Design for Internet of Things
Prof. T. V Prabhakar
Department of Electronic Systems Engineering
Indian Institute of Science, Bengaluru

Lecture - 23
Buck Converter - 01

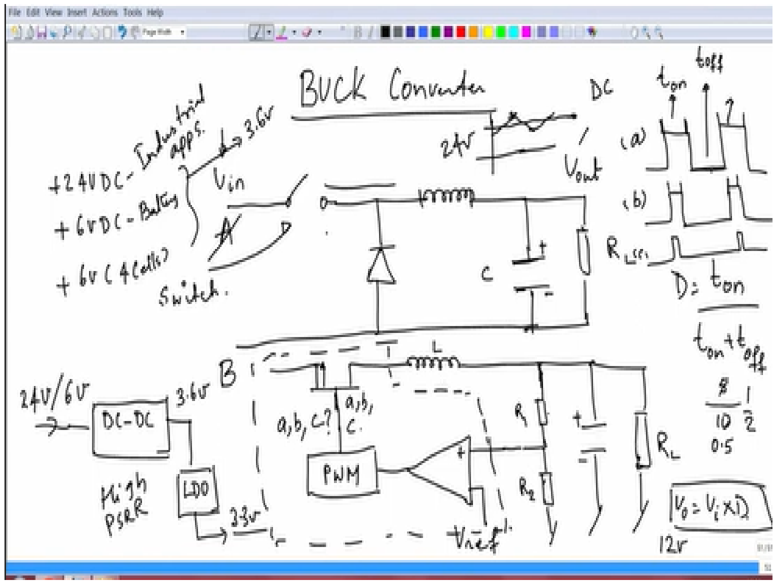
Welcome back. Let us now look at one more component which is part of the SOC. We said the power supply block has two. One is the LDO, the other is the buck converter. And we also did that little experiment using that website link where if you choose between the LDO and the buck converter the power savings, particularly with respect to time on the x axis and current consumption on the y axis changed quite drastically.

That is because the DC-DC converter or buck converter in this case is highly efficient because it is switching at a very high speed. It is not, it is giving the load a feeling that the current is available continuously. But in reality, it is actually pulsing that current into the load and therefore, the average current comes down. That is the beauty of the whole system. So, if you connect a battery since the average current consumption comes down the life of the battery improves.

So, this is an important thing about an IoT node. And how does it work? This buck converter, how different it is from LDO, may be bothering you. So, it is important to know the basic functioning of the buck converter then the little exploded view of the buck converter and what is it that governs the output voltage of the buck converter should be known to us. Then we can take one data sheet, understand a little bit about the datasheet parameters.

And then see if you can apply them in some major example. So, that is the goal for understanding a little bit on the buck converters.

(Refer Slide Time: 02:17)



Let me draw your attention to this little picture I drew here which is the simplest possible buck converter you can ever think of. The switch is here and right now the switch is in open condition. So, I have to connect it here. This is a DC input and what you are getting out is also DC. That is why it is called a DC to DC converter. It is taking one level of DC converting it to another level. What are those levels in the IoT world?

Well, if you are operating in the industrial world, it is usually 24 volts DC. If you are using a battery, it can be a 6 volts battery. If you are using two pen torch cells right? you will get 3 volts or if you are using 3 cells you may get or four cells you will get 6 volts. This is like one battery. All these things essentially are the inputs and what you want is definitely none of them. What you are interested in is either 3.3 or usually it is 3.3 or it can also be 2 volts.

Sometimes even 2 volts 1.8, 2 volts and so on. Maybe if we go by the classic way of working with buck converters, we may want to make this. If you want 3.3 you may want to make this 3.6 volts and what will you do? That is the beauty. You will have 24 volts IN or 6 volts IN, you will take in and then you will generate via DC-DC you will generate 3.6 volts but this is highly noisy lot of switching noise. So, what will you do? We discussed this together.

You will pass it through an LDO which has a high PSRR and what you will get here will be a clean 3.3 volts. That is what you typically want to do. So, you see now your 24 volt or 6 volt battery or cells or whatever is taken in and typically this is how you apply the buck converter systems. Now what I am trying to tell you is how this circuit basically works. And then we will look at a slightly detailed view of the same circuit.

Basically, when the switch is closed, let us see what is the path for the current to flow. The current path will be like this through the load and back like this. So, that is the path of the current. It cannot go this way when it goes like this because this diode is reverse biased. This is reverse biased. It is reverse biased when this switch is closed but it is forward biased when the switch is open and let us see what actually happens. The switch is closed.

This is a path, this is the inductor, this inductor will start building up, the energy on the inductor will start building up and it will also deliver the power to the load. It will also deliver the power to the load plus it will also charge the cap. Then once this capacitor, the output capacitor, once this goes open the direction of the current is now the same. But this diode is forward biased. So, it goes like this now.

Because there is no path here there is nothing that it can go back to the input voltage, input side. So, now this is the current path. This diode gets forward biased and nicely the current continues to flow irrespective of whether the switch is open or closed into the load. Sometimes it is delivered from the inductor into the load and when it is closed it comes from the source not only goes across the L but also stores the energy across the C across the capacitor and also delivers to the load.

So, this action essentially goes on and on and on. And you get a current waveform which is going up every time the switch is closed the inductor charges, the current across the inductor increases, so it goes up. Every time the switch is closed the inductor goes down current across the inductor goes down and again when the switch is closed the inductor goes up. And it is going down when it is off and this cycle repeats all by itself.

Now how long should it be on and how long should it be off is the question. Well, that depends directly on what is it you want to do. I will give you a simple exercise, I will give you a 24 volt source. And I will give you a very simple formula which is V I times D and what is D? D is T on, the time over which the switch is on, T off is the time over which the switch is off. D is T on divided by T on plus T off. Very simple and how to visualize T on?

This is the time over which the switch is closed. This is the period over which the switch is open and this is the period over which the switch is open again. So, this is ON, this is OFF and this is ON again and it goes on in this manner. Now you can see this is waveform A, there is also waveform B. Waveform B is exactly half the time it is on T ON by 2 is this on. And this is OFF for a longer time. It is on for a longer time. Now if you look at the waveform assume that T on is some number.

Let us say it is 5. It does not matter. You just take a number 5. Now OFF it also appears to be almost like ON. So, OFF is also 5, so ON anyway is 5, this is 10 and therefore this is half which is nothing but 0.5. If D is 0.5 and your input is 24, what will you get at the output? 12 volts, that is, it. You are already reduced from 24 to 12. Now if I make T ON as you can see here, half of the previous one you will have to calculate what will be the output voltage.

That is easy by just looking up, please do that calculation. You will realize that the buck converter does just this and nothing else. It knows how much voltage is required at the output and it has to calculate the duty cycle. It calculates the duty cycle and on and off the series pass switch at that rate and then you get the output voltage which is very simple to even visualize now. So, this is what I wanted to say. I also mentioned that the current goes up if you take the time axis.

The current goes up when the switch is closed. It decays when the switch is open, again increases when the switch is closed and goes on that way. You can take an average number here; an average comes here which is this one divided by 2. Nothing else but divided by 2. That is your average. This line is your average, current average. So, you can see what is required for the load was this current but what was delivered was this average.

Load never ever felt that the peak was not achieved. And therefore, the current drain on the battery is also reduced significantly. More of this when I show you discuss in detail about one more small note which I wanted to talk to you about. But before we go on, let me explore a standard commercial buck converter which is available in the market. This is easy to connect because this is the same picture that you saw with respect to LDOs.

Same, ditto picture except that there is one additional block and that block is the PWM block. Because you need to control the duty cycle ON, OFF, ON, OFF, of that series pass transistor and that is what actually governs the output voltage as well. If it is 0.5 which I showed you, your input is 12 volts, your output and if the duty cycle is 0.5 then you get 6 volts at the output. That is a very simple expression which we did. So, that governs the output voltage.

So, you need that PWM. So, that PWM is an additional circuitry. By looking up at an LDO and a PWM you can easily say which one of them will be faster. All these gotchas of PWM generation and so on and so forth does not exist as far as LDOs are concerned, they are linear devices. And therefore, no question of switching on and off. You need a switching circuit for driving the transistor and you have to drive it to saturation and you have to put it to cut off saturation, cut off, saturation, cut off and so on.

So, that is another issue. Therefore, PWM generation and the governed state where you have to move the transistor from to saturation and cut off and so on. That is definitely a much slower loop compared to an LDO. Therefore, buck converters are sluggish, they are slow. They need , they use switching because they are switching and because of the switching added nature of the whole system ripple is bound to be there at the output.

It is there not their current is increasing, current is going decreasing and suddenly current increases, current decreases and so on and so forth. Of course, that prominence on the current increasing and decreasing and current increasing and decreasing becomes more prominent based on the load. If the load is drawing a lot of current then you will see this physical dipping. But in the light loaded condition, then you will only see like this little bit twist.

And then you will think that almost you are getting the right kind of DC voltage. But actually, you will be, it is actually switching at such a high speed that you cannot, at a high frequency that you cannot even make out that. You are getting a switched pulsed current at the output which is being driven into the load. Anyway, now because of that I put back this block here. You can see all these parts are basically the same as that of an LDO.

Now I am looking at picture B and not picture A because we finished A. So, let us look at B. This is the same series paths that can go and get replaced with this picture. It is the same one that we also saw here and then you know that this is the PWM block it is connected to the gate. So, the gate gets a modulated input which is based on PWM and the PWM signal whether it should be A or whether it should be B there can be a C waveform. It will be even more pulsy.

Now C is half of B and B itself is half of A. All these things whether it should be A waveform, whether it should be B waveform or whether it is C waveform depends on what actually happens here across the sense resistors. It will, if you have a huge load then you have to go back to A. If it is light load, maybe B will be good enough. But if it is negligible load, it may be even C. So, the fact that you need to shift between these different waveforms.

Means PWM output should generate either A waveform, B waveform or C waveform depending on the R L that is connected to it. Therefore, this loop is a bit on the slower side. Look what I have done very carefully and cleverly. I put this dotted line here, but I have cleverly excluded the inductor from this picture. That means even in an IC, buck converter IC, inductors are placed outside because big inductors typically cannot be, are difficult to be fabricated on the silicon.

So, you may have to put it outside. So, this is the L which is placed outside R 1, R 2 are sensing resistors, plus and minus is here and this is the load resistance. Now we need to see how you got this? V out is V I times D.

(Video Starts: 18:23)

For that you can I will share this document. So, you can go through this document and it is actually available on the web. So, just to connect back until you see this picture. The same familiar picture that I drew. He has put actually a MOSFET here, otherwise, there is no difference between what I have drawn and what is shown here. Now I showed you about T ON that is here, T OFF is the state over which it is off, it is kept down here. Now T ON plus T OFF is T S. That is the full cycle.

That is also shown here. Now you can do a lot of simple calculations based on Ohm's law. For instance, you might be interested in finding out what the voltage across the L. Obviously, the voltage across the L is nothing but the output voltage Vo minus the input voltage Vin or you can do Vin minus Vo. So, that you can avoid a negative sign. That is the voltage and then you see Vin minus Vo is shown here.

That is V L and that happens only when the state of the PWM is between 0 and T ON. That means you are starting from 0, the inductor is not yet charged. You are simply going to go up to T ON the time period over which the switch is closed so, that the inductor can build up on its current across the inductor. And there is also a voltage drop across the inductor. So that V in minus Vo is shown here. What is the current across the inductor?

Well, you are just applying initially the current was 0. So, that term is here. Then it charges to, the current increases to the difference in voltage that is V in minus V o divided by L. This is nothing but applying Ohm's law for a period of time T. Actually, this should be time T on. It will increase from up to that point only or increasing. So, anyway, this is I L0 plus V in minus V o by L times T, some period of time or which the current is flowing through the inductor.

Now why it is not T on when it is actually T? Perhaps it is because current continues to flow even after the switch is open. Otherwise, how will the load get the current. So, maybe he considers this T for that reason that he wants to find out the inductor current, I L at any instant T. So, this is important. So, that is why he is going from 0 up to T, to whatever instant you want to measure the current that is the instant which is up to T but you are starting with time t equal to 0.

The inductor is completely discharged and there is no current flowing through the inductor. So, that is the point about this expression 2. Now what happens when the switch is off? Supposing you push the switch off, well, that is pretty straightforward if it is off. What you will have is the voltage across the, basically when you keep it off the output voltage will be the V L t which is nothing but let us see the difference is now nothing.

But the minus of the output voltage which is it will get a minus sign which is minus V o. The voltage difference across the inductor is V L t is minus V o. You do not have that term anymore of V in because V L t will now be equal to minus V o which is the power switch is in off state. The inductor voltage is the same output voltage with negative polarity. So, the voltage across the inductor is the same voltage with the negative polarity.

Now, on the contrary, the inductor current. Now what happens to the inductor current when the switch is off? Well, that will simply decrease linearly. I mentioned this point already. This coming down look at this picture.

(Video Ends: 23:08)

This is the fall in the current, this is the rise in the current. Now the current is dropping. This is the inductor current waveform. So, this is the fall and this is the rise. So, let us look this up again here.

(Video Starts: 23:22)

Now look back at this picture here. You will see that the inductor current will decrease linearly. What is the slope? It will be minus V o. That is what is there which is across the inductor. The voltage across the inductor is minus V o divided by L which is the value of the inductor slope. So, that is essentially what you will get. You will now see that the inductor current in the off condition is it has already gone up to T, 0 to T it was going up.

Now it is going from t to the point where it has to, we go back to on state, t minus T on state. So, this will be nothing but i L t on that is the current that was flowing during the time when it was in on state minus whatever is getting discharged now. V o by L T minus T on. So, essentially you get I L T minus T on is equal to this expression. So, from this voltage this balance of an inductor voltage 1 and 3 from this equation 1 and 3.

It is easy to tell you that the LC basically the LC that you see at the output is an important thing which controls the output voltage V out, therefore, it is nothing but V in times the duty cycle. This is exactly what we had discussed this. So, it comes so easily from this expression here. Now you look at the figure this one B here. This is your full duty cycle T on plus T off is nothing but the point here which is T s which he calls is nothing but T on plus the T off together.

It is essentially the full T s as you can see here. He has shown the T off separately, he shows T s here which is both T on plus T off. Point is about the ripple factor. Now if you look at the current it has started from some point. It has built up, it went up, it went down when the switch is off it went up again and went down, goes down when the switch is off and so on. Obviously, you can see that during the on state the current increases that is shown here.

And it also decreases after the switch is kept off. So, it goes down here. So, on, off completely will indicate the full time period which is T s and that is also shown here. This is the going down slope during this slope time this is the time equivalent of the PWM switch giving you an OFF condition, 0 condition. So, the current is going down here. Now you can calculate the ripple current. What is the ripple current flowing into the load? It is nothing much.

It is just the peak here that you see here and the trough here. You see the distance between the peak and the trough which is delta I L and the output is simply an average of the two as I mentioned. So, what do you do? You take I L on T on plus I L at 0 divided by 2. It started with 0 then it built up to T ON, I L t on you add the two and you divide by two and then you get the average current which is I 0. Now the ripple factor is pretty straightforward.

Now that you know this distance essentially it is a distance, this delta I L, you divide this delta I L by this term. The one that you see here is essentially the ripple and that he denotes by this symbol. The rest of the discussion is pretty straightforward. There are two modes of operation of these buck converters. One is called continuous conduction mode and the other is called the discontinuous conduction mode. These two modes depend on the ripple factor.

If you want less than some number then the converter should operate in the continuous conduction mode. And if you are okay to live with higher ripple perhaps then you can go to discontinuous conduction mode. At full load is desired CCM obviously is the one that you desire. And it is the one that is used for buck converters for its lower current stress in power semiconductors. The CCM operation was what we were looking up.

And this expression here that you see the ripple factor is this delta I L divided by this line here is what this ripple factor is actually shown. You can do substitutions for this expression which he does here and then simplifies you get this expression. That is all he has done. For a fixed inductor the higher the input voltage, the higher ripple factor is. If you have higher input voltage your ripple is going to be higher.

But if your input is fixed, the ripple factor is higher when the inductance is when you put a smaller inductance value. So, a lot of things to optimize here folks. Now higher ripple factor means more ripple current flowing through the capacitor. If the same ripple voltage is required, a bigger capacitor is necessary. And that is how you design the systems for buck converters. Thank you very much.

(Video Ends: 30:08)