Design for Internet of Things
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Lecture - 10
Designing with LDO's, switching regulators and case studies Part I

Let us do one thing; we need to also have completeness in terms of the kind of series elements series pass elements that we are going to introduce.

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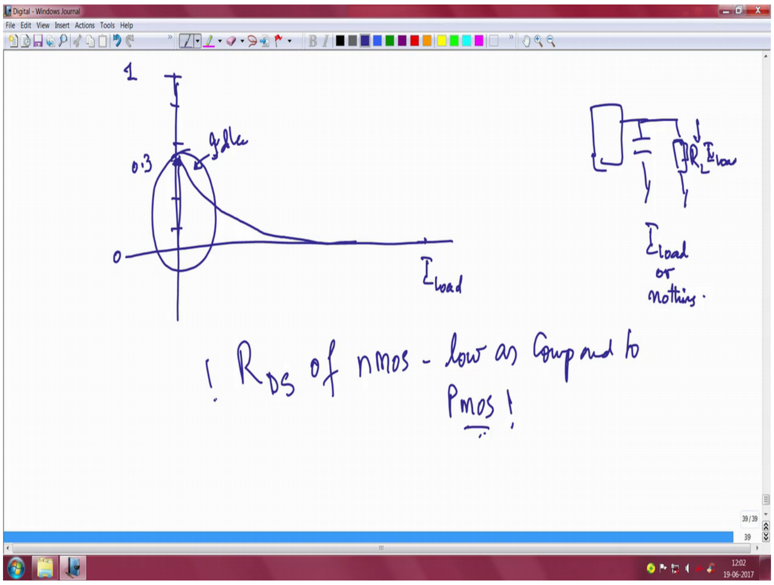

So, we said that there is a possibility to use nmos as a series pass element because it has a lot of attractions. For example, the R DS the R DS of nmos at MOSFET transistor, nmos is low as compared a Pmos, but we it is also always a good idea. So, this is what we said it is always a good idea to actually sketch the circuit diagram of a Pmos series pass element as well. So, let us do that let us put that thing so that we understand exactly how both the circuits really work because in the case of in the nmos case we you needed a charge pump right to ensure that the gate control is there because the gate voltage have has to be higher than the output voltage.

So, and that is the only the only way you can do that is to introduce a charge pump charge pump circuit how it functions will worry about that separately, but that is what we will be required in the nmos case, but in the Pmos case you do not have to worry about it, because simply getting down the gate voltage or increasing the gate voltage we will ensure that conductance of the series pass element is taken care. So, let us quickly out down that circuit and then quickly explain if you think so that that part of the study on l d voice also completed. So, let us start with that. So, let me take a fresh page and put back our famous circuit where we talk about the Pmos element.

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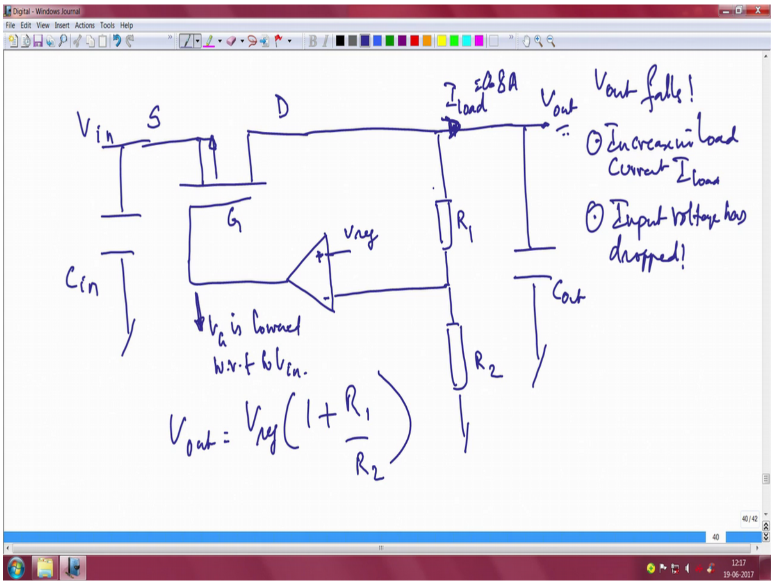

So, Pmos ma p MOSFET p channel MOSFET. So, now, drain is the output source is the input and gate is the control point, and as usual feedback comes from the center point you have R 1 you have R 2 and you know this thing now very well this is V ref right and this is incomplete if you did not have an output capacitor this is also incomplete if you did not have an input capacitor right. C out C in there are very very important in a MOSFET because I need a LDO because that these are the components that actually give you stability right these are the ones that give you the stability of the controller.

Now, it is quite simple right. So, if I load now if I load. So, let us say the output drops. So, the output drops for some reason. So, the reason why I, V out might actually drop could be because of two possibilities right from a broad perspective one is increase in load current increase in. So, we out falls I will say why does V if out fall it can be because increase in load current which is nothing, but I load has gone up has increased load current I load or it could also be because the input voltage input voltage has dropped these are the two possibilities right. Now the way that you essentially take care is you bring down or increase the gate voltage, this is the gate right essentially that is what you will have to do.

Now, the V out drops V g this is gate voltage is brought down right is lowered with respect to V in nothing, but the source point. So, we can see that this it what ultimately a Pmos as series pass element control is all about. You would have had a charge pump here or a V bias which is fed from men outside recall you had a point here which essentially was connected I will just draw it in dotted line. So, that you do not get confused this was either a charge pump slash V bias which was connected to if it is in the case of n channel MOSFET, but in p th channel you do not have to worry about that directly if you lower or increase the gate voltage with respect to V in you have a good control . So, this is a nice thing which in the case of Pmos circuit, you could essentially build a simple system.

Now, one important thing that you will come across every time when you select in LDO: so here is every time we have this problem of selecting. So, let me take a new sheet I will remove this and I will go here you want to select. So, election is our problem selection of an LDO not only selection you may have to look at the data sheet slowly we had to discover the data sheet only, then you actually know how to choose one I will draw a very simple intuitive result and let us see how to build the story from here.

Typically, this is the I load let us say for some reason you have chosen I load as 8, 0.85 amps which is here right this is this is what I am saying this I load this is chosen 0.8 sorry where is the point here yes this is the point for some reason you have chosen 0.8 point eight amps right.

So, let me connect back. So that is your, I load which is 0.8 amps.

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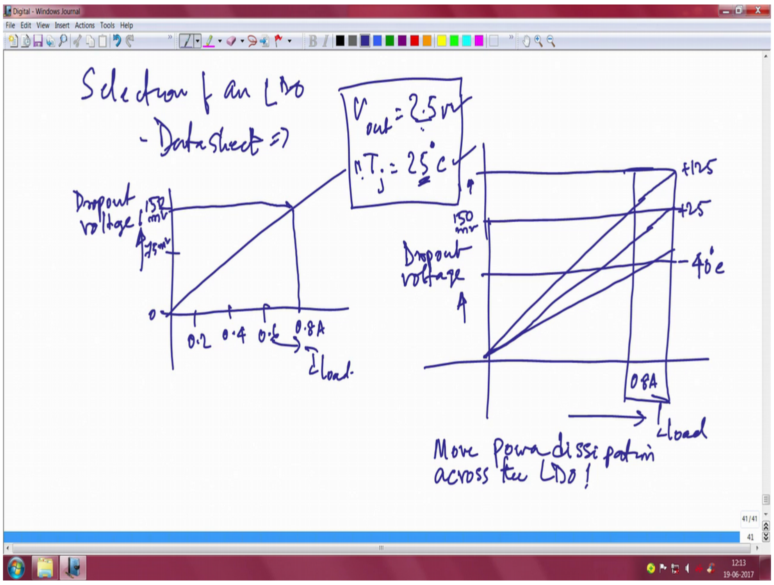

You have to look at the data sheet and always discover for this load current, what is the dropout voltage? This is so, this is access is dropout voltage and this axis is the load current. So, you can put here 0.2, 0.4, 0.6 and 0.8 it is not uniform. So, let me move it the little bit so that be show 0.8, this is 0.4 this is 0.2, this must be 0.6 right this is 150 millivolt please note this must be half of that 75 millivolt and this is 0 right. So, look out for data sheets which essentially give you this kind of graphs view graphs, I have not completed the story here for you what you should also look at is what is your V out this is at what V out.

Let us say your V out is set to 2.5 volts, again insufficient spec this is specified at what junction temperature. So, you cannot escape looking up these additional parameters as well this of course, you have to look up because you would have designed your LDO for a given output voltage, but you must look out for this important parameter as well and why is this important? This is important because of this result let me again redraw and show you let us put amps in other words let me put I load I will just redraw, I load which is please note this is what I mean this is that I load and let me draw the dropout voltage dropout voltage right it turns out that it will be something like this. In fact, I should make it a little bit being a bit unfair. So, it will make it a little more uniform.

Let us say that this reason is the 0.8 amps. Now this is minus 40 degrees this is plus 25 and this is plus 125. So, now, you see put back the numbers you know very well this is

150 millivolt from the previous this result, you can see now this is gone up which means there is going to be more power dissipation across the LDO, why because the dropout voltage has increased right it has to maintain a higher voltage differential and has to drop sufficiently high voltage so that you can continue to draw this load current of whatever we specified. This is clearly and important parameter which you must consider moving forward on design on the choice of the LDO.

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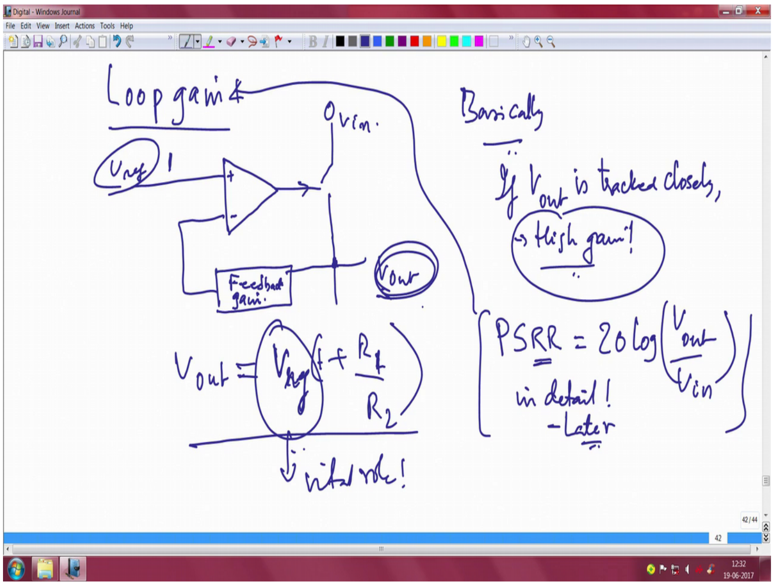

Now there is one parameter which we keep sort of coming back to you each time on the LDO, and that is with respect to the loop gain.

So, why is this important? So, let us put back a very simple diagram here, but this time we will abstract it. So, that we do not get you know we do not mentioned too many things on this particular thing. So, let us just put on a very simple diagram to intuitively explain again this thing of loop gain. Remember you are error amplifier, this is a the LDO has an error amplifier right and the error amplifier is essentially we will have a gain right it will have a gain. So, that is V in this is the feedback and you know what this is V ref please recall the V out formula right let us see if we actually put that down earlier. So, that we are actually know from whatever we wrote previously.

So, let me pull that out and see if we I do remember having written that down. So, I the V out. So, I think we should take this and this is this will be helpful V out, go back to the operational amplifier basics you will find is nothing, but V ref times oh maybe R 1 by R

2 right which clearly indicates that the error amplifier is always trying to match the output always looking up monitoring the V out and trying to match to ensure that the difference between V ref and V out is always very very small right this is a simple expression for actual output voltage which is this is nothing, but the gain term which is coming from these two resistors. So, coming back this is the feedback you know the V out here this is nothing, but V ref v ref times 1 plus R 1 by R 2 and this; obviously, is the gain feedback this has a gain and this is the gain parameter of interest.

So, question is this why are we discussing amplifier gain and all that. Basically, if V out is being tracked closely right this is possible only because of the high again right. So, sensitive because of the high gain it is able to sense the track the V out very very accurately. So, moment the ability of the LDO, ability of the LDO looses its ability are has lose in high gain, you are in the LDO is not anymore going to function like a regulator. So, the gain of the LDO is so critical right now the gain of the of the LDO also has to do with its ability to reject ripple, and there is a term which again data sheets will look at and which essentially leads us to a very important data sheet parameter which is called power supply rejection ratio PSRR as it is called.

So, PSRR also is nothing, but the PSRR is simply nothing, but as 20 log off V out by V in. We will discuss PSRR in detail in detail later, but I have to connect this PSRR, I have to introduce this term because it is related to the gain of this error amplifier the gain that is provided by the error amplifier. What I am a trying to say in summary is the high loop gain gives you the required regulation.

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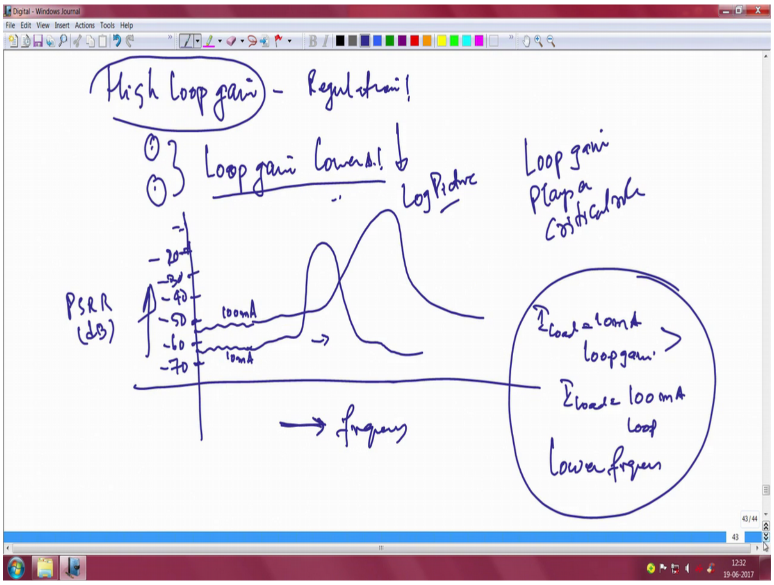

High loop gain because of its high sensitivity is able to do the regulation and so much so, you may also have to look at situations where this loop gain lowers what are the situations under which loop gain lowers, for that you must look at the ability of the op-Amp or the LDO the ability of the LDO to reject ripple.

So, let us connect that together, I will draw another picture here and everything will sort of get summarized. It turns out the ability of the error amplifier the LDO. So, this is essentially the PSRR expressed in dB expressed in dB this is minus 70, this is minus 60, minus 50, minus 40 and so on the deeper the better the deeper the better right. So, you can say an LDO which has minus 70 PSRR is much superior compared to something which you get you get an LDO which has a PSRR of minus 50. Clearly, it is a much the minus 70 p LDO is a superior one that is one part, for all of that how well does it sup get supported in terms of its response becomes critical I will put one nice picture here I will just continue the story here this is frequency and this is PSRR.

It turns out the same LDO behaves something like this please note that this is a log picture you have to because I mentioned it in dB this is all these a lot right, but just for some simplicity and quick understanding let me put it this way this is lower frequency and this is higher frequency sorry this is higher also lower frequency, but these two pictures are different this is at low road and this is at typically at higher load, then you can draw something like this and then you can draw something like this.

So, please note this is a log I did not elaborate, but I want to bring out a very important point here. The point is the loop gain plays a critical role. Under low load what do you mean low load what we mean by low load is just this that the I load here we are referring to the I load if l load is only 10 milli amperes you get better loop gain higher loop gain as compared to I load at 100 milli amperes this is greater. Also you have to bring in the other point that the x axis is frequency at low frequencies at lower frequencies.

Now, you can see this is the ability of the LDO to reject ripple its ability to reject ripple and its ability to reject ripple is much superior at lower frequencies and at low loads, but if the load current increases then you have the problem that LDO is loop gain actually gets lower and as a result its ability to filter the ripple input ripple is also poor and the cause for all this is indeed as I said the fact that the loop gain takes a beating a particularly as you moved higher in frequencies and higher in loads higher in I load when the I load increases, I load current, I load when I say I mean current I have output current increases.

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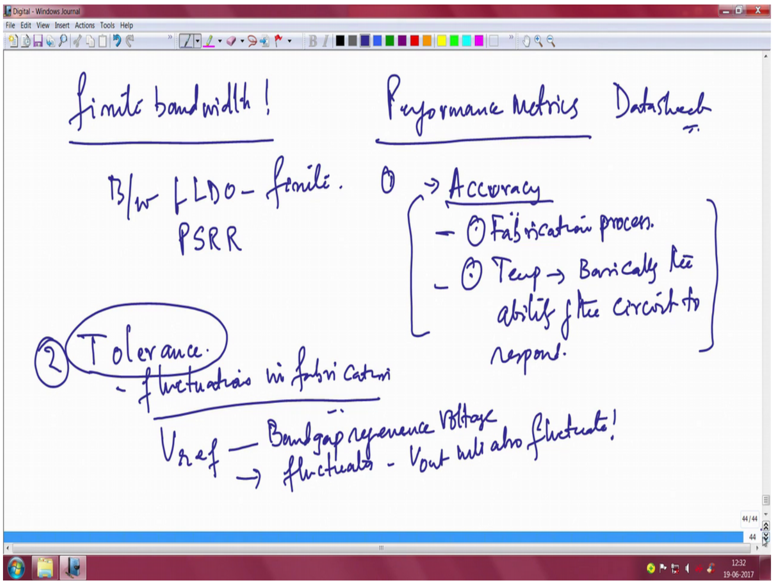

So, all this clearly shows that LDO'S have finite bandwidth. In fact, this is a clear indicator right this picture itself tells you we can see that PSRR is reducing because you are going closer to 0, this is minus 30, minus 20 and so on is reducing its performance its ability to filter out ripple, its ability to filter out noise is also reducing as the frequency increases and as the also with respect to the increase in load current ok.

All of this means there is a problem that the loop gain is not you can maintain a high loop gain because you do not have a infinite you would I do not have any infinite bandwidth the bandwidth of the LDO is finite. So, bandwidth of LDO is finite look out for this important parameter, because it is linked to the power supply rejection ratio or ripple rejection ratio as well. So, in summary the whole system if you look at the LDO the performance matrix if you start putting down performance matrix for an LDO again I am driving you in the direction of the data sheet please note. One important parameter that will come to you will you will have to see is with respect to accuracy ok.

Now, why is this important; why is this actually see so important. Because it comes from LDO to LDO the fabrication process is a variable you cannot has as much as you are able to control it can have certain variability. So, it can come from fabrication process and it can also come from the ability to it can come because of temperature, temperature is another important parameter. And therefore, you can basically it is all about the ability of the circuit to respond to basically the ability of the circuit right, basically the ability of the circuit to respond given the change in temperature this is another these are. So, these are the two important parameters which basically it basically you have to keep in mind.

So, you will have to look out for a parameter which we will highlight the accuracy of the LDO another important. So, this is one thing, second thing is you may also want to look at tolerance again this largely comes from fluctuations in fabrication. See it brings down to a very important point that you go back to this basic expression right if you go to this basic expression, you clearly see this place the most vital role what is this? We did talk about it V ref is the band gap reference r e f e r in c e band gap reference voltage, if this fluctuates then V out will also fluctuate I hope you will agree, because we have been discussing LDO so much that V out depends on, this V ref right and if this fluctuates this V out we will take away a we will take a beating as well.

So, all the control loops all of it means that you must look at tolerance of the LDO which you may want to you know the data sheet parameter should tell you something about the tolerance of the LDO as well. So, other thing which perhaps we will have to worry about is there are other parameters as well for example.

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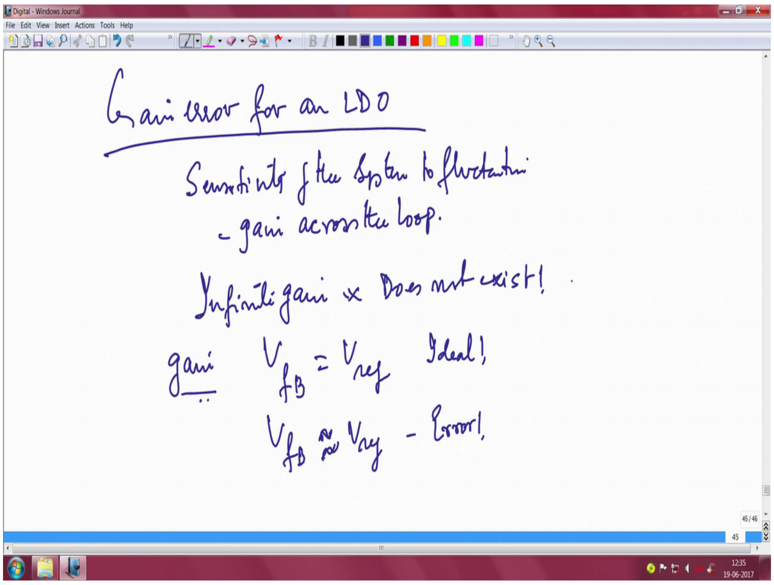

There is something called gain error for an LDO. What this simply means is the sensitivity of the system to fluctuations sensitivity of the system to fluctuations; ultimately ress on the gain right gain across the loop very very important. Infinite loop infinite gain infinite gain LDO does not exist does not exist at all you cannot you cannot be talking about that right.

So, the basic thing about the fact is that e unless sorry I think unless. So, what is the gain trying to do? The gain is trying to follow you are adjusting the gain so that V ref is always equal to V f. So, V f B that is the feedback that you get you are always trying to adjust that any error that you are not able to if it becomes an approximation. So, I think it is good to put it the other way, the V feedback ideally should be equal to trying to match V ref this is ideal, but in reality it is close now this means this is the error in gain right that indeed is the gain error for a LDO.

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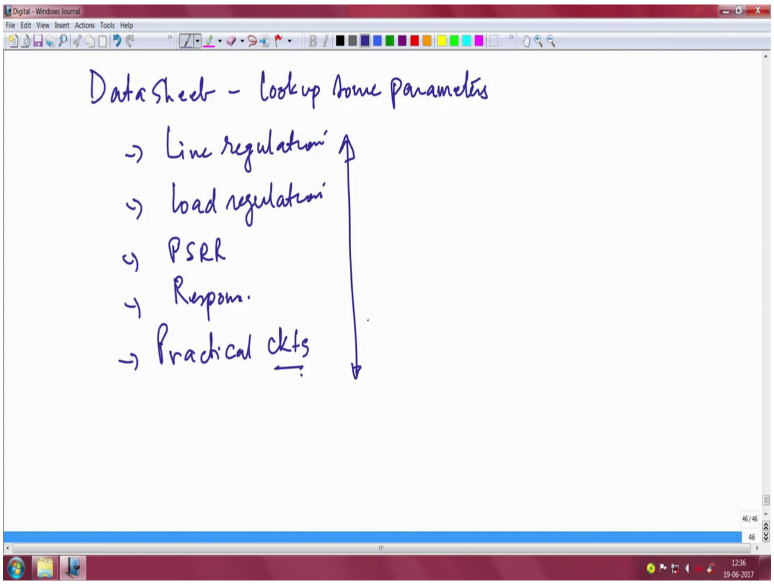

So, let us now in the next when we start further what we should do is, summarize all this and take data sheet, open a data sheet and look up some parameters and see if we can explain other things as well things like line regulation ability for the LDO towards line regulation, load regulation and then see also try and see power supply rejection, ripple rejection this one and look at the response and then look at some practical circuits how people have used LDO.

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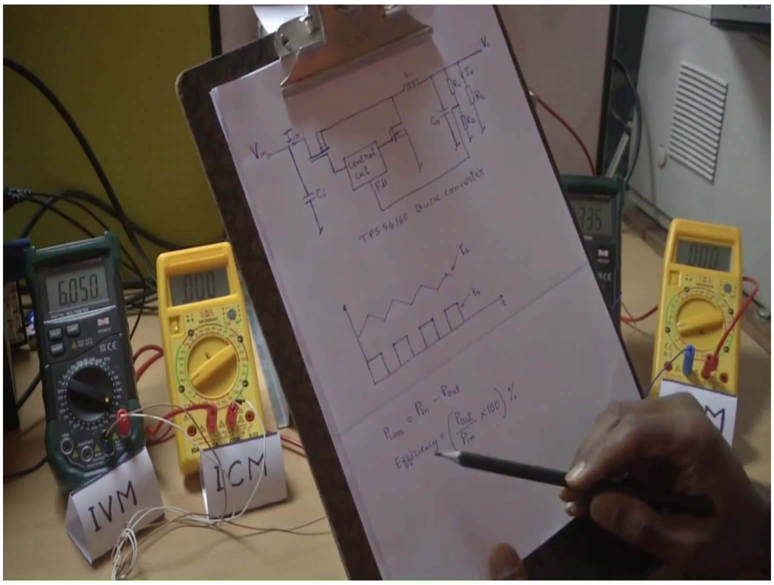

All of this will perhaps allow us to choose this very important system component. So, now, let see a working of a buck converter essentially you can see that we have a series pass transistor and the other transistor every time the series trans pass transistor switches off the other transistor switches on and then you have the current circulating through the load through from the inductor to the load and back.

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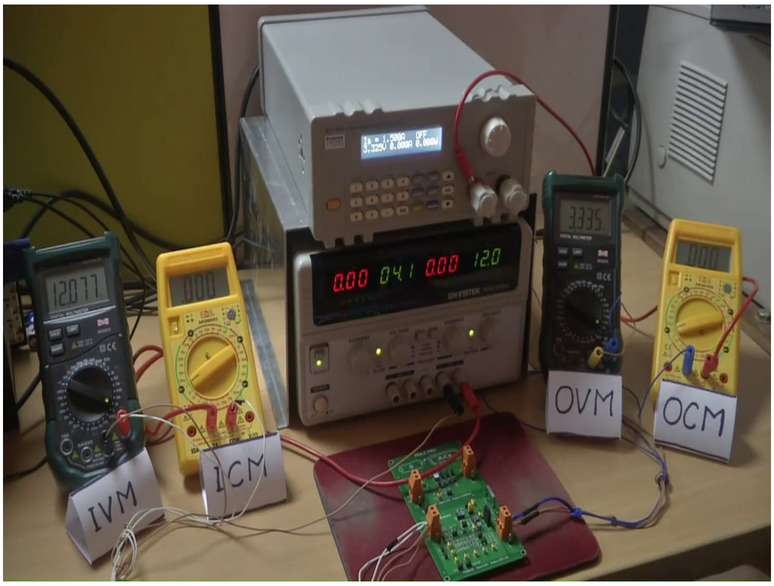

What you have here is the usual setup you have a current electronic load which is placed on top of a power supply, left side is the input voltage and input current that you see and the left hand with the power supply, the right side is the output voltage and the output current that you see you can see that this experiment is we are in is basically to per what we have performing is to understand the power loss. Essentially what is the power that is being delivered at the input and what is the power that is delivered at the output you just want to find out the difference between the two, and this we in fact, if you do this experiment you understand many related things with respect to efficiency and so on.

So, now you can see that input is here a set at 6 volts and the current here is. So, let us go for from the out output side I need to back whatever is the input to an output of 3.3, and I need a current of 100 milliampere. In order to do that other input which I have said in order to get to this I am trying to back and input voltage of 6 volts. Now for when I apply 6 volts at the input, the current consumed is a 125 milliamperes in order to deliver 3.3 volts bucked output and 200 milliampere current as you can see that there is a very small difference that you see at the. So, you see at the output this electronic load is right now connected to the output of the buck converter.

So, this experiment was conducted over range of in out load currents starting from 50 milliampere to 200, what you see right now on your screen is the fact that the load current is at 500 milliamperes. In fact, this experiment is conducted up to 1500 milliamperes and we will take you directly there. So, this is a snapshot of 3.3 volts and the output load current which has been set to 1.5 amperes.

Now what you do you have a set of readings right because you are done a sweep of a different for against different load currents. Now what you do you go and change the input voltage from 6 to 12 and repeat the whole experiment, then what you do? You change the input voltage again to 18 volts and do the whole experiment, then you again set it to 24 volts and do the whole range of experiments and also you do the whole range of experiments for 30 volts.

In other words for different input voltages you conduct the experiment by wearing the load currents. Now what is very important in this stage at this stage is; what is the switching frequency. The switching frequency under which this experiment is done is for 250 kilohertz, what you can also do is repeat the whole set again for 500 kilohertz switching frequency right at the end you will end up with a nice set of nice stable and from there you can actually make out what is actually happening. So, now, you can see that we are showing you for an input of 10 volts. Now, actually it should be a step to it should be 12 volts twelve volts yes input is a set a 12 volts, and as you can as I was mentioning 18 24 30 for 250 kilohertz. And then again 6 12 18 20 430 for 500 kilohertz as you can see input was said to 50 milliampere.

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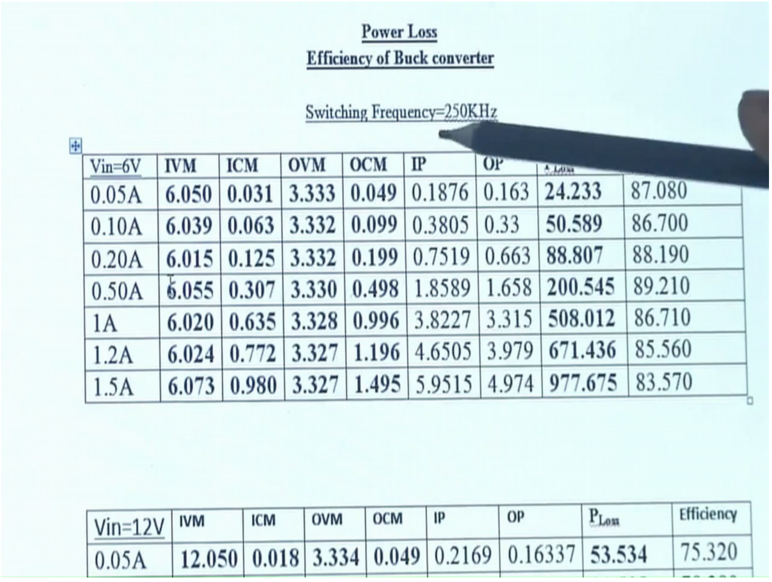
Power Loss

Efficiency of Buck converter

Switching Frequency=250KHz

Vin=6V	IVM	ICM	OVM	OCM	IP	OP	[illegible]	[illegible]
0.05A	6.050	0.031	3.333	0.049	0.1876	0.163	24.233	87.080
0.10A	6.039	0.063	3.332	0.099	0.3805	0.33	50.589	86.700
0.20A	6.015	0.125	3.332	0.199	0.7519	0.663	88.807	88.190
0.50A	6.055	0.307	3.330	0.498	1.8589	1.658	200.545	89.210
1A	6.020	0.635	3.328	0.996	3.8227	3.315	508.012	86.710
1.2A	6.024	0.772	3.327	1.196	4.6505	3.979	671.436	85.560
1.5A	6.073	0.980	3.327	1.495	5.9515	4.974	977.675	83.570

Vin=12V	IVM	ICM	OVM	OCM	IP	OP	P_{Loss}	Efficiency
0.05A	12.050	0.018	3.334	0.049	0.2169	0.16337	53.534	75.320

And then we did a sweep and the. So, all these are all essentially all the tables of switching frequency there was 250.

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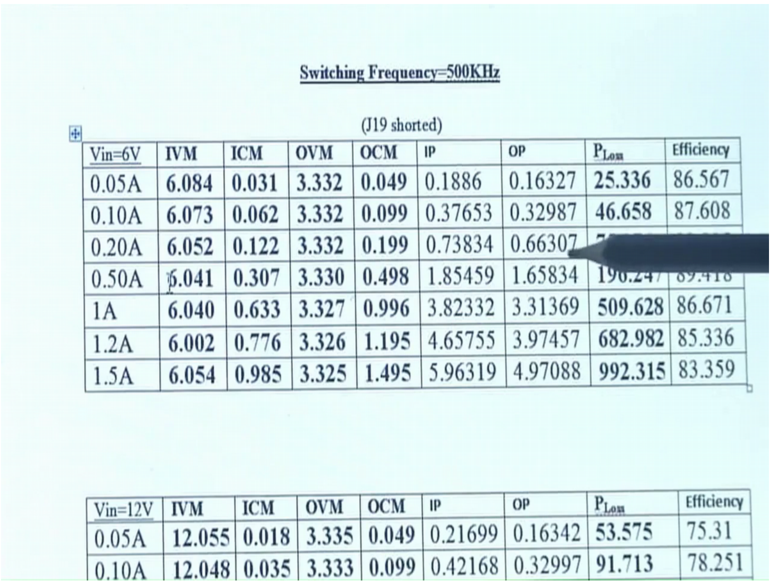
Switching Frequency=500KHz

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Vin=6V	IVM	ICM	OVM	OCM	IP	OP	P_{Loss}	Efficiency
0.05A	6.084	0.031	3.332	0.049	0.1886	0.16327	25.336	86.567
0.10A	6.073	0.062	3.332	0.099	0.37653	0.32987	46.658	87.608
0.20A	6.052	0.122	3.332	0.199	0.73834	0.66307	[illegible]	[illegible]
0.50A	6.041	0.307	3.330	0.498	1.85459	1.65834	[illegible]	[illegible]
1A	6.040	0.633	3.327	0.996	3.82332	3.31369	509.628	86.671
1.2A	6.002	0.776	3.326	1.195	4.65755	3.97457	682.982	85.336
1.5A	6.054	0.985	3.325	1.495	5.96319	4.97088	992.315	83.359

Vin=12V	IVM	ICM	OVM	OCM	IP	OP	P_{Loss}	Efficiency
0.05A	12.055	0.018	3.335	0.049	0.21699	0.16342	53.575	75.31
0.10A	12.048	0.035	3.333	0.099	0.42168	0.32997	91.713	78.251

This is 500 kilohertz, and then we generated all these tables right whole range of measurements a and then this is the power loss as you can see.

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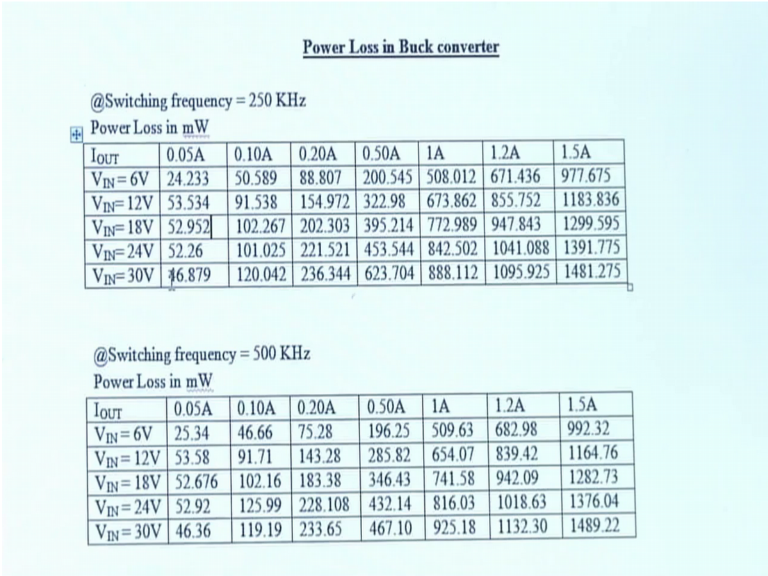

Power Loss in Buck converter

@Switching frequency = 250 KHz

Power Loss in mW

I_{OUT}	0.05A	0.10A	0.20A	0.50A	1A	1.2A	1.5A
V_{IN} = 6V	24.233	50.589	88.807	200.545	508.012	671.436	977.675
V_{IN}= 12V	53.534	91.538	154.972	322.98	673.862	855.752	1183.836
V_{IN}= 18V	52.952	102.267	202.303	395.214	772.989	947.843	1299.595
V_{IN}= 24V	52.26	101.025	221.521	453.544	842.502	1041.088	1391.775
V_{IN}= 30V	46.879	120.042	236.344	623.704	888.112	1095.925	1481.275

@Switching frequency = 500 KHz

Power Loss in mW

I_{OUT}	0.05A	0.10A	0.20A	0.50A	1A	1.2A	1.5A
V_{IN} = 6V	25.34	46.66	75.28	196.25	509.63	682.98	992.32
V_{IN} = 12V	53.58	91.71	143.28	285.82	654.07	839.42	1164.76
V_{IN} = 18V	52.676	102.16	183.38	346.43	741.58	942.09	1282.73
V_{IN} = 24V	52.92	125.99	228.108	432.14	816.03	1018.63	1376.04
V_{IN} = 30V	46.36	119.19	233.65	467.10	925.18	1132.30	1489.22

This is this is for 250 kilohertz and you will see that V in 6 to 30 volts, the power loss for small currents you have 24 milli watts, and it goes up to about 46 about 47 milliwatts for 50 milliamperes.

So, and you can actually go directly and also look at what actually happens as the higher currents increases, you have 977 milliwatts of power loss and 1481 milliwatts for 30 volts. Change the switching frequency to 500 kilohertz you get a set of range of values 25 milli watts to 46 compatible to that of the other one, and quite comfortable to also the highest thing higher currents.

But I want to draw your attention to this particular table which is for 500 milliamperes, you can see 200 it is the more than three times 623, and here it is a 196 and it is two and half time something roughly 2 and half times. Keep this in mind this should somehow show up as efficiency numbers right again you concentrate here you will see 89 72 for 250 kilohertz this is the efficiency and for this current and of course, efficiency is fantastic perhaps quite a very good also for the same current at 89 percent when the input voltage is 6 volts. So, it is quite a high number.

Essentially, what we are saying is that this table should be used should be prepared and find out in this matrix where do you get the maximum efficiency and whether it matches the required load currents a load output power the load power that is required whether it will allow you to get into an efficient term the buck converter gives you the best efficiency. Why is that important because energy harvesting I is an input to all these systems. And therefore, unless you have high efficient systems, these systems may not give you good battery life.

Thank you.