Design and Simulation of DC-DC converters using open source tools

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Lecture – 07
DC-DC converter concepts

This week we shall focus on DC-DC converters. We shall begin with non-isolated converters, you may already have heard about the buck converter, the boost converter, buck-boost converters that are the primary objective in these particular weeks' lectures. We will see how they operate, how they work simulate and then how to design them too. You have a DC voltage and you need to supply to a load which demands DC, however you will see many situations where the DC voltage which you have battery or coming from the rectifier filter is of a value which is not a directly usable by the load. The load may demand high volts, it may demand plus minus 15 volts for analog circuits, it may demand 3.3 volts or 1.8 volts for most of the digital circuits.

So, you need to see that a power interface or power supply something like a power supply is built which will do this job of properly converting a DC of one level to DC of another level. So, how is this done? One is by linear regulators, we use linear regulator for the most popular and in the advent of the switch mode the power converters some one and half decades ago. The linear regulators are very accurate, very precise, very good regulation, however they are not efficient. The switch mode regulators are definitely more efficient, there are no lousy components. In an ideal sense no lousy components within the switch mode DC-DC converters, however the quality of the DC output that you get out of the switched mode DC-DC converters of not as good as a linear regulator.

However, the DC-DC converters switched mode have become very very popular and they have improved in quality and performance over the years and today they are most popular and they are used in most of the power supplies in DC-DC converters. Even in our PC’s in the monitors and many electronic equipment the front end portion would be a DC-DC converter.

So, we shall try to see what inside that we can gain by studying these non-isolated and isolated converters and go towards understanding the real DC-DC power converters which go in to most of the products today.

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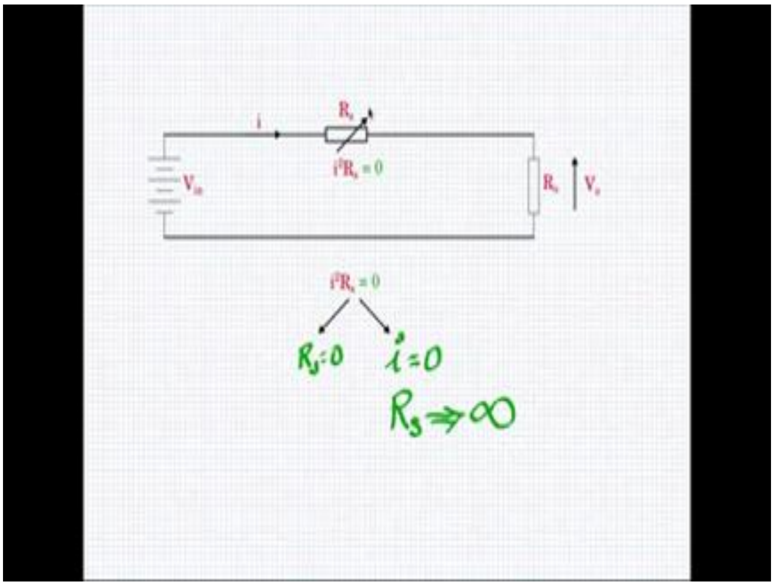

Let us discuss about the basic of the DC-DC converter. It consists of an input source, could be a battery or the output of the rectifier filter which we discuss in the last week. Now it contains a load which expects a DC voltage. Now these two needs to be interface the simplest and easiest way of interface would be to put a resistor in between this would be the simplest DC-DC converter.

Now, let us make the wiring connection, so that we have circuit diagram. Now that we made the connection we have to source the (Refer Time: 04:04) resistor and load resistor. Let us give some names. We will call this one as V the input voltage, we call this is the output voltage, we will call this as the load resistor, and we will call this as the series resistance which is in between. Now this is what will act as the drop such that the output voltage is according to our wishes. Now let us say for example, we have 48 volts at the input and we need 5 volts at the output here remaining 43 volts has to drop across this resistor. This would be a series drop resistor and this is the typical concepts that are used in almost all in linear regulators.

Now this resistor can be a varying resistor so that you can achieve regulation. So, as the input voltage varies, vary this resistor such that the output is a regulated level at 5 volts or 12 volts or whatever voltage that you now set. Unfortunately the problem with this type of simple DC-DC converter is that Rs is a resistive, there is a current flowing through this circuit, there is a current i flowing through the circuit. Then there is dissipation across Rs and that is i square Rs. Now these are finite resistance and therefore the power dissipation is finite and this can be a (Refer Time: 05:45) power dissipation. Therefore, this type of regulators are highly dissipative and very very in efficient.

Now, our interest is to see that the drop in the series element is 0. How do you make that happen? You can make i square Rs equal to 0 in two ways; one is by making Rs equal to 0 another way you can make i equal to 0. Now i is equal to 0 implies Rs can be an infinite value. So, what does this mean; means that when the switch is a short circuit in that case the voltage across the switch is 0 there is no power dissipation. When i is equal to 0 the switch is a open circuit. So, when you make the switch open circuit the current through that are 0 and then also the power dissipation (Refer Time: 07:01) switch is 0. So, the only two conditions when the switch is not dissipating power is when Rs is 0 and when Rs is infinity and the switch is short circuit, fully on when the switch is open. These are the two conditions that are permissible from the point of view of power dissipation in the series circuit in power dissipation the series element.

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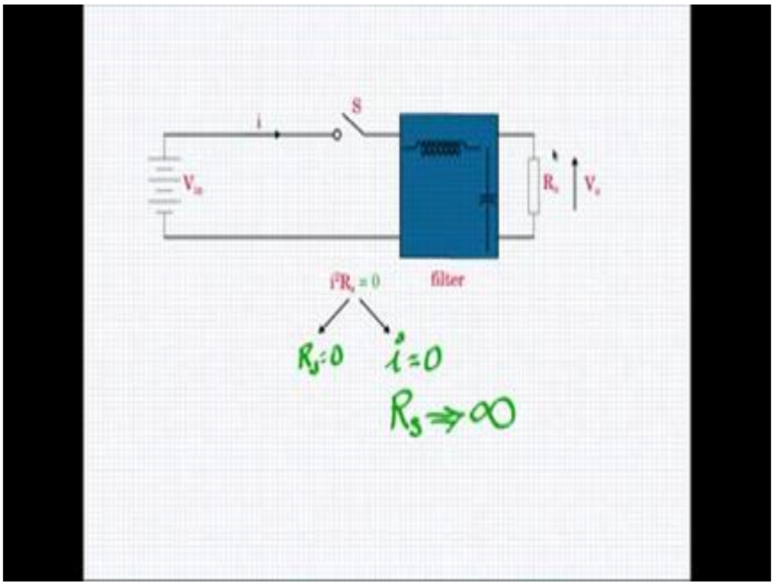

To achieve this let us replace the resistor by a single pole switch as shown here. So, when the switch is on V in comes to the output and the switch is off V naught is 0 and this way there is no dissipation in the switch either when it is on during convection or when it is off will be open the circuit situation. However, the voltage now V naught is no longer continues to your DC, it is pulsating. When the switch is on then you have a DC-DC voltage or V in appearing here, when the switch is open the voltage across V naught is 0. So, it goes high-low, high-low pulsating voltage and this becomes a chopper. So, it is called a chopper voltage and this circuit becomes a chopper. This is not what we want. We would like to have the output voltage V naught as a pure DC, so which means that we would like to have a kind of a filter circuit here.

Now, this could be a filter and this could be composed of L and C’s. It could probably have an inductor something like that and capacitance something like that or these L and C’s together would form second order filter and this chopper switch plus the filter together will provide a DC voltage at V naught. And together they form a switched mode DC-DC converter.

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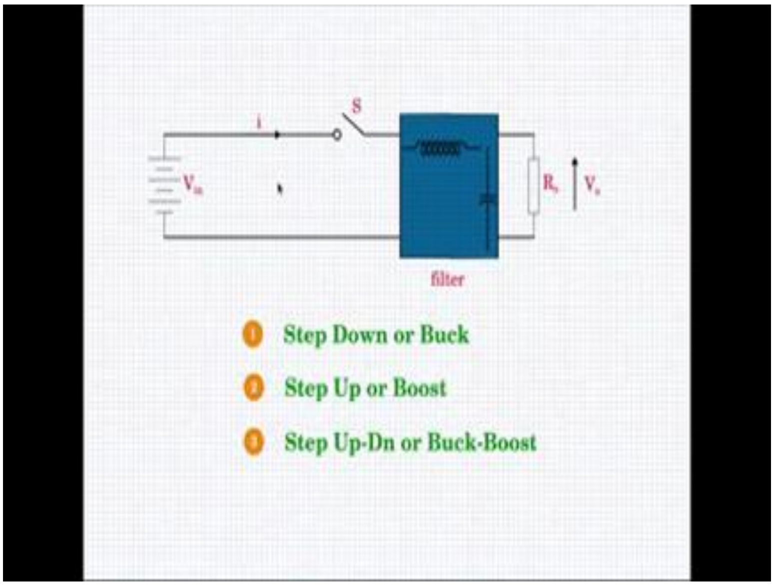

There are many configurations in which this switch and the filter can be put together. If we have one switch, one inductance, one capacitance to make up the DC-DC converter elements then we call it as a Primary Topology. In the primary topology itself there are three possibilities; one is a step down converter or a buck converter, another is a step up converter or a boost converter, yet another you have step up-down or buck boost converter.

Basically, step down has a main indicates converts the input voltage into a lower output voltage. Step up converter converts the input voltage DC value into a higher output DC value or boosting it. Step up-down converter can do either under certain duty cycles it will be step down and the certain other duty cycles it will be step up. We will of course look at all three types of converters in this week. All these three type of converters do not have any galvanic isolation there is they do not use any transformer they are non-isolated converter and already important and there are many applications with which these converters can be used, if you look at its operation, if you look at how to go about simulating it and also to design it.

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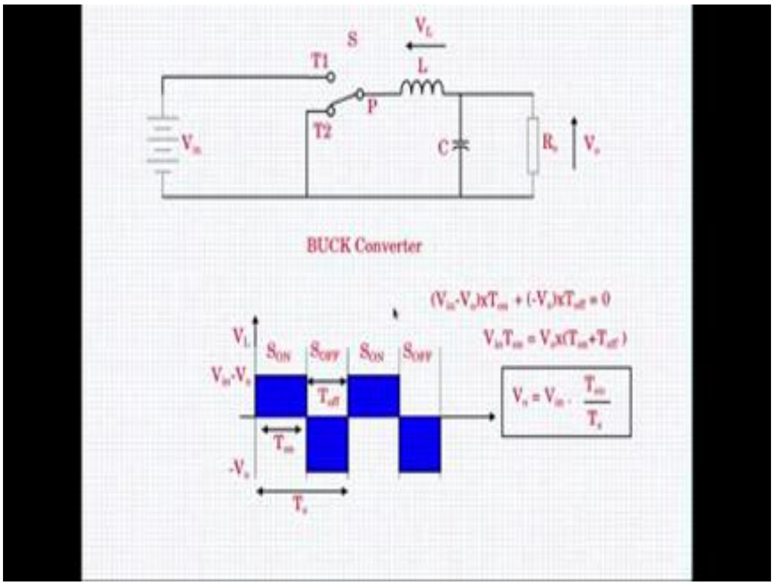

This is a chopper circuit; the switch is a single throw switch. When the switch is on the pole is connected to the throw the throw is connected to the positive of the input which is V in. The pole voltage is same as V in which is transferred to the output V naught. When the switch is off the pole is floating and the pole voltage is undefined, so also is V naught which is undefined. This is not a recommended way of drawing the switch we have to replace the switch with a single pole double throw switch where there are two throws and both the throws are connected to well define potentials.

In such a case the pole whether it is connected to one throw or the other will have a defined potential and therefore the output V naught. The switch S is now replaced with the single pole double throw switch. It has two throws; throw one T1 is connected to the positive of the input supply, throw two is connected to ground. When the pole is connected to T1 then the pole voltage is same as V in which is transferred to V naught. When P is connected to T2, T2 is connected to ground and therefore the potential of V naught is 0, therefore V naught as well defined potentials at both positions of the switch S.

The chopper is now slightly modified. The pole is connected to the inductor L and a capacitor is connected across like this, and this L C forms a filter as a second order filter which filters out the chopped wave form and gives a smooth DC to the output. The operation is pretty straight forward when the pole is connected to throw T1 pole voltage is V in, the inductor starts charging up magnetically the capacitor also charges up, when the switch switches to the other position T2 this pole is at 0 potential. The inductor current reveals through the capacitor and the output load and discharges the magnetic energy into the capacitor and the load. Then again the cycle begins by the pole getting connected to V in. This is a DC-DC converter called the Buck Converter.

Here, the output voltage V naught will have a value less than that of V in. Let us define some nomenclature here, when the pole P is connected to T1 we will call it as S on; switch is on. When the pole P is connected to throw T2 then we say the switch is off. We shall now try to plot the voltage across V L. V L is one critical component that you will have to study and the other component that you need to study here is the capacitance C, the voltage V L across the inductor. Let us draw a couple of axes; let us have our x axis which is the time, let us have the y axis which is the real axis the voltage axis. We shall put in some time lines and let us say this is the on time of the switch where pole is connected to T1, this is the off time of the switch, again on time of the switch, again off time of the switch. So, let us define it and name it in this fashion. S is on during this period S is off during this period again S is on and then S is off.

So, let us plot the voltage that we see across V L. Now the V L will be a bidirectional voltage. It may be good to shift this up so that we can see the bidirectional voltage on the screen here. When the switch is on the pole is connected to T1 and the voltage at the pole here is V in. The voltage on this side of the inductor is V naught and therefore at that instant the voltage across the inductor is V in minus V naught. So that will be the voltage that you would see at this point. And when the switch turns off the pole P is connected to the throw T2 and the pole voltage is 0. And the voltage across the inductor is now 0 minus V naught, which means that the voltage goes negative. And again when the switch turns on; the cycle repeats in this fashion the inductor voltage going positive and negative like this.

What is very important here to note is that under steady state conditions the area under the inductor voltage curve on the positive side and area under the curve on the negative side should exactly match, let us give it some color. So, you see the blue part on the positive side on the blue part one of the negative sides should match, which means the average voltage across the inductor should always be 0 in the steady state conditions. This will prevent the inductor to go into saturation there will not be a magnetic flux build up and make the inductor to saturate. So, it is very important that there is volt second balance in an inductor.

Another case the capacitance, the average current should be 0. If there is an average current there will be charge build up in the capacitance. In the case of the capacitance ham second balance should be there, in the case of the inductance volt second balance should be there. These two are very very important concept which I will explain shortly.

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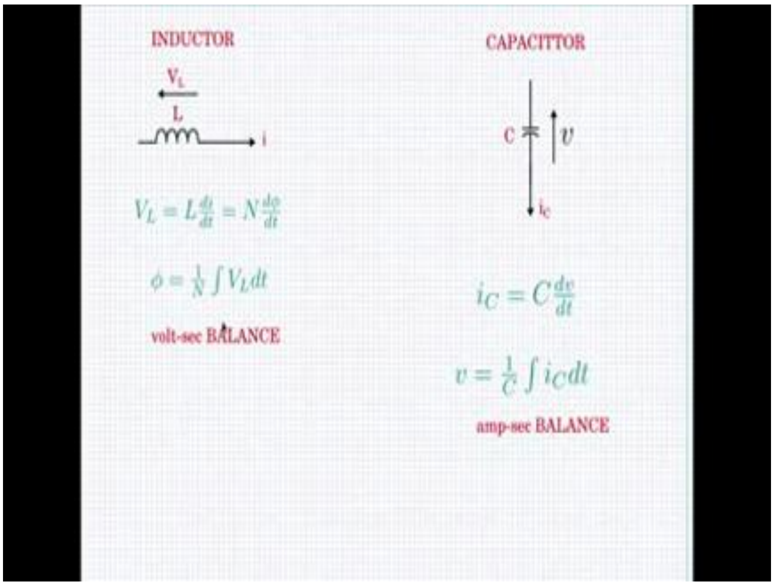

Two very important components that we will use in most DC-DC converters are the inductor and the capacitor. Inductor is one of the dynamic elements that this part of the filter in most DC-DC converter, and the voltage across the inductor that as I was mentioning earlier is a point that you need to observe and that is a critical voltage. Likewise, in the case of the capacitor which is also a very important dynamic component that will be using in DC-DC converters. You have to monitor the current through the capacitance.

Now let us look at the inductor first. The inductance L and the voltage across the inductance L and the current i which is flowing through the inductor are related by the Faraday's law. So, by the Faradays law if you look at that you will see that the L is equal to L di by dt. And the inductor is generally warmed upon on a magnetic core which has N turns and there is a flux by which is flowing through the magnetics and a little bit the coil. Now, the relationship is as given here V L the voltage across the inductance is L di by dt plus N d phi by dt. Let us look at this part of the equation N d phi by dt. What is the flux within the core? Now the flux within the core is basically rearrangement of this equation. Now let us say V L is constant across the inductor then integral of V L dt would be N phi the (Refer Time: 22:25) phi the flux in the core is one by N integral of V L dt.

The important part here V L dt, if V L was 0 then phi would be a finite value by this equation. If V L was not 0 but has an average value which means it is like a DC value then it starts getting integrated with time and keeps on increasing and the flux also keeps on increasing than at one particular point depending upon the material it will saturate. Once it saturates there is no longer and inductance effective he well just be a piece of (Refer Time: 23:10). Therefore, it is very very important that V L does not have average value, which means this volt second; is volt second has to be balanced as I had been discussed in earlier.

So, in the inductor very very important that you need to know is that there should be volt second balance in the steady state. This volt second balance is only in the steady state, in the (Refer Time: 23:46) there will not be volt second balance because the energy within the inductor has to change. In order to make it change there has to be imbalance in the volt second. But in the steady state there is no volt second balance has to happen so that there is no build up of (Refer Time: 24:04).

Likewise, in the capacitance by governing equation this i C which is equal to C dv by dt; where dv is the voltage across a capacitance, i C is the current in the capacitance. And rearranging this you will get the voltage across the capacitance which is one by C integral of i C dt. Imagine there is an average current which means there will be some equivalent d C value the integral of the d C value dt means that this value will keep on increasing, and the voltage will keep on increasing which means the voltage across the capacitor will go towards infinity and finally (Refer Time: 24:49) now growing the capacitance. And therefore it is important that i C should not have an average value, i C dt should be balanced by the amp second balance should be there.

So, in the capacitor in the case of the capacitance which is the dual of the inductor there should be amp second balance during steady state; very important to note during steady state. And during the (Refer Time: 25:17) there will be some imbalance so that the voltage across it will be built out or discharged. And once the steady state is reached there has to be a unsecond balance cycle by cycle. Now this is a very key concept, in fact the input output relationship of all DC-DC converters switched mode DC-DC converter is based on these two important key concepts.

The volt second balance under steady state condition is used to determine the input output voltage relationship of converters. The amp second balance is used to determine the input output current relationship. Of course, one could also use the volt second balance to determine the input output relationship and assuming an ideal converter to determine the input output current relationship tool.

So, remember these two, in fact they will be using the volt second balance in almost all converters to find the input output relationship. If every result the buck converter circuit that we give you earlier let us put some generic values. Now this amplitude is V in minus V in V naught as we discussed earlier during the (Refer Time: 26:46) the pole is connected to T1 the voltage across the inductance is V in minus V naught. During the time and the pole is connected to T2 it will be 0 minus v naught, so it will be minus V naught here the amplitude. Now, this is the time period which we will call T on and this is the time period we will call T off, that is for duration of time T1. The inductor voltage you see V in minus V naught, for duration of time T off the voltage across the inductor is minus V naught.

Now let us apply the volt second balance to these parameters. Now consider this part of the equation V in minus V naught into T on, this is basically the area of this rectangle V in minus V naught into T on. So, this height into this width is the area of this rectangle or this is the volt second of this positive part of the inductance waveform. Now this is minus V naught into T off which is the width, so let us add to that plus minus V naught into T off this part of the area. So, this volt second plus this volt second should be equal to 0. Then we say that there is volt second balance. So, this equation if you rearrange you will to see that it is of this form V in T on minus V naught we can take it to the other side minus V naught T off to other side we have V naught T on plus T off. T on plus T off is nothing but the total switch in period. So, the total switch in period is T on plus T off; this is Ts.

So, still further rearranging we see that V naught is equal to V in T on divided by Ts, this is Ts. So, this would be the input output relationship for this buck converter. This is just as an example I thought I will mention this to you, the importance of the volt second balance of the inductor. Whatever may be the converter if you take the volt second balance relationship of the inductor you will get the input output relationship. This is the key concept that I want to convey in this particular video of the lecture.