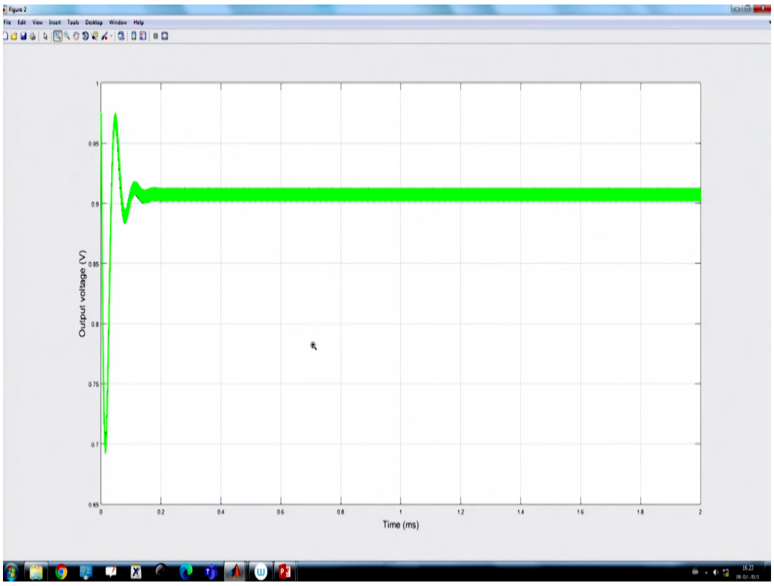
(Refer Slide Time: 50:48)



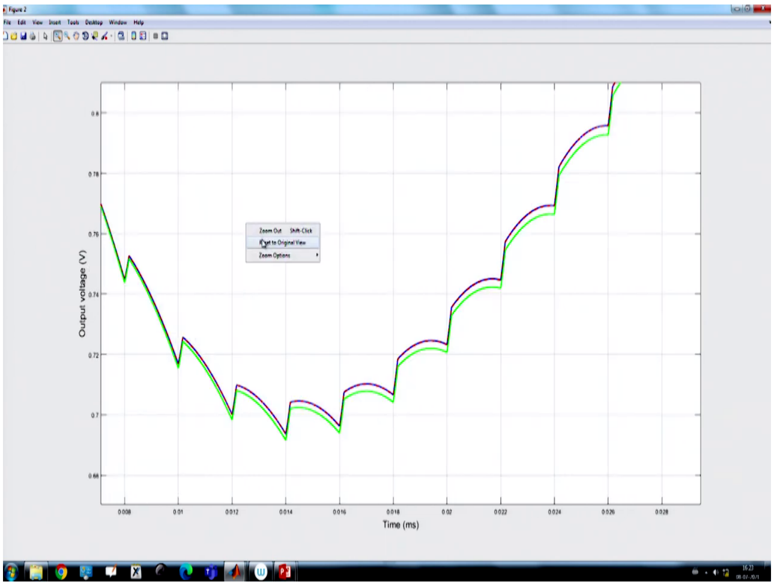
And that is why we can see the effect due to the supply variation. So, that means, we have to be very careful, when we are connecting a power supply for running a buck converter. Our buck converter should be attached very close to the power supply and if the length of the cable is too long. That may introduce the inductive effect and that can create a lot of problems in the converter.

So, that will introduce LDI DT will increase and also, the oscillating behavior will come ok. So, that means, this is one of the very important point.

(Refer Slide Time: 51:27)

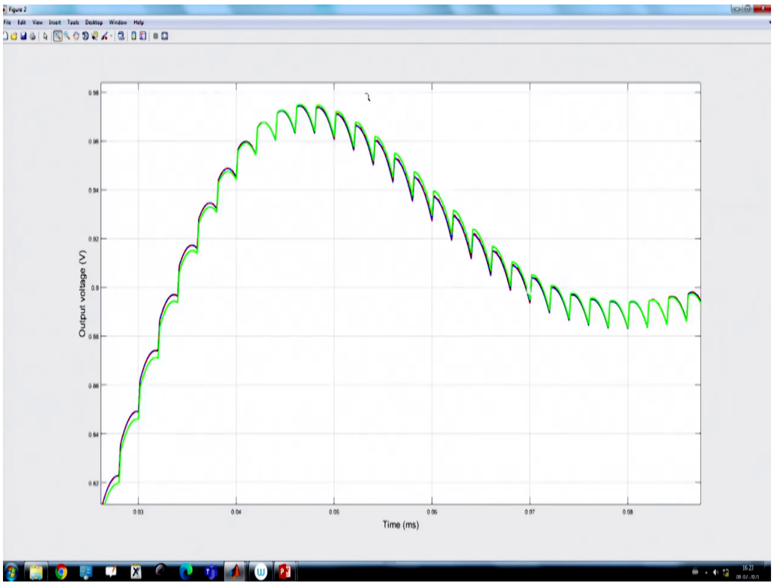


(Refer Slide Time: 51:33)

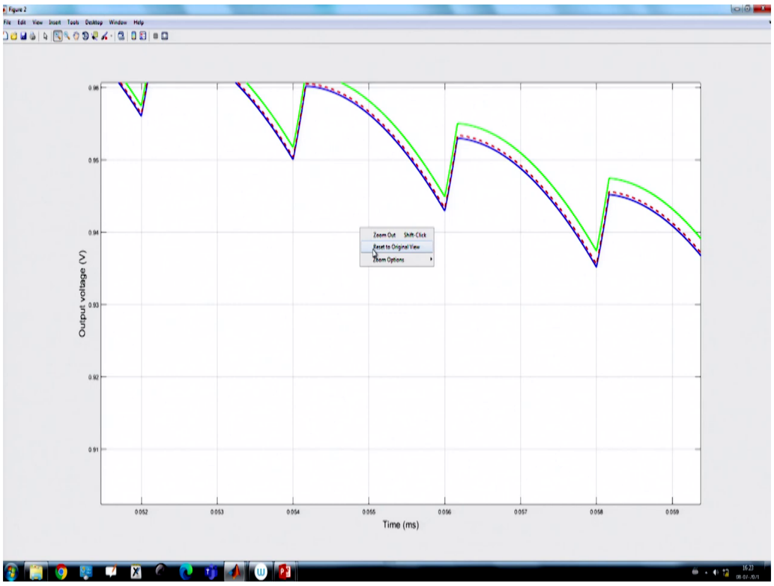


And if we want to see the effect due to the output voltage, as of now output voltage effect is not very significant, they are somewhat similar.

(Refer Slide Time: 51:38)

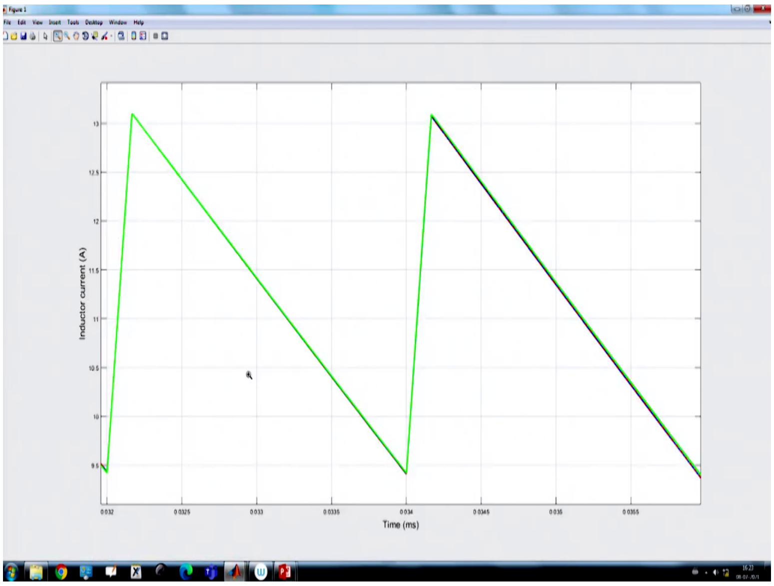


(Refer Slide Time: 51:41)

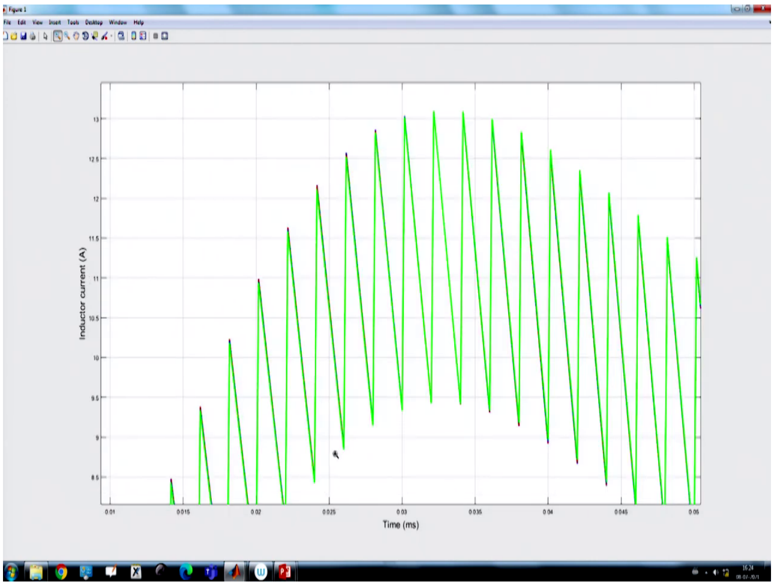


But if you keep on increasing this inductance value, then it can be severe; that means, you know the effect can be really severe.

(Refer Slide Time: 51:46)



(Refer Slide Time: 51:49)



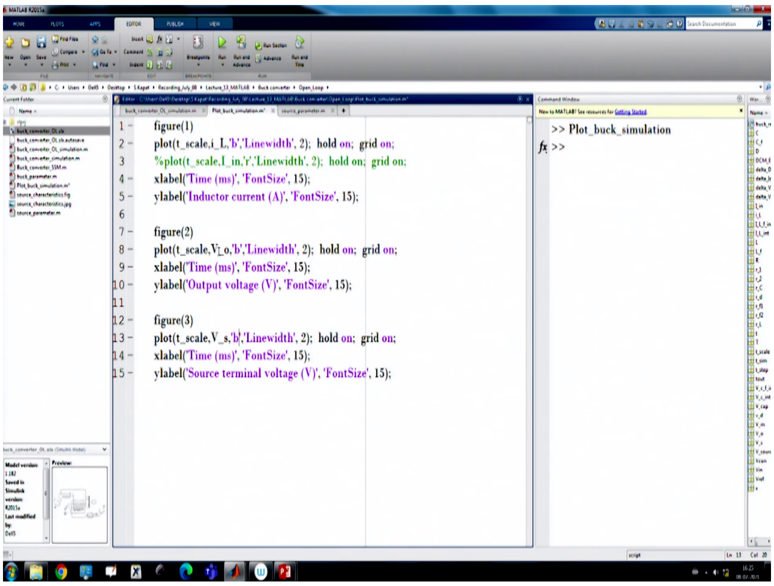
And if you see the current waveform, they are not significantly different; but at the same time, they are not exactly identical. So, there is some difference. So, that means, we have I have shown you the effect due to this ideal and practical voltage source. Now, understanding this conducted EMI. Since the input current is discontinuous and you have some parasitic effect and the source impedance effecting the voltage supply.

So, we saw that the voltage of this output voltage is actually affected and you can see there are high frequency components are present there because even if you want to take the Fourier series of this; you know particularly corresponding to switching frequency, there are dynamic.

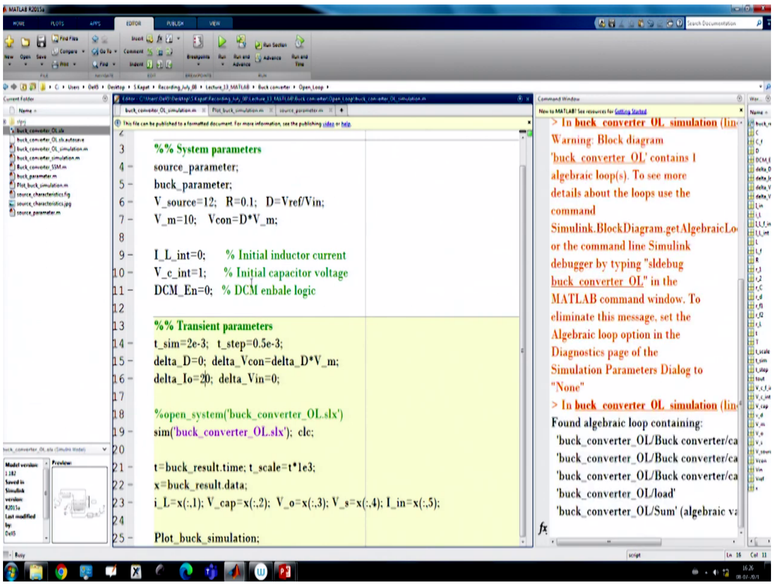
So, that means, if you take one cycle here, one cycle here. So, there is a transient effect here. So, this transient effect if you take because there can be rise time for time, we still have not incorporated the switch model. That means, the parasitic model of switch, if you include, then it will have some ringing effect and that is why it will introduce some you know distortion in the power supply and that will lead to conducted EMI problem ok. So, conducted EMI.

Then, we want to see a transient response; supply, load and duty state. So, right now, what we are doing? We are making a steady state response. There is no transient. Now, I want to see; so, with this field I, let it be there, I want to see what is the effect due to the transient.

(Refer Slide Time: 53:23)

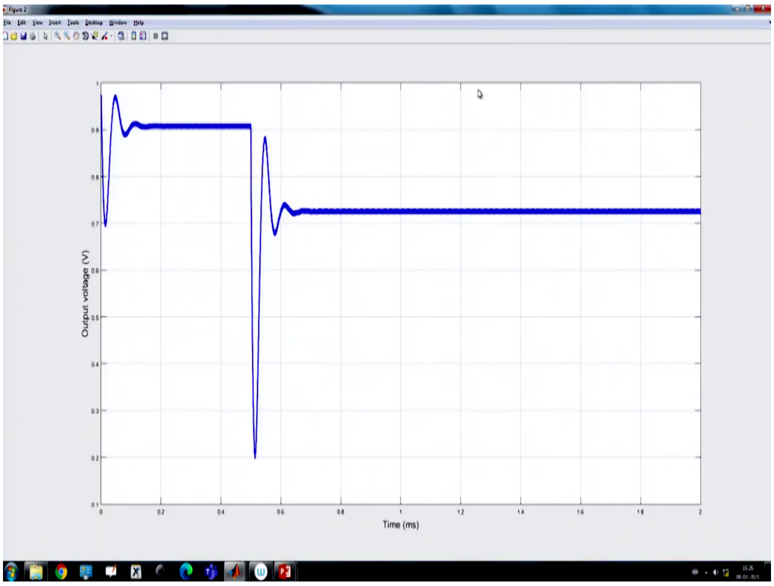


(Refer Slide Time: 53:42)

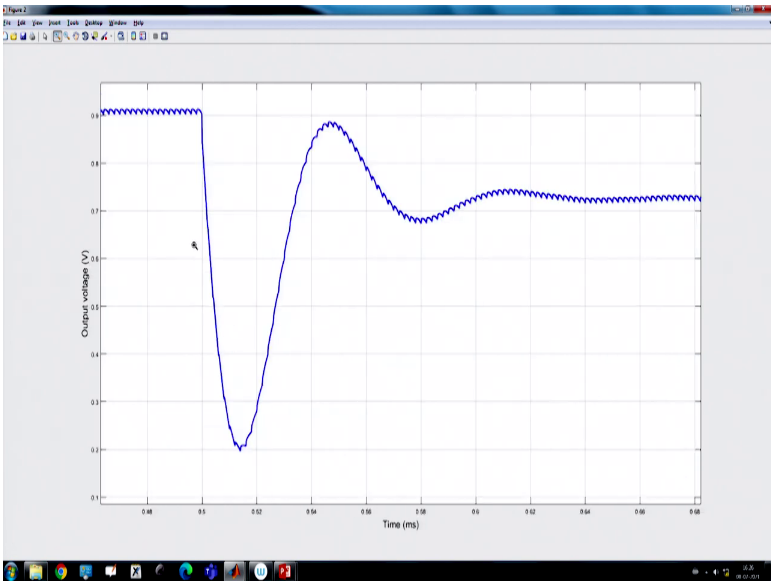


So, let me first you know make this blue color blue ok. So, now, I want to create some transient cases, what I want to do? I can make a load transient by introducing a 20 Ampere load state and let us see what happens. So, I want to see the load step transient ok.

(Refer Slide Time: 54:02)



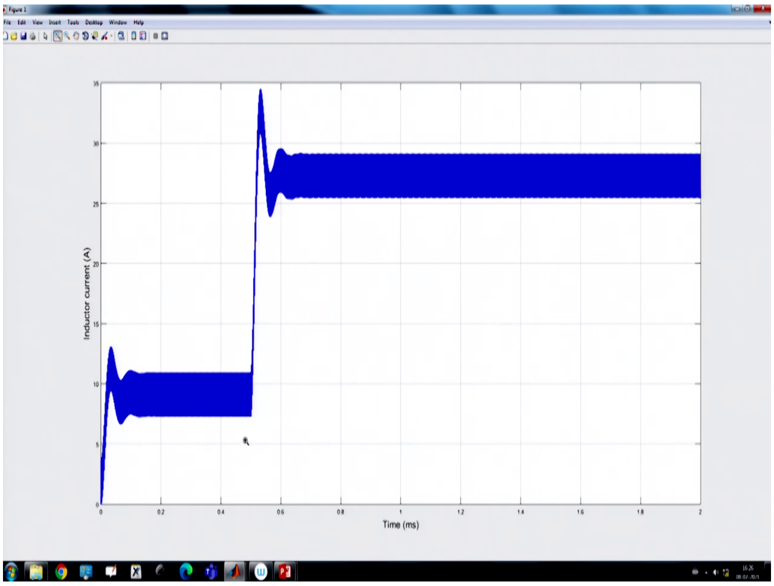
(Refer Slide Time: 54:07)



Now, this is with a practical voltage source and you see this is our output voltage because it is under open loop. We have just discussed that open loop, the steady state point will get shifted because there is a DC drop and that can be the DC drop can be visualized by considering as a series or resistance output resistance of the source. You can think of.

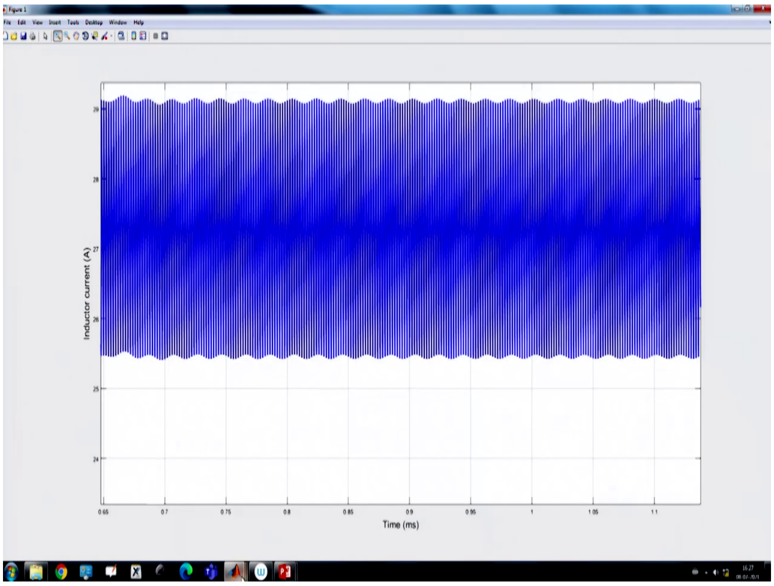
So, DC-DC converter can be treated as a source, where it has a in open loop, it behaves as a finite output impedance DC value. It also have transient effect that we have seen, we saw in the previous simulation and there it is also clear here.

(Refer Slide Time: 54:40)

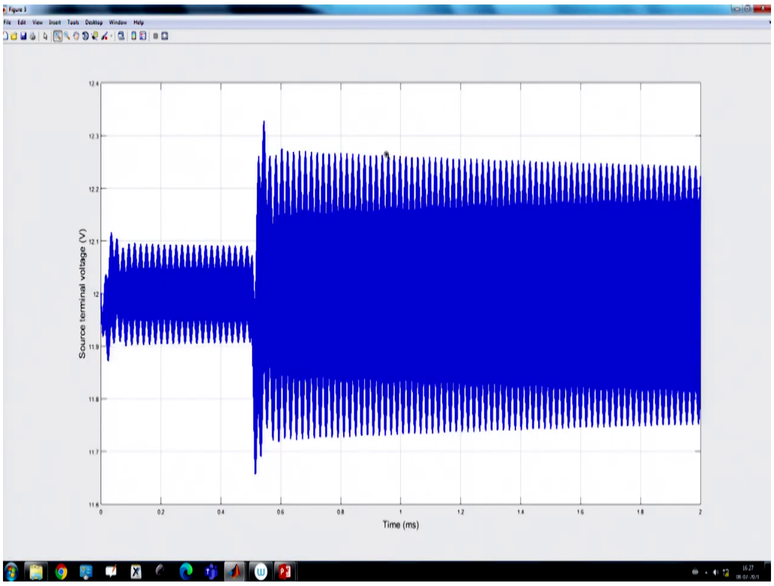


And if you take the inductor current waveform, then the inductor current waveform also has this transient effect. But you can also see on top of its switching behavior, there is some small scale oscillation is happening.

(Refer Slide Time: 54:58)

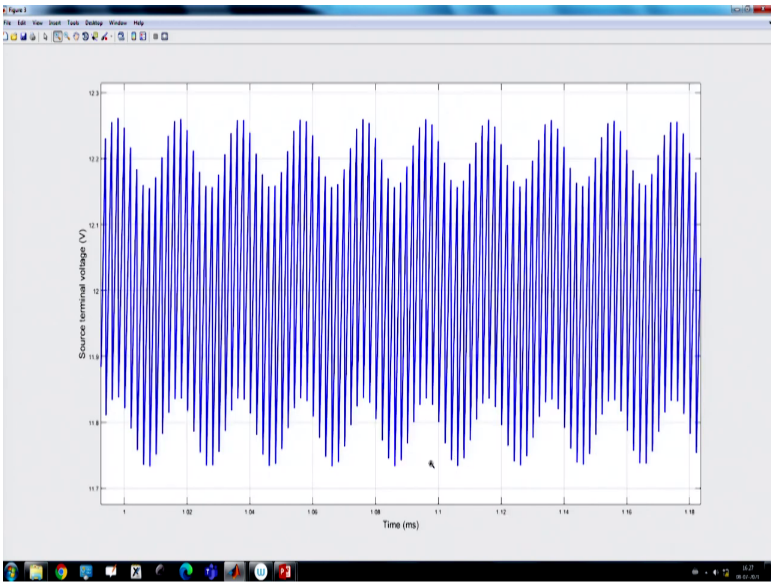


(Refer Slide Time: 55:05)



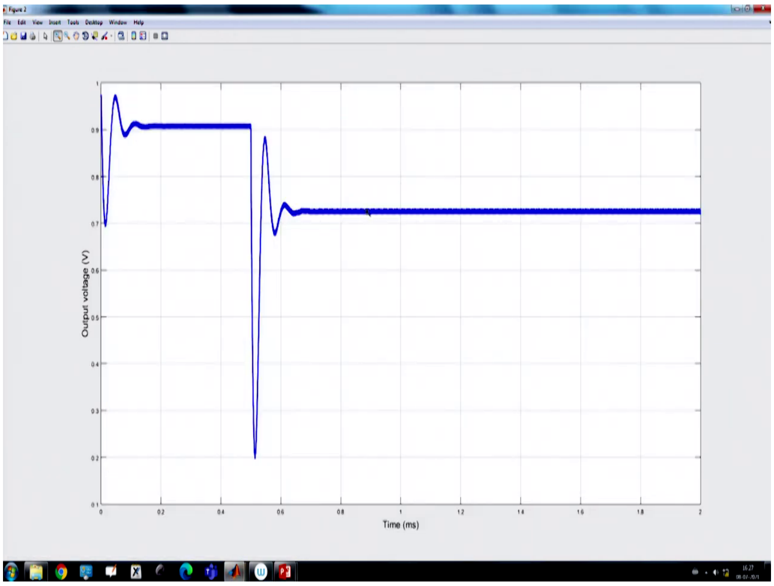
This oscillation if you take this oscillation; that means, if you zoom, this oscillation is due to this filter oscillation; that means, if we go back.

(Refer Slide Time: 55:08)

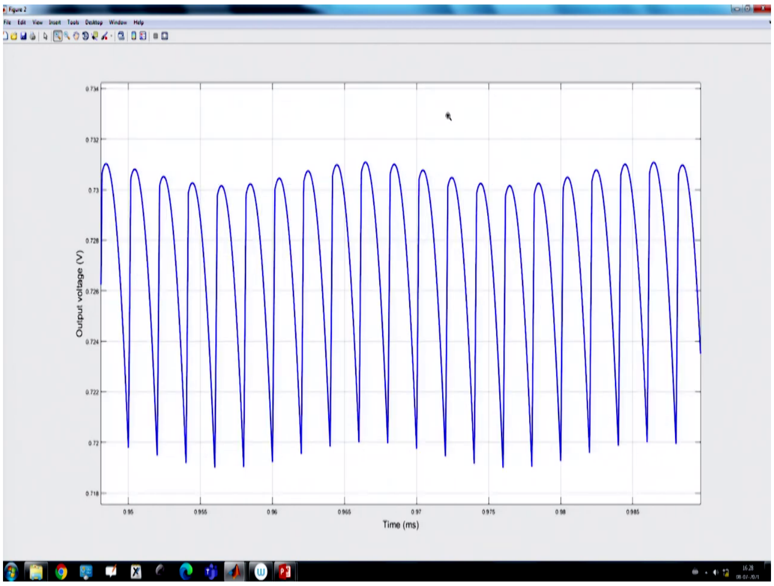


So, it is getting reflected into the wave form, this oscillation; that means, a supply oscillation is getting reflected to the output side through current.

(Refer Slide Time: 55:20)



(Refer Slide Time: 55:26)

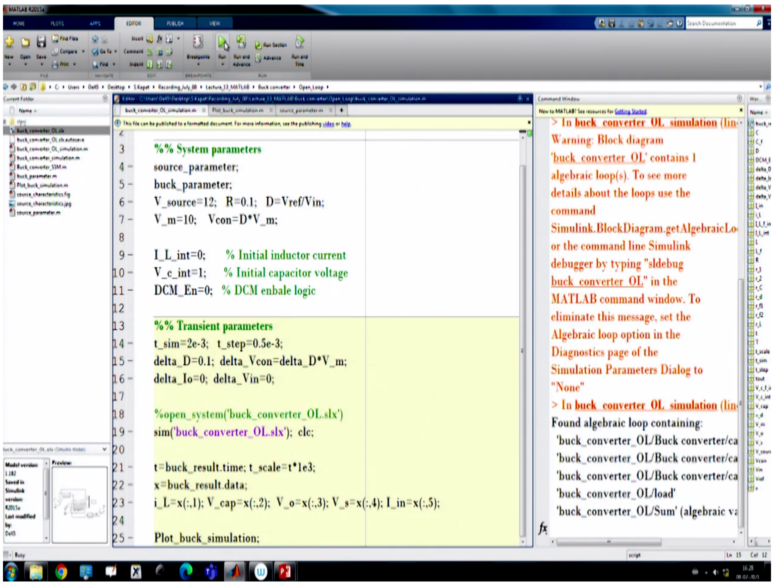


And if you take the waveform of the output voltage, if you zoom it, you will see the oscillator behavior; that means any oscillatory behavior in the input side is reflected in the output side to some extent along with the DC value, and this particular term is known as audio susceptibility.

That means, if the supply voltage has any you know disturbance you know in terms of oscillation, whether power supply is able to reject it or it will appear at the power supply here and that is what we are going to audio susceptibility effect. And we can clearly see that this slow scale oscillation on top of switching frequency is coming due to you can see that low scale oscillation in the output voltage is due to the supply oscillation; that means, this is something we have to talk about ok.

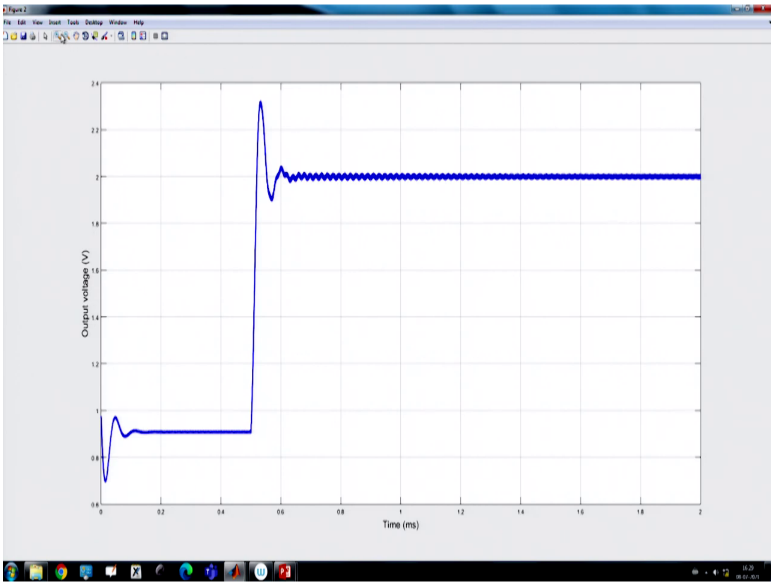
So, we learn about power supply. We saw about duty load step, we can talk about duty ratio step ok that will give some kinds of bandwidth concept, then we can also talk about the supply. Now, we want to see you know other transient effect just to get ok.

(Refer Slide Time: 56:38)



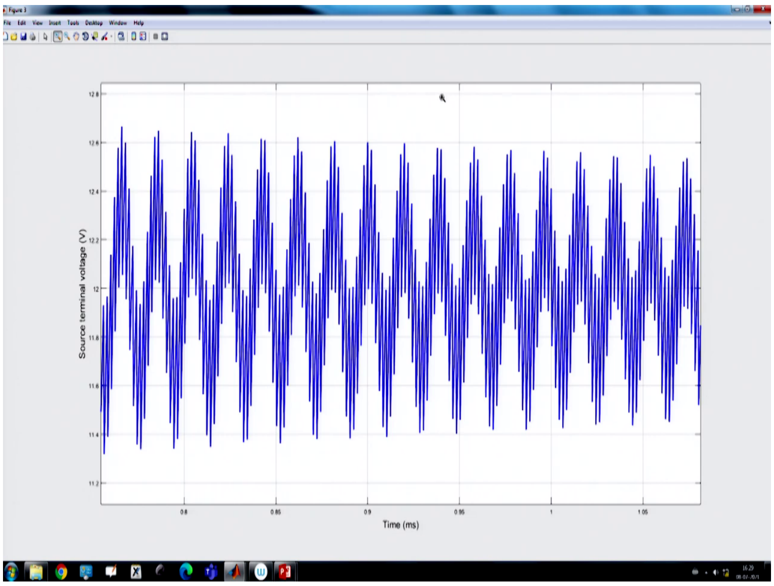
So, this is load transient we saw. Now, you want to see if you give a duty ratio change of 0.1, that means you apply a duty ratio 0.1. We want to see what happens if we apply a duty ratio step? That means you want to increase the output voltage.

(Refer Slide Time: 56:55)



Again, we are increasing the output voltage and output voltage was originally here. It was the duty ratio is 1 by 12. Now, with that duty ratio, we added 0.1. So, it has increased.

(Refer Slide Time: 57:06)

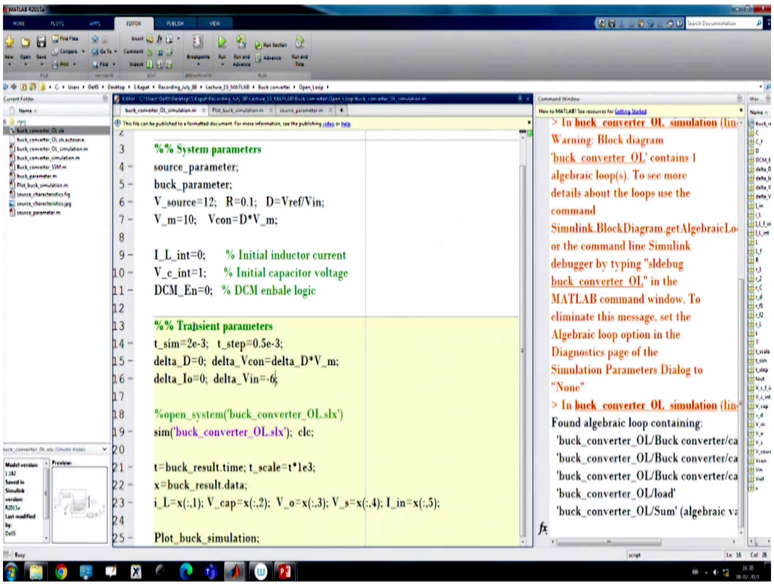


And you can see clearly see the oscillator behavior and it is coming because of the oscillator behavior of the output voltage that means the source. So, source has this oscillatory behavior;

that means, you have not connected you know the cable properly. So, the cable is carrying impedance and your source also is not is have nice source.

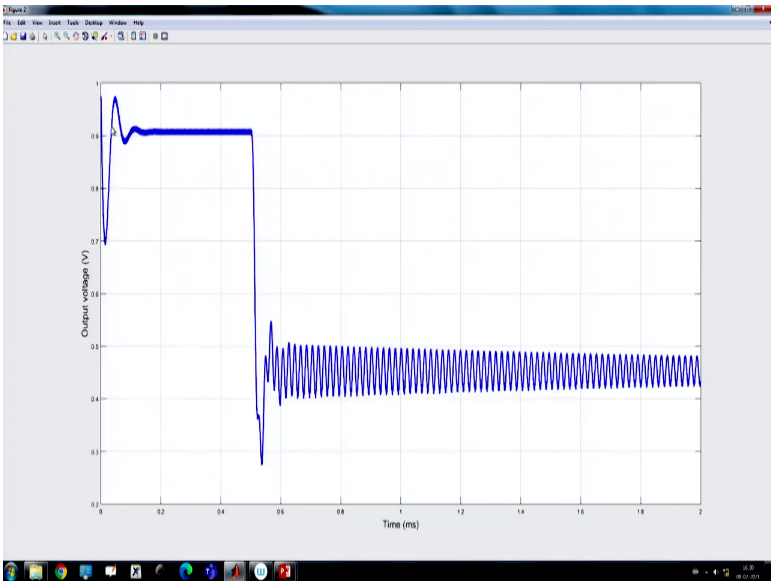
That means, while we are talking about DC-DC converter, we should use you know good power supply as an input to the DC-DC converter because if the power supply output impedance is not good enough, then you will get such impact in the converter performance also ok. So, we saw that and the last part that we want to discuss is that if we apply a supply transient; that means, we want to apply a supply transient. Let us say we apply some minus 6 and we want to see the effect.

(Refer Slide Time: 57:55)

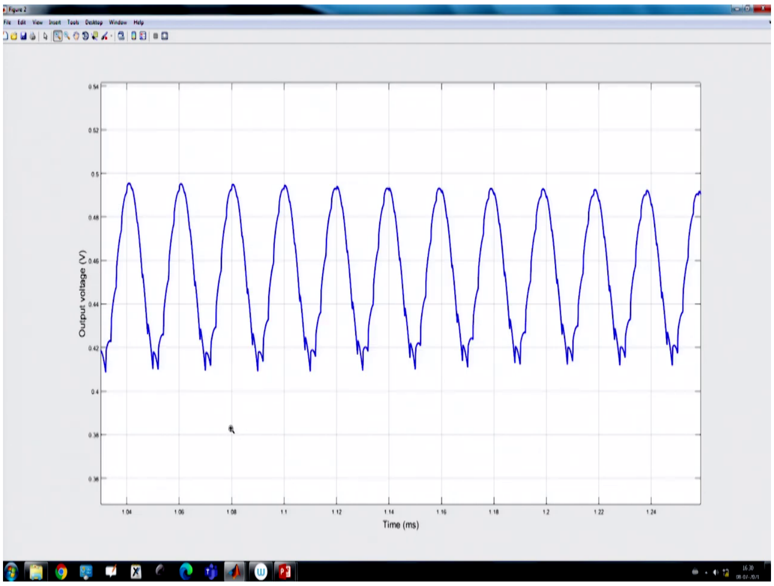


So, in this case we have not applied any duty ratio load transient, it is a supply transient.

(Refer Slide Time: 58:04)

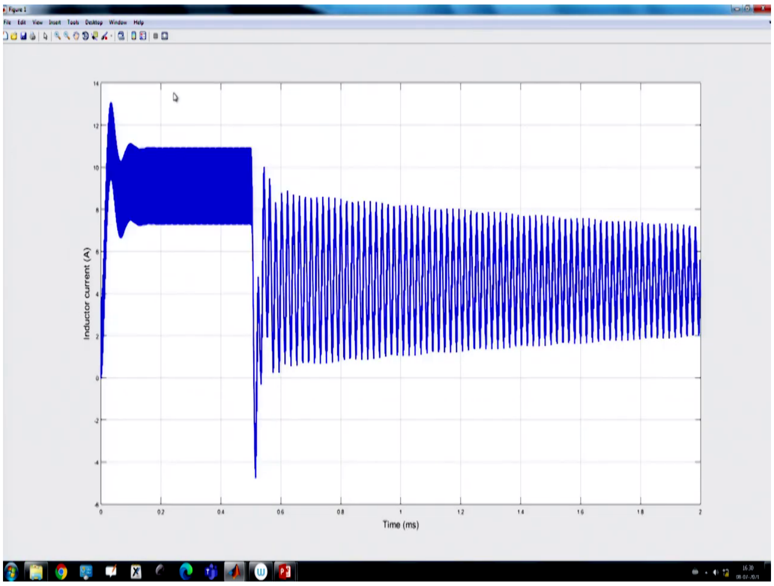


(Refer Slide Time: 58:14)

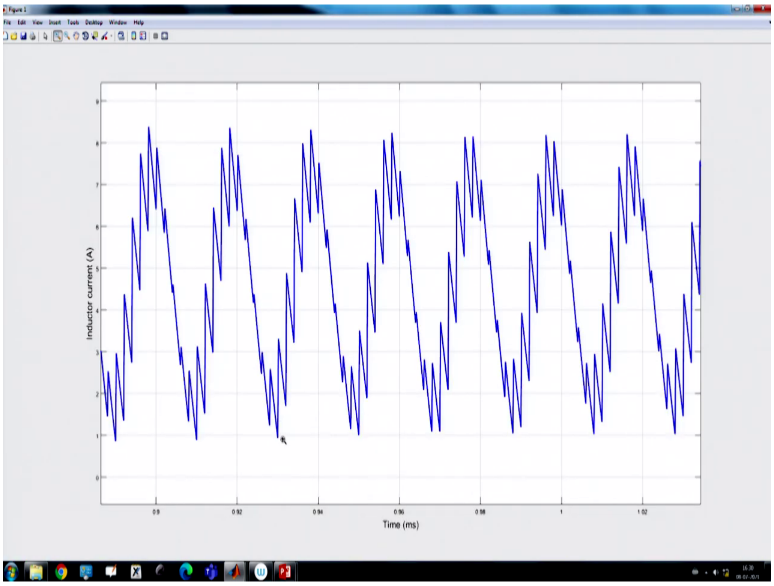


And see we have applied a supply transient, and we wanted to we have changed the output input voltage from 12 volt to 6 volt and you can see severe effect. At lower input voltage, the effect is very much severe.

(Refer Slide Time: 58:21)

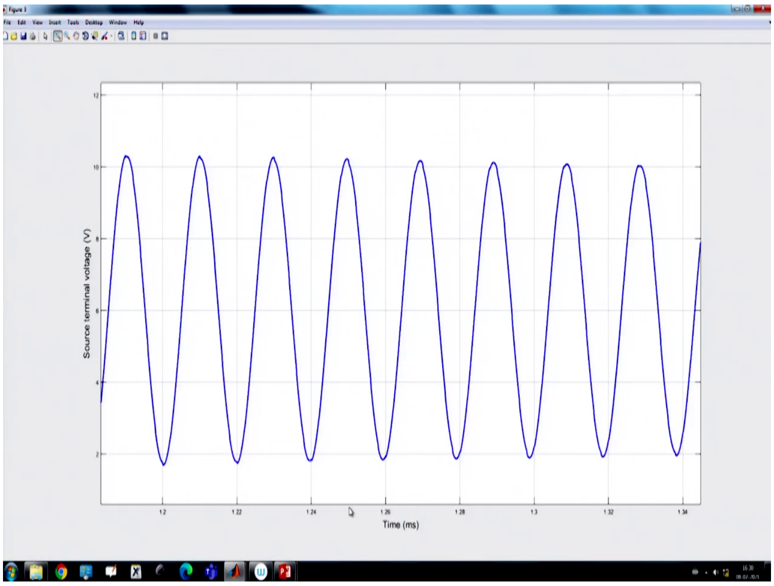


(Refer Slide Time: 58:26)



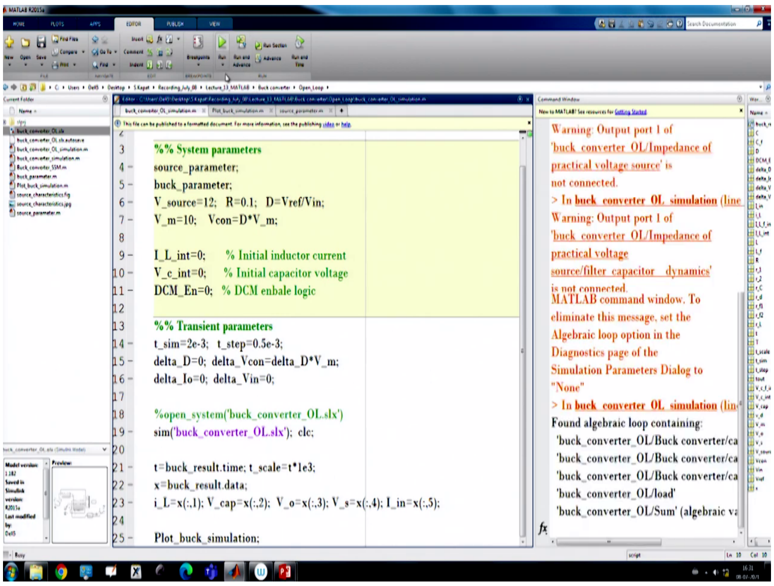
And it is clear even from the inductor current waveform. That means, there is an effect due to the source dynamics, and it is coming from the source.

(Refer Slide Time: 58:36)



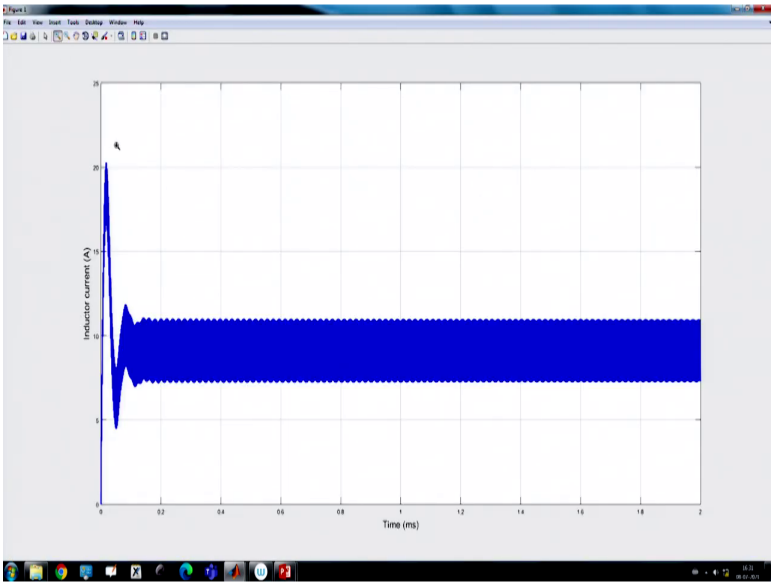
So, source voltage is fluctuating too much, and that is not acceptable. So, this motivates us. That means we have to check the transient performance. So, if you take ideal such oscillation will not come. So, we understood this now the start up behavior; another thing we want to check is the startup behavior ok. So, if you want to check the startup behavior; that means, we are not applying any transient ok.

(Refer Slide Time: 59:00)

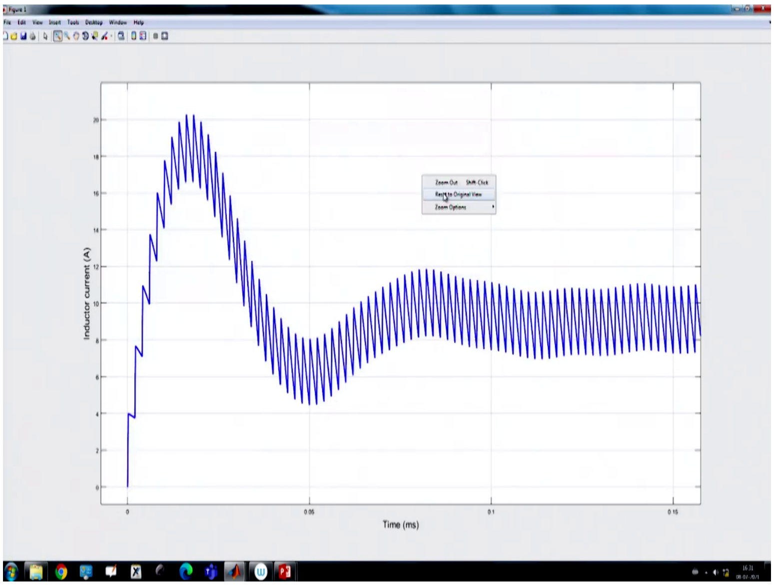


But we want to start everything from 0 ok and we want to last thing that we want to check is the start up behavior.

(Refer Slide Time: 59:14)

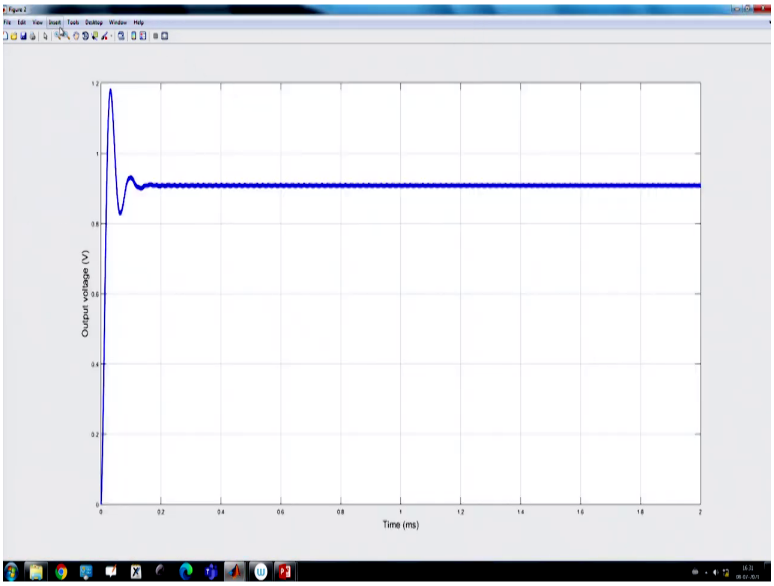


(Refer Slide Time: 59:17)

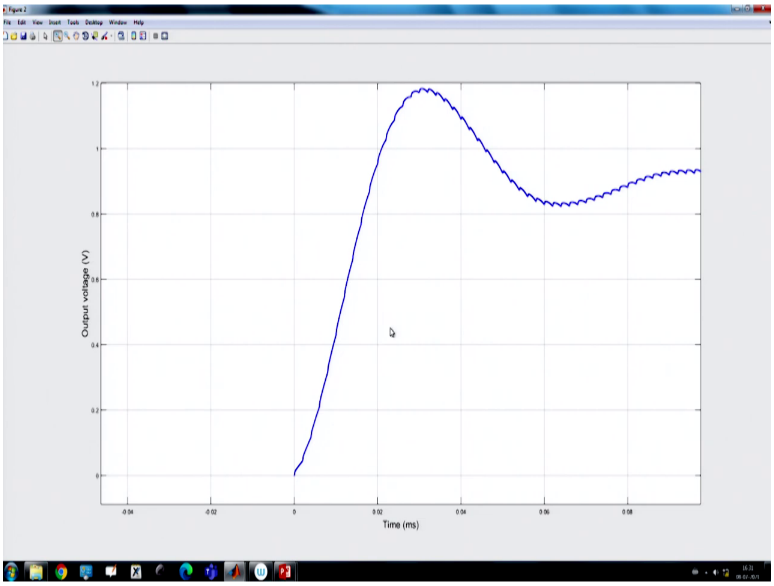


If you start the power supply ok. So, this is a start-up process and if you see the startup process, the current starts from 0 Ampere. It is ramping up and it is coming. Again, it has oscillatory effect due to the input supply you know that impedance.

(Refer Slide Time: 59:30)



(Refer Slide Time: 59:38)



And output voltage also you know changing from. So, this is an open loop condition that means we are running the converter under open loop. So, this is very much clear that the process, this startup is giving a huge voltage overshoot which is not acceptable ok and the startup time is also too large in terms of millisecond.

You can see it is taking you know, like around 0.15 millisecond. And another point is very important is the current is too much. That means, your start up current is also too high ok.

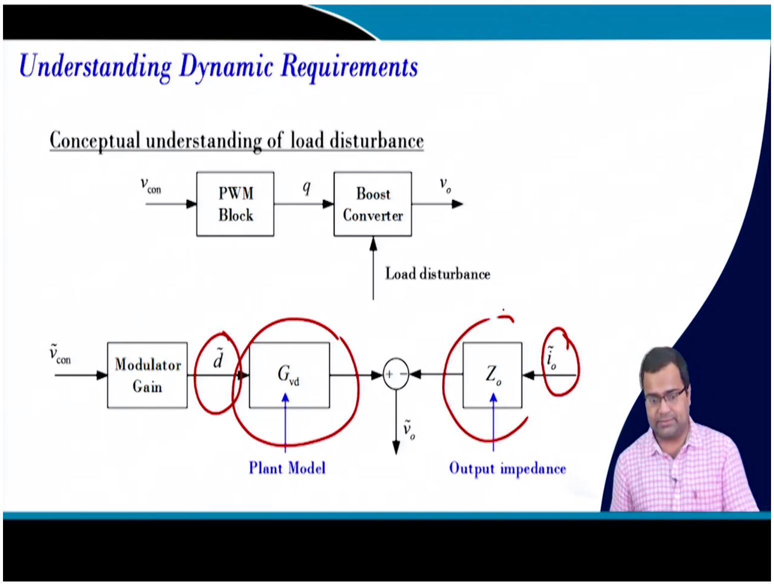
So, with this we want to now realize that we need some start up behavior and we can also realize the short circuit, open circuit behavior from this and from that it is very clear that supply disturbance can severely affect the performance of the converter and it can introduce a lot of oscillations.

So, if you connect many power supply in a single source and if one of the power supply introduces some inject such behavior and if your source is not properly regulated, then it may propagate to the other converter and it can create severe problem to that connected converter; interconnected converter. So, we need to really.

So, one of the requirement is to put an input filter for each converter. But, putting a large input filter for each converter can penalize the power density. The closed-loop bandwidth of the converter will be affected by the input filter. We will also discuss in another lecture ok.

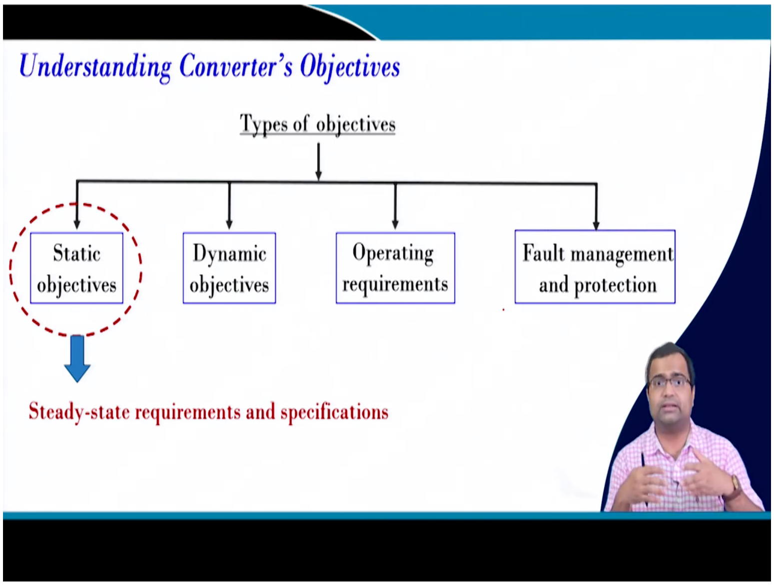
So, that means, it requires a closed loop control which can instead of putting too much emphasis on the circuit part which we have to do some minimum amount. We need to stress on the control part; how control can ensure such transient behavior will not be propagated to the output side. Even though input has a disturbance, output should reject it ok and it should be also stable so that the filter requirement can be reduced.

(Refer Slide Time: 61:36)



So, dynamic requirement now we understood, we can take a boost converter. So, that means, we will see in subsequent lecture, if there is any change in the duty ratio, it will affect the output voltage and where we can derive a control to output transfer function. If there is change any load current, it will affect the output impedance ok.

(Refer Slide Time: 61:58)

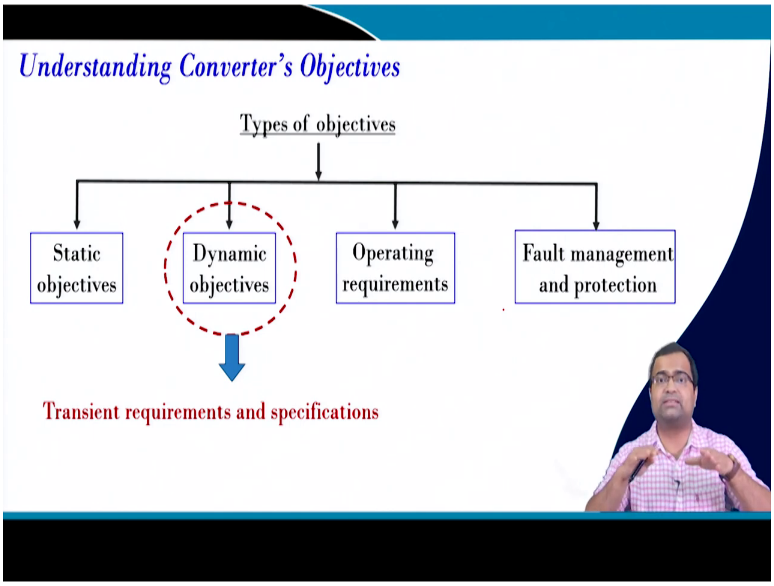


So, the converter objective can be divided into static objective, dynamic objective, operating requirement, then fault protection and management. So, the static objective is a steady state;

that means, you have to make sure what is the voltage ripple, current ripple, what is the DC average value and this thing we have discussed in previous lecture and today, we want to touch upon you know briefly how to design the power stage.

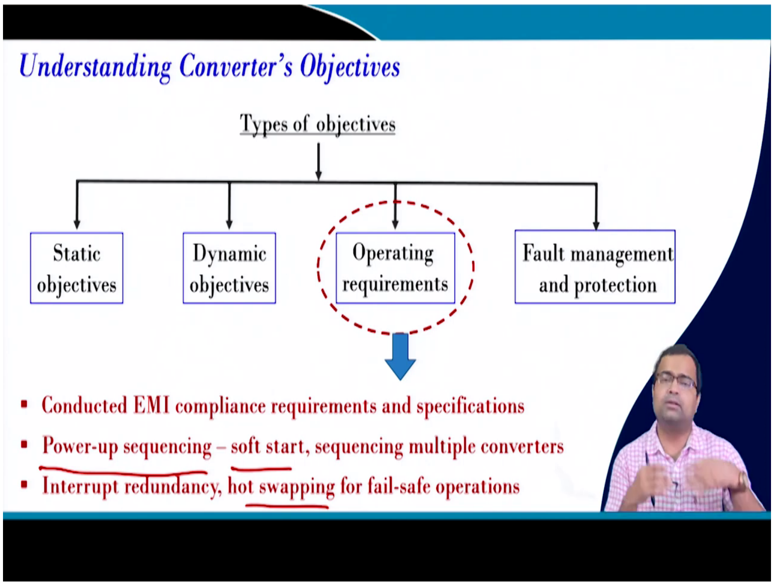
And we also want to show some you know web bench design tool from different you know industry like you know as a designer tool.

(Refer Slide Time: 62:31)



Then, dynamic objective, we need to meet certain transient requirement; we need to cut down the overshoot undershoots within a limit; we need to you know reduce the settling time ok.

(Refer Slide Time: 62:43)

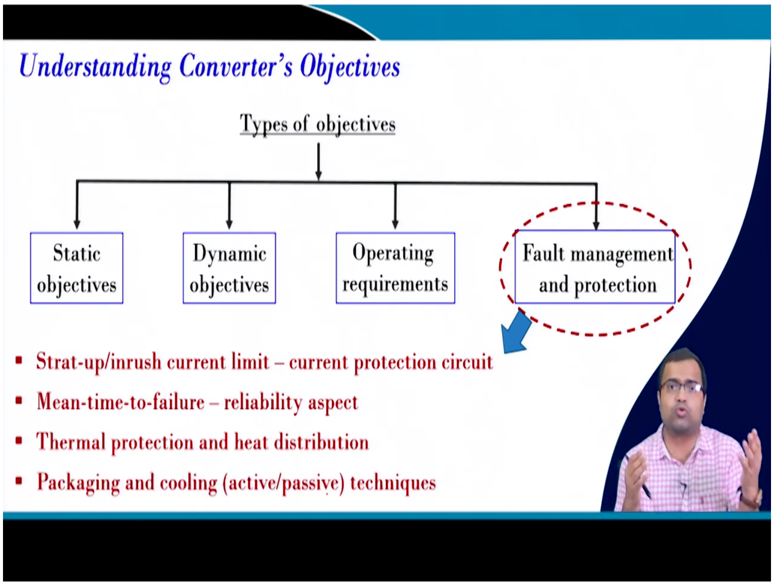


The operating requirement, we need to make a compliance with the conductor EMI because we saw the source characteristic can drastically affect in a converter. So, we need to put an input filter to reduce the EMI. The power up sequence is something that means, if there are multiple converters are connected and if all of them want to go to load transient, then we cannot enable load transient for all the converter because that may collapse the power supply.

So, we need to make a sequence of transient such that you can prioritize which one is the critical so that we can save the power in a source side ok. Similarly, the soft starts is required so that we can limit the current and at the same time, within the current limit the startup can and we can we can achieve fast start up.

Then, hot swapping we told about, that means, we can remove one of the power supply if it is faulty in the network without turning of the whole network. So, that should also be possible and you can create similar this case study in MATLAB, what we have discussed today.

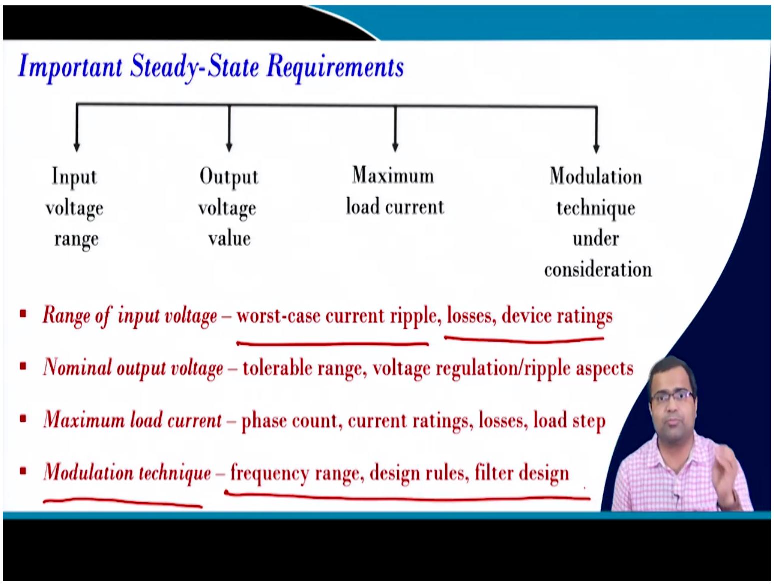
(Refer Slide Time: 63:47)



The fault protection and management, we need to consider start-up circuit; we need to protect the inrush current so that the current should not exceed the tolerance limit of the component. Then, reliability is important, and we need to check the component and try to estimate the health condition of the component.

Then, the thermal production because if too much current is carrying and if your impedance has more resistive effect, then it can get heated up and if you have a more conduction loss of switching loss, then you need to have proper thermal management and heat distribution ok. And particularly, for present age, where we are going more towards gan and silicon carbide. So, packaging and cooling is a very important requirement which should be part of this.

(Refer Slide Time: 64:31)



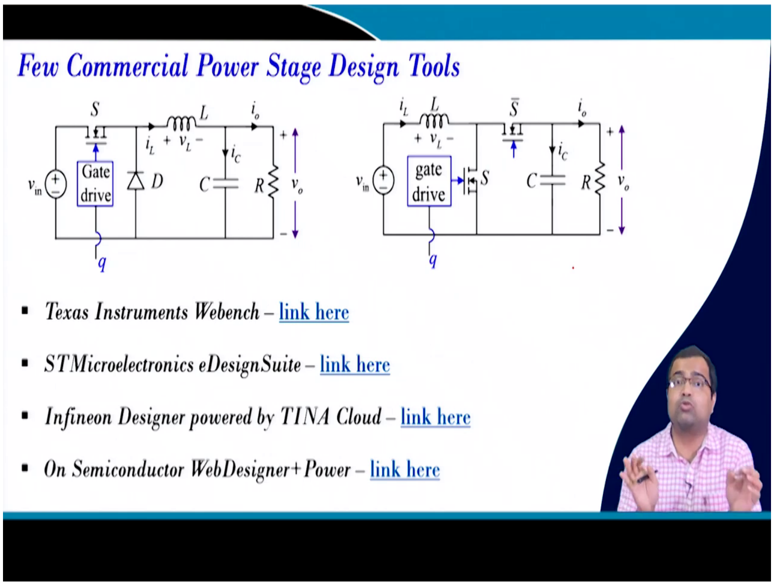
The important requirement, steady state requirement input voltage range, is very important; the worst-case current ripple, the losses, the device rating that will decide on and we will also talk in the loss analysis that range of input voltage is important particularly for light load efficiency. Then, the nominal efficiency it will decide the switching frequency as well.

Output voltage value is important to know what is the maximum or the minimum duty ratio that we have to achieve using the converter ok. Then, what is acceptable ripple limit? Then, what is the acceptable undershoot, overshoot? Though it is the steady-state characteristic, we will not talk about overshoot undershoot.

Then, what is the maximum load current that will decide how many number of phases? For a single-phase converter, generally, 20 Ampere current is reasonable; but if you go above that, we need to consider a number of phases. Then, another important is the modulation technique which in most of the cases we do not consider because we by default consider PWM.

But in this course, which already talked about, you know, constant on type constant off time control. And in subsequent lecture, I will show you the worst-case scenario can be drastically different under different modulations technique. So, in order to decide the frequency range input filler design, the ripple characteristics, we should consider also the modulation technique.

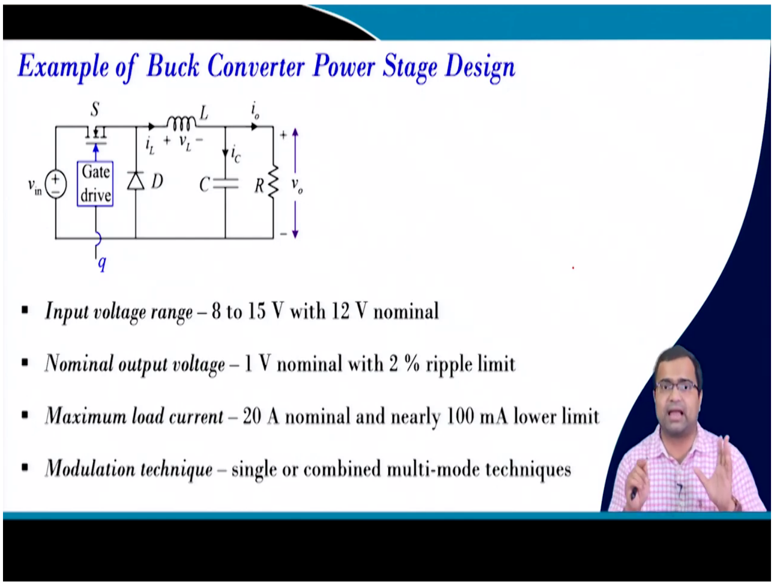
(Refer Slide Time: 65:53)



Now, there are few commercial tools; I mean I am just presenting few of them like a Texas Instrument Webench, then ST Microelectronics eDesign Suite, Infineon has its own, then On Semiconductor and there are other industry also, they have their own tool and if you go to the tool.

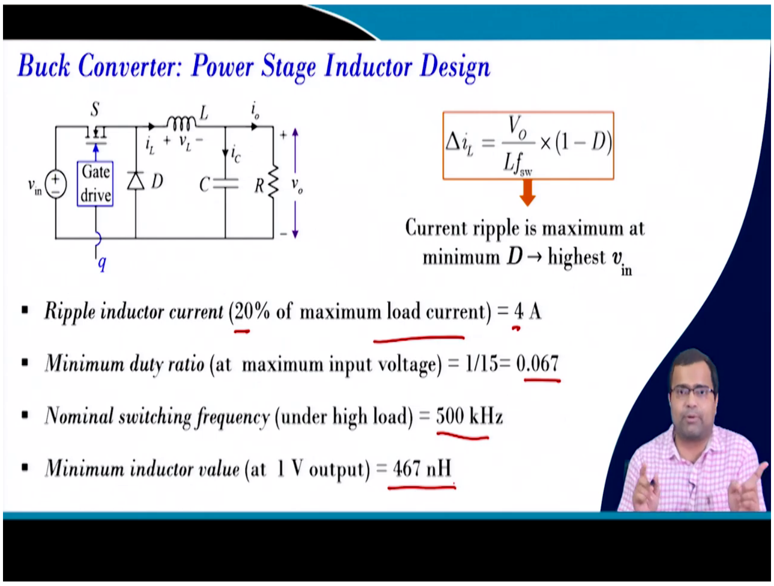
And if you give your input output voltage, load current specification, it will create a bill of material so that you can even know the parts of the inductor, capacitor. It will be helpful in the power stage design also ok. But you can have your own controller.

(Refer Slide Time: 66:28)



Then, if you take an example of a buck converter for 8 to 15 volt with a nominal 12 volt input and we want to achieve 1 volt output with 2 percent ripple. The maximum load current is 20 Ampere and the modulation technique; we can use the PWM or a combination of thing because we will discuss this in the light load control technique.

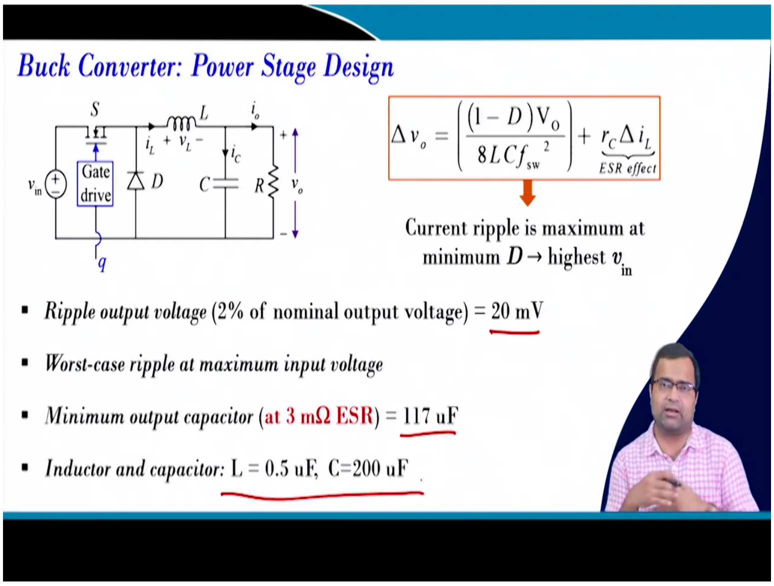
(Refer Slide Time: 66:50)



So, in the inductor design, we know under PWM, the worst-case ripple that we have discussed that will happen at the highest input voltage. So, if we keep 20 percent ripple criteria of the maximum load current. So, ripple is set to 4 Ampere and we should calculate this ripple at the highest input voltage because there will be a ripple will be worst.

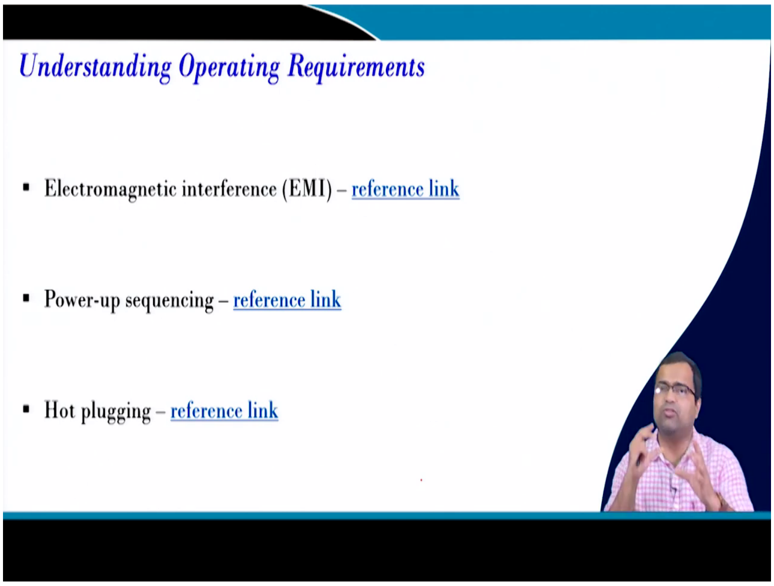
Then, that will give us the duty ratio range and at that duty ratio, the nominal switching frequency if we create 500 kilo Hertz if you take, then our minimum inductor value should be 467 nano Henry and in our simulation, we took 0.5 or 500 nano Henry or 5.5 micro Henry.

(Refer Slide Time: 67:28)



Similarly, if you take the output voltage ripple, we can calculate the output voltage ripple at the highest input voltage that will be the worst-case. Then, if we consider 2 percent of the nominal ripple, then it is 20 milli volt and that should be calculated at the worst-case and this will give us the minimum output capacitance to be 117 micro Farad. So, in our simulation, we took 200 micro Farad. So, we choose these two for our subsequent lecture in our future lecture.

(Refer Slide Time: 67:58)

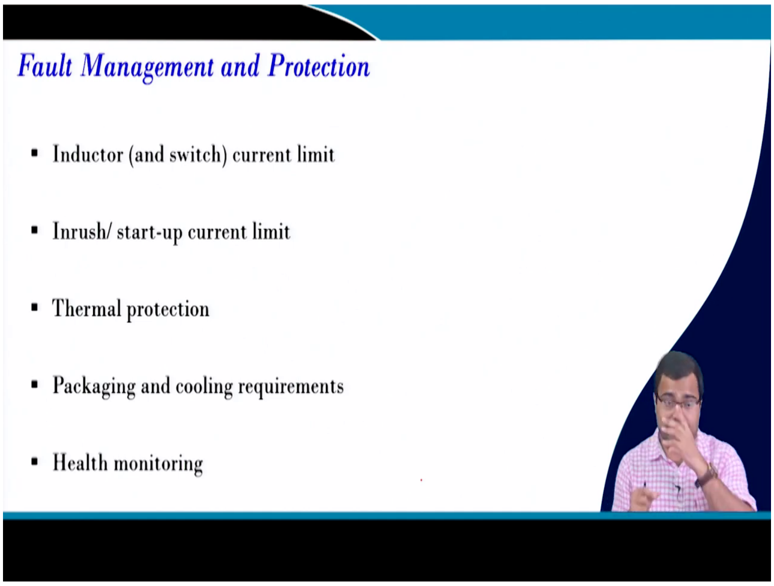


Then, understanding operating requirement, we discuss about electromagnetic interference effect. The power up sequencing; that means, multiple converter, if it undergoes transient, then we need to create a sequence of even and now, power management bus actually is coming up and which can be used for digitally control converter to you know communicate between multiple subsystem.

Because we talked about you know multiple POL for a smartphone, where each POL will undergo different transient while driving its load and, but the battery is a single source. So, we cannot accommodate all transient even to happen at the same time, then the battery will collapse. So, then we have to create a sequence of transient so that we can reduce the burden of the battery and that is also important.

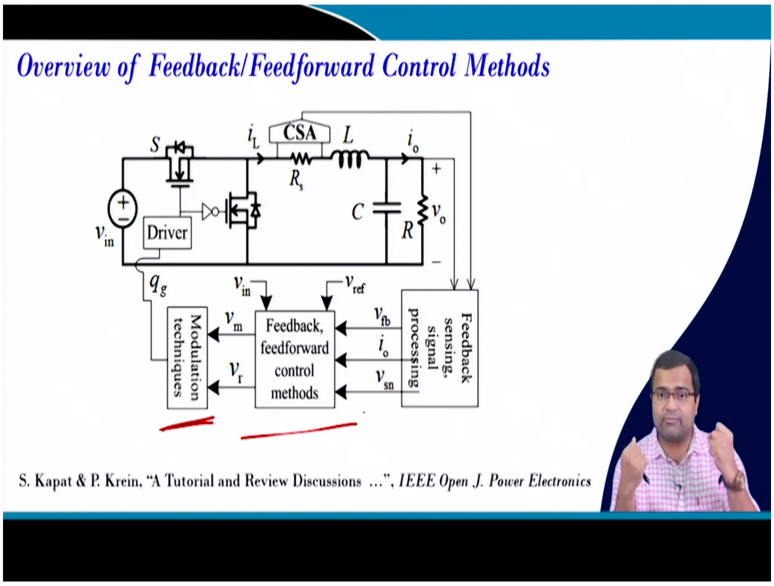
Then, what plugging is also important so that if you go to data center, there are racks and your rack power supply. If you want to take out one of the faulty units, then the whole system should not be stopped. That means, it should be in the running condition, we can replace the unit.

(Refer Slide Time: 69:02)



So, those features are important. In the fault management, we need to put an inductor current limit. Inrush current is important. Thermal production is also important. Packaging and cooling requirement is very important and you have to check the health monitoring.

(Refer Slide Time: 69:16)



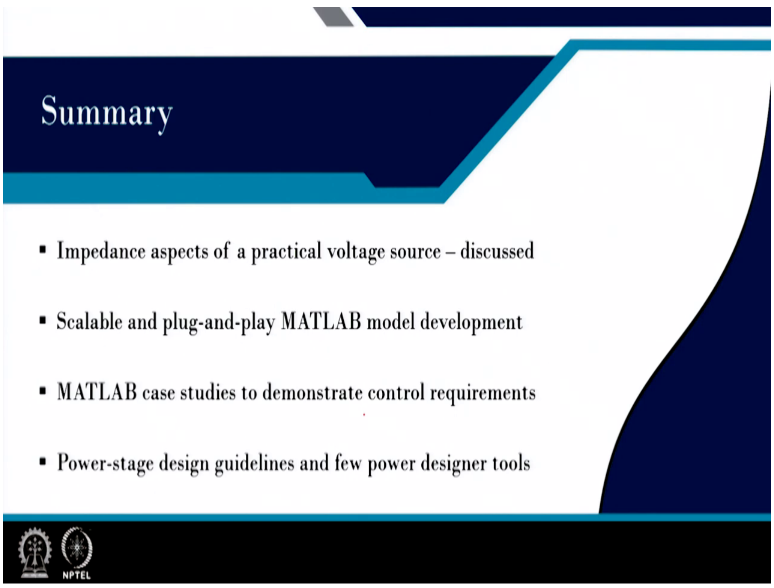
Then, overall thing, it turns out to be that control will play a significant role because we can take the control technique using that we can actually incorporate the start up behavior. We can shape the start-up behavior. We can shape the inrush current, we can put it. If there is a fault by means of a current limit, we can save; we can disconnect the power supply.

Similarly, you know we saw about the effect of source variation in the output that can be rejected completely by means of control ok, by means of feed forward or even feedback or a combination of feedback and feed forward that will see in the subsequent lecture.

Similarly, by means of modulation or by means of control, we can do active EMI reduction by means of frequency modulation. So, all these can be incorporated into the control. So, control can play a significant role in order to improve performance, in order to achieve close to output impedance, in order to achieve you know the fault protection you know I think fault tolerant power converter.

So, all these can actually enable this feedback and feed forward control can play a significant role. So, in the rest of this lecture, we are going to take now we have somewhat very clear the need for the control ok.

(Refer Slide Time: 70:38)



So, in summary, the impedance aspect of a practical voltage source was discussed. The scalable and plug and play MATLAB model development that process that also we have discussed. Then, we also discussed MATLAB case studies to demonstrate control requirement and we also, you know, discuss briefly the power stage design guideline and few power designer tools. So, with this, I will finish here.

Thank you very much.