

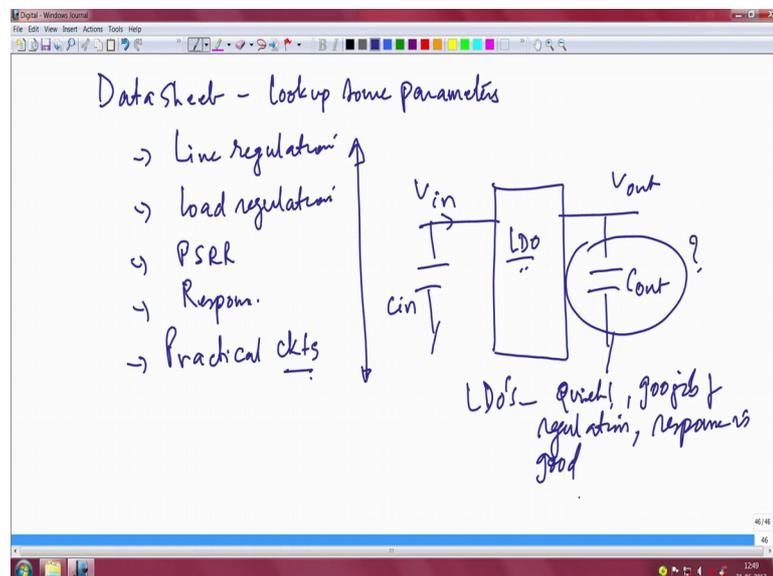
**Design for Internet of Things**  
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**Lecture - 11**  
**Designing with LDO's, switching regulators and case studies Part II**

So, we need to summarize several things on the LDO and then look at sections related to buck converter and again you had back to the same problem on your design of the IoT device right embedded IoT device. LDO or buck converter what should we do suppose we have a problem of let us say you have 5 volts  $V_{in}$  in, you want a stable  $V_{out}$  of 2.5 volts what will if your choice whether it will be an LDO or this.

So, it is the same thing all over again recurring thing problem we mentioned about several aspects of the ability of the efficiency is an issue with respect to LDO; it does drop and so on and so forth. But let us go a little more deeper, because when you start designing you realize all kinds of peculiar problems even to rig up a small LDO circuit.

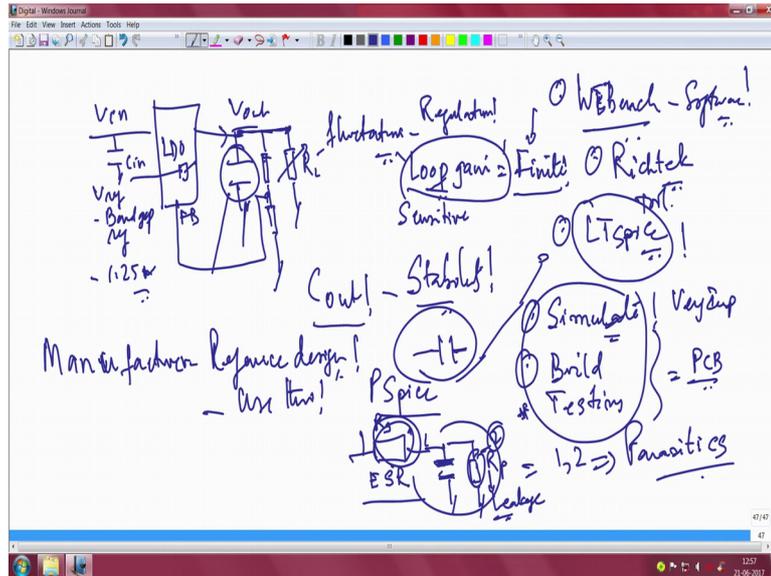
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So, it is important and that is why we need to spend sufficient amount of time. First thing you will notice if you take an LDO is you will have  $V_{in}$  and you have  $V_{out}$ . Moment you put this first thing we always do is we have AC out capacitor and we put AC in capacitor right this is something that we always do and this is our LDO. Now I have an spent time talking about what is this C out capacitor and what is it is actual functionality.

The thing I wanted to elaborate at this stage is to actually tell you that LDO'S may be considered to be quiet and they seem to be doing a good job of a regulation and so on of regulation and their response times are good response is good and so on and so forth, we went on saying many nice things about the LDO, but there are issues what happens if the LDO's  $V_{out}$ .

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Let us say the LDO's what happens when the LDO when the LDO'S output which I will simply denote by some load ok.

This keeps changing right based on how you operate the blocks within the load it keeps varying. So, there will be a huge amount of supposing. So, there will be huge amount of fluctuation in the load itself; because of this fluctuation in load there can be situations where a significant amount of time the output can go out of regulation actually you can go out of regulation, but then we mentioned several nice [FL] right, we already said that loop gain is very good for an LDO and how is that if the loop gain is high and it as the result of the loop gain being very high it is very sensitive, this is very sensitive to any changes in the this is the set point  $V_{out}$ . I am not drawing the error amplifier here; I assume that you know that the feedback is actually applied. So, just to complete it you take the feedback point and then connect it here this is the feedback point I am assuming that this feedback is actually compared with the  $V_{ref}$  here right there is a  $V_{ref}$  block inside.

So, this reference is the band gap reference we said this is the band gap reference reference typically this is one point let me band gap reference, and this is typically one 2.5 volts. So, I am just not going to draw that all over again. So, it is very sensitive and all that, but remember loop gain is cannot be infinite right. So, it is actually finite and that is the reason why you will continue to have problems at  $V_{out}$ ,  $V_{out}$  not getting into not being exactly at that point where you had actually set it two.

Now who takes care of all the misery for the LDO with all this finite fine nice control loop yet having fluctuations at the output well that is the job of this  $C_{out}$  I did mention to you it has to do with stability right it is to do with stability and therefore,  $C_{out}$  is a very critical value please note and it will start bothering you when you start designing your systems in a when you are trying to build your own IoT system.

So, you have to choose this carefully manufacturer would have given you manufacturer would have given you a reference design reference design and use this use this as a starting point I have been doing this regularly, manufacturers reference design you should use as a starting point because you would have experimented quite a bit and actually come out with a typical value for  $V_{out}$  sorry  $C_{out}$  because that is a very critical thing same with the story of  $c_{in}$  please note that.

So, you must take care of finding out what is the value of the  $C_{out}$  that he has put. See you also know from our basic electronics that if you take a capacitor and you put it into there is a model for the capacitor right most of the circuit modeling you can actually use P spice kind of tools and actually model the complete circuit. In fact, all this modeling all this regulator itself can be modeled by manufacturers specific tools.

For example if you go to t I t I will give you something called V bench let me put it in capital V bench. You can use v bench and WE bench you can use this V bench software and actually design your system. So, please note if you go to let say Richtek they will have a tool. So, you can use Richteks tools if you are going to linear technologies you have LT spice if you many things can be done in LT spice is nothing but a version of what you know the Barkley spice that we know very well models are available there. So in fact, you can also take several components from takes us instruments LDO and actually change parameters and actually do simulations also and other kind of tool.

So, you can you have to use tools there is no choice you should use LT spice if that is required and your using linear technologies LDO'S and buck converters. If you are using t I tools do to go back and look at why w e branch tools are available download it put it into very simple straight forward put in numbers put in the model put in the type of LDO that you are trying to use, and directly do a simulation before you understand even before you rig up the circuit.

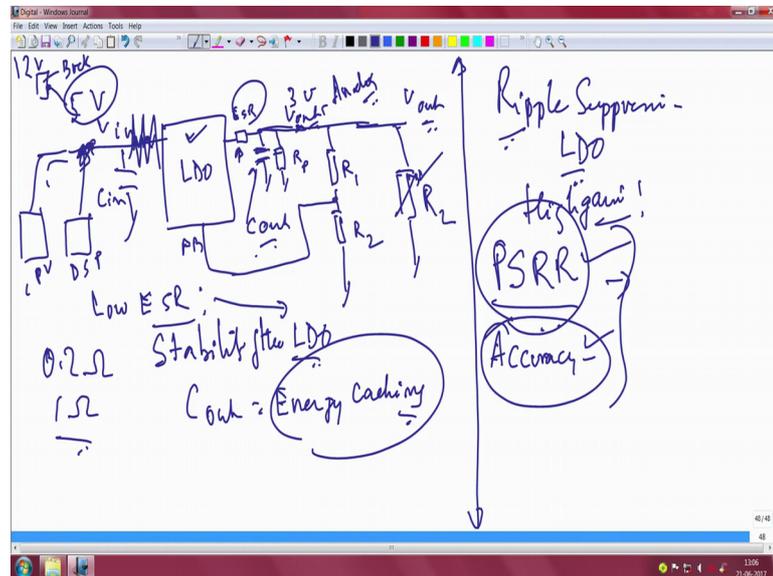
So, model should be always simulate do not rule out this possibility, simulation is a very important step go to the manufacturer to you do not have to build a simulator please note you do not have to build anything there already available. So, simulate it then build it you build it and then you do the testing, testing on the breadboard sometimes breadboard sometimes you may even have to make a PCB depending on what you are trying to, how you are trying to do your testing.

So, you may have to follow these steps. So, there is no choice. So, let me now come back and co complete the story on loop gain, it is a finite loop gain and therefore, you have to choose a the C out capacitor that we are talking about the LDO, we will actually have to be the right choice that you will have to look up the manufactures reference design perhaps do a simulation using that value, and then go ahead and actually solder that particular capacitor.

Now, I did not complete the story you know very well that if you buy a capacitor from the markets it is equivalent model will be like a series resistor, and the actual capacitor and in parallel to that is another register this is parallel resistor this is series resistor and in fact, this is the one that contributes to the equivalent series resistance of the capacitor. Now what are this one and what is this two; obviously, one comma two are nothing but parasites or nothing but these are parasitic you cannot by a capacitor without having an equivalent series resistance, you cannot by a capacitor which does not have this invisible parallel for which gives you the leakage this is the problem right, a capacitor leaks because it has a finite leakage resistance across it is two plates and you cannot by a capacitor whose efficiencies brought down because there is a certain volt amount of voltage drop across the series resistance both are them are hidden, both of them are hidden their part of this capacitor.

Now, go back and connect everything back to this C out you must obviously, if you put back this picture let me redraw this picture and let me remove all this so that now in fact, let me go and make another sheet right. So, that is never going to be a problem.

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So, let me redraw the LDO, let me put back C out, and let me put back V in, put me let me put back C in capacitor let me put back the feedback point you should be able to quickly redraw all of this now quiet con confidently because you know what actually is happening, and we will put the load register here we will call this R 1. Now what you should do get it up this C out and put it in terms of it is equivalent model, what does it mean? This line will go this line will go here this is the equivalent model this is the ESR this is the parallel resistance this is the actual C out.

So, you see boy this has come in the middle and it is going to create a mess for this V out as well it is further going to create stability problems for this capacitor for this LDO. So, therefore, manufacturer will tell you make this value as small as possible, put a capacitor that has a very low ESR low ESR very important. So, you have to go round and actually find do not by any capacitor that is available in the market, go and find out from the data sheet what is the value of the ESR and put that recommended value provided by the as a guideline by the manufacturer. So, this is an important parameter which you may have to consider because that has a bearing on the stability of the capacitor of the LDO, this is very important. It in fact, contributes to this stability of the ca capacitor of the LDO in

other words this C out is nothing but an energy cash right it is doing nothing but cashing energy cashing storing energy into that system.

So, that you will be able to supply every time the load varies and it requires a higher amount of power delivered to the load in fact, that is not really coming because of the control loop it is not because of control loop, but because the C out is chosen in a manner that the energy cashing which is done on this capacitor on this let us write it neatly, this is C out. So, let me rewrite it and show you that it this is the C out and this C out actually is the one that is doing all the energy cashing. So, what is this typical value of this ESR that we should look for? Well it should be as low as possible, but in practice you will get 0.2 ohms to about 1 ohm. So, you may have to look out and see; what is a suitable value as proposed by the manufacture before you know put into simulation, and then actually understand; what is the performance of the system.

So, that is the key point I wanted to derive home for you as for as the C the output capacitor is concerned. So, and of course, is the cost of the system will go up based on the price that you pay for this C out capacitor. So in fact, low ESR capacitors can cost you quite a bit of money sometimes equal into the price of that of an LDO. So, you may even have to take care of these the these issues fine this is all what I wanted to say about the stability of the capacitor, load dump is an important thing. Let me tell you something very very general keep in mind that the most important point you have to note about an LDO sum big summary of the LDO is that the gain of the LDO is finite, and it is the gain that determines this stability the ability the stability of the LDO to maintain fixed output voltage irrespective of changes in the R I ok.

This is the most important thing and you also know that because of this problem of finite gain. In fact, if you now start moving a little forward the gain of the LDO starts reducing at higher frequencies, why are we talking of higher frequencies because this is a DC input DC output. Where does this frequency come in yes of course, we did mention about ripple right you will get start getting ripple how do how does ripple enter the LDO it enters from here, it enters from here and why it is that the ripple enter from here yes we did mention to you about the fact that this is let us say 5 volts and this is 3 volts here DC of course, this 5 volts is just not being connected to this LDO, but indeed it is connected to other loads as well and they can be very switching load this could be a DSP this could be another CPU or some other load which is actually pumping and this is

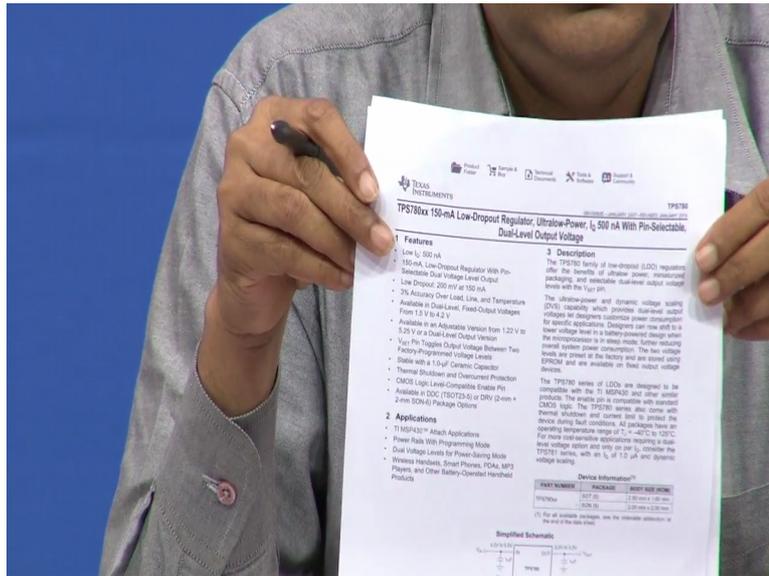
switching and that switching is creating a ripple input which is riding on top of the actual DC that you have feeding in. It could also be because remember one diagram which I have drew this 5 volts can actually be coming from 12 volts and in the middle is the buck converter which is bucking it from 12 volts to 5 volts.

So, that buck converter switching frequency is also appearing at the  $V_{in}$ , and a lot of it is actually getting filtered out the ripple is getting suppressed by the suppressed ripple. So, ripple suppression ripple suppression is actually being done by the LDO because of the high gain right high gain is actually doing a lot of ripple suppression, but it may not be a significant it is a ripple is very high and therefore, the ability of the LDO the ability of the LDO to remove ripple is actually given by power supply rejection ratio right and we did put down the expression for this.

So, look out for this parameter ensure that your output here  $V_{out}$  is always clean particularly if you are driving analogue loads which cannot to tolerate any changes in  $V_{out}$ , although the gain is very high although it is doing a. So, it is very simple right if the way gain is very high it is very sensitive. Any small variation in the input here which appears at the output is quickly corrected back by the LDO because of it is high gain because of it is high sensitivity. but if it indeed swings a lot like this I you will not be able to get any stable output here therefore, ability of the LDO to do this conversion of taking a very small a taking a  $V_{in}$  which has an amount of ripple and reducing it and giving you a clean output is indeed what LDO is PSSR parameter has to be.

We also looked at accuracy we also looked at you know the fact that this is another parameter you should look for PSSR accuracy are all important parameters, this will start becoming clearer when I show you one data sheet. So, let us now turn our attention to looking at a data sheet I will show you this data sheet ok.

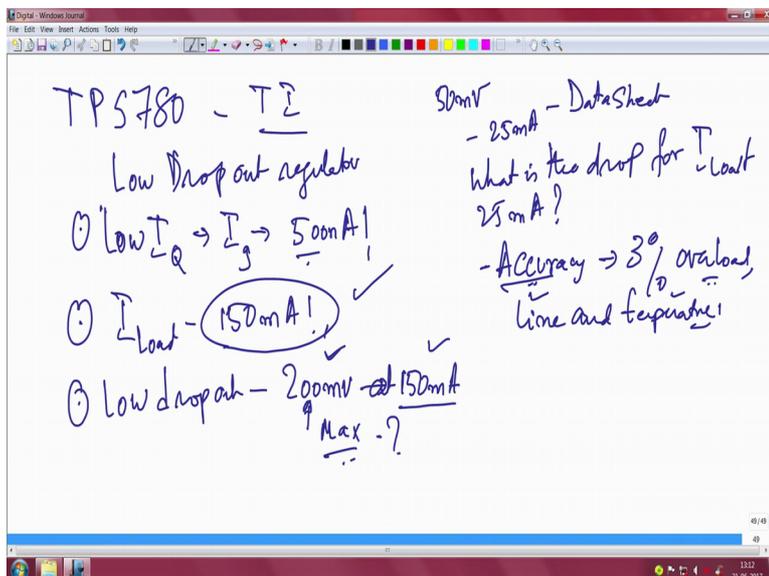
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Now, this data sheet I have no bias for any manufacturer any vendor, but I must tell you that I pick this only for the purpose of convenience. So, let me put this here. So, that no background. So, you can download this it appears that it is not very clear.

So, let me write down one specification for from this LDO give your numbers please look up whenever you have time you do go to the internet and do look up this regulator I have no specific preference to any vendor, but I still have taken it taken this is an example look up TPS, TPS 780 ok.

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This is from the I just took this as an example this is a load dropout low dropout regulator and in the very first sheet you will see some nice numbers first thing you will see is low I Q you know; obviously, you know what this means this is nothing but the ground current this is nothing but the current taken by the LDO for it is functioning, this is 5 hundred nano amperes fantastic it is not even 1 micro one 500 micro. So, 1000 nano is one micro right. So, it is half a microampere right. So, it is half a microampere which is very good it can give you I load of maximum 150 milli amperes right we can give you 150 milliamperes, it is it has a load drop out i between 200 millivolts and 200 millivolts at 150 milliamperes.

Hey guys now you understand what a nice peck this is, you will see that this must be the maximum dropout agreed why is this the maximum dropout because the maximum current it can give you is 150 milliamperes. Clearly this 200 millivolt is at the maximum current this will be lower and lower perhaps even 50 millivolt low dropout if you are current that your drawing is perhaps 25 milliamperes. For this again the data sheet will help you can find out you can ask a question what is the drop what is the drop, what is the drop for I load of 25 milliamperes.

If you ask this question data sheet will tell you. So, please look up your data sheets of this and we can take this discussion forward, I am just helping you to understand one data sheet you will see that most often this them more or less all the data sheets will be like this. So, that is one thing then accuracy there is another parameter accuracy we did discuss this I will not get into the detail, 3 percent accuracy over load line and temperature.

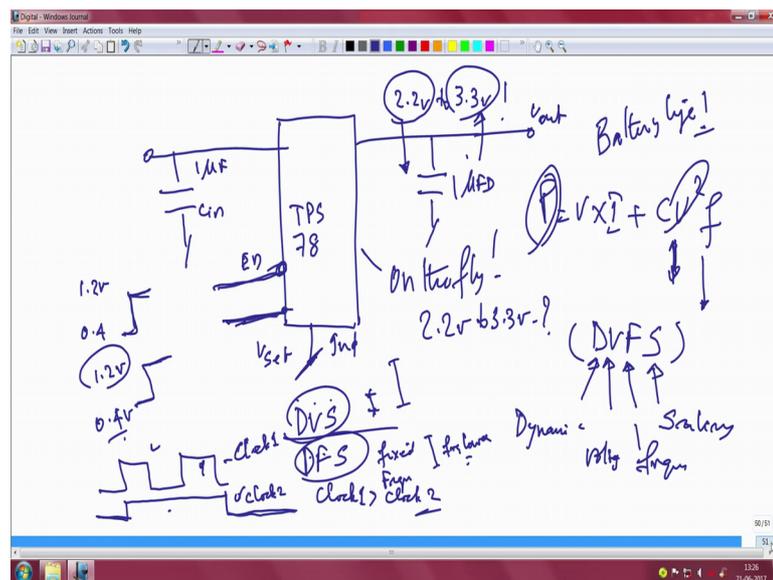
See how beautiful this sentence is, this is load regulation line regulation and temperature remember we mentioned one very important point, everything seems to be good and nice V in is supposing V out you need is three point 3 volts, input is 5 volts you are connected a load which does not exceed the maximum V in has not fluctuated V in seems to be stable therefore, V out is stable current drawn is also fine, yet V out is fluctuating all the time why?

Because the reference the reference may have gone for a toss the reference may have actually fluctuated if the reference fluctuates the output; obviously, is going to change; and why did the reference of why is the difference fluctuating because temperature is

affecting it you tested everything in an AC room to did all the calculations and all that it worked very well moment you put it in the field inside a let us say a power supply, where there is a you know power dissipating component like a heater or something which is hitting the I c; obviously, the temperature as risen around it and once the temperature rises the junction temperature mentioned measurement I mention to you about the characteristics of the LDO when you look at data sheets.

Actually specifies what is the drop out that is to be planned if the temperature rises so; obviously, it is going to go out of control and that is an important parameter for accuracy of this particular LDO. What are the other important parameters? Available in dual fixed output voltages from 1.524 volts that is another parameter, available in an adjustable version from 1.22 to 5.5 or a dual level output version.

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Here is another interesting option that this TPS 780 seem to have. Let us see how you can design your system based on this TPS 780 what does he say you had to take v in.

Say I am now going only in to a block diagram situation right c in you know this very well he gives you a value it should be one microfarad. So, let us put back that one microfarad, he says you should put out a V out, V out is programmable from 2.2 volts to 3.3 this is an programmable LDO, it can give you and he suggest that this C out should be one microfarad and this is your V out. This is ground very good here he has given by

more pin this is called v set I will explain this in a moment and then there is this enable right enable, enable is also like you have to give a triggered.

So, this I think I do not want to confuse I will just show it like this V set here again, I will show like this I will show enable sorry I think it is better I move this here enable and v set 2 pins are there we have enough for the moment he has not shown as where the feedback is coming do not worry about the feedback this is ground. So, it has to be shown properly sorry for the error. So, this is ground this chip can give you on the fly very important on the fly 2.2 volts to 3.3 volts question is why do you want it and how do you do it.

It simple you have v set if you set it in fact, there is a spec on this, you can look up that spec I think this is 0.4 and this is 1.2 volts, this is 0.4 volts and 1.2 volts. If you do 0.4 volts you will get 2.2, if you do 1.2 volts on this pin you will get 3.3, that is the beauty on the fly it remember it is already connected this is an LDO connected to the load micro controller is there perhaps there is a radio that are sensors connected so on and so forth why is this important, why do you want to do this? Well you know the first standard equation of power dissipation right power dissipation comprise of static power voltage into current plus  $c v^2$  f.

If you get down v if you put keep mo moving v down, the power dissipation of the system also keeps coming down. If you do not mind compromising on lower voltage see lower voltage is it is just not like you know why not we have just go on reducing the voltage it does not work that way, if you reduce the voltage you are bound to more or less because of design you will also have to reduce the f the f also reduces; that is why people say DVFS.

In fact, you will see lot of literature on DVFS; dynamic voltage frequency scaling this is scaling, this is frequency, this is v for voltage d for dynamic. Some people say DVFS also that is they will separate out and say I will change only v, but I will not worry so much; I will not without worrying so much about F dynamic voltage scaling dynamic frequency scaling, but it is this is definitely there these are two different things that you can actually play with as livers.

But if you start reducing voltages significantly low, you are bound you cannot actually function with a given frequency. So, you will be forced to also pull down the frequency

in other words there will be a small range over which you can do only  $d \propto v \propto f \propto v \propto s$  without changing the frequency, but if you do larger change your bound to reduce the frequency as well. So, you cannot separate them out that is what have to note, sometimes you can and sometimes you cannot separate out. So, you can separate them out if the change in voltage perhaps is low by keeping a  $I$  will read write this is fixed frequency you can fix the frequency and only play with or alter only the voltage, but sometimes this will be the situation in which case frequency also has to be lowered, if you are lowering the voltage you have to lower the lower the frequency.

What is the impact of lowering the frequency? Lowering the frequency means clock instead of going like this is going to go is going to have a lower you are going to have let us say something like this; that means, you will see that instead of a rising here it actually did not rise here. In fact, it fell down here and this is a lower clock frequency right and then as compared to this.

So, the here there is a clock this is clock 1 and this is clock 2; obviously, clock 1 is greater than clock 2. So, this is going to be an impact if you do not mind you know your system running with the lower clock for perhaps just acquisition of some sensor data where you can reduce the clock and just acquire data, but if you are doing some very important to compute or you really require a stable clock for certain transmission operations or for certain operations with res with respect to communication, you must do a you must have a clock of a certain frequency; that means, you may have to increase the clock frequency in which case you may have to also pull the output voltage to higher the rail voltage has to go up. That is a time when you will actually do most of the work in 2.2 and when you it is a 2.2 volts for sensor acquisition and so on.

But when you want to do computation and you want to do other data transfer or data communication you actually have to pull you will be able to pull the the rail voltage of the system embedded system to 3.3. Overall the idea is to save power right for a large duration of time if you are doing at 2.2 volts; obviously a power consumption is come down which means what is the impact your battery life simply improves. So, do look for an LDO which has the ability for you to set the output voltage dynamically from 0.24 volts to 1.2 volts.

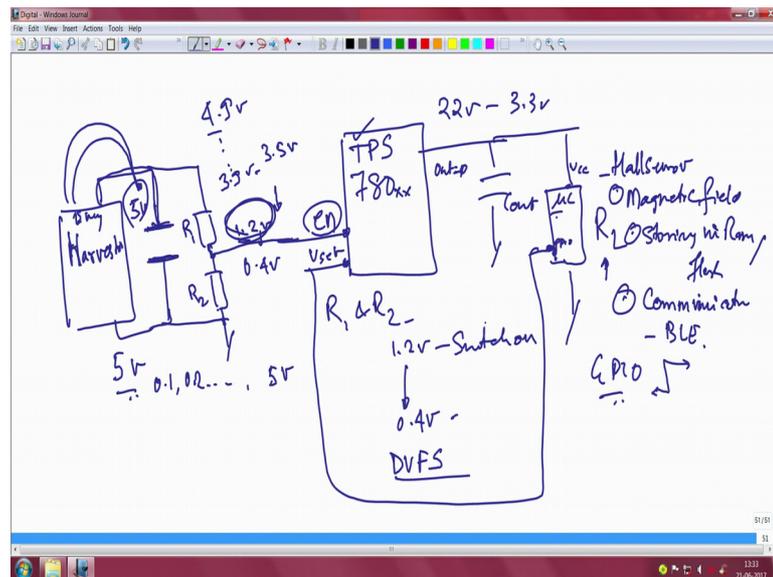
So, look for it scout around in the Google or any other search engine because I am not biased to any specific search engines, use a do a proper search find out from different companies like a either it could be t I, it could be a linear technologies it could be a rich tech right or magazine or any one of these big large companies which make LDO devices find them read this specifications carefully.

Why do you think people have so many LDO's in the market, there is a specific reason they would a found a gap before they are actually manufactured went in and actually introduce that component for the end user. So, you have to choose the component correctly and that is a choice, choice means design that is why we are talking about designed for internet of things. So, everything gets connected in this way. So, this chip also gives you that ability two set, this chip also does an interesting thing and I want you to look up this point of e n this is nothing but enable pin. Let me also put back let me you know explain to you why this pin is important.

Remember the previous classes what did we say we took an example of the bearing tight and we it showed that bearing condition monitoring of the bearing means you are trying to monitor the temperature of the ball bearing and we are doing it indirectly, we are putting neodymium magnets we are reading the magnetic field and we are converting magnetic field, that we read through those neodymium a magnets and mapping it into temperature right that is what we said is a good indicator of the condition of the ball bearing.

But we also put those arc magnets neodymium magnets so that you could leach some amount of energy from by putting a coil there so that it becomes a self powered system. Now we also said that first step is to go and acquire data and then wait until energy is available for a communication right. Now you see the connection moment you have sufficient amount of energy only you want to do all these activities right to begin with only if you have a certain amount of energy that you have stored in your capacitor, you want to actually go either read the sensor value that hall sensor value or you may want to do a communication and so on and so forth. You see that if you focus back on this thing here I will redraw this TPS for you again.

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So, that you really understand this enable pin pretty well what I do. In fact, I will move this to the right so that I have sufficient space on the left side here this is TPS 780 x x the so many versions of them. So, just take this enable pin here I think we had the convention of writing it outside. So, let me write it here enable I have a harvester energy harvester, which is storing energy into a large capacitor this is what I am accumulating energy this is my harvesting capacitor.

Now only once you know that there is sufficient. so slowly this voltage is building this capacity let say it has to build to let us say it has to built to 5 volts as an example right. So, it is starts with slowly as the energy keeps pumping into it slowly start building 0.1 volts, 0.2 volts and so, on and so on an so on let us say it comes to 5 volts. Once you know that it has come to 5 volts only then you want a stable V out here which obviously, I would like to denote the R I here which is essentially nothing but the electronics which comprise of what all sensor we for reading the magnetic field a magnetic sorry magnetic magnetic magnetic field reading the magnetic field storing in ram or flash right and then doing a communication and we said we can use Bluetooth low energy as a possible communication of this system; fantastic.

So, all this is what we discussed in the previous class on the bearing monitoring project application that we had in mind, how do you trigger this now; well it is pretty straight forward right put two resistors oops put two resistors in parallel and this is your V out

which you can connect. One and you how do you choose R 1 and R 2, you choose R 1 and R 2 such that now here is the game here this enable works if you go back to this picture enable is here it is 0.4 it is of 1.2 volts it is 1.2 volts is it is on. So, your design should be such that you get 1.2 here anytime you have 5 volts here, I am not going to do resistor divider network please find out the appropriate values of R 1 and R 2 such that you will get 1.2 only when there is 5 volts across the harvester. So, you can see how beautifully you can use this enable pin even with harvesters that is the link to the bearing and that is a link in which you can actually design a nice power board.

So, that only when there is sufficient energy harvested, your complete system works very well. You also want this enable see now what will happen you think about this situation if you have 5 volts here you will get 1.2 this will give you whatever require let us say it will give you 3.3 volts and moment it the load turns on this 3.3 will remain stable because LDO is expected to be stable and that is coming from this 5 volts, and the harvested is only slowly putting back energy into this system.

Let us say there will be an instant when this becomes 4.9 volts although energy is getting replenished at some instant it is 4.9 volts. If it is 4.9 this is obviously, is going to go down right and it is going to go lower and what will happened to this enable pin will be the question. Well there are LDO's which if you remove if you go below this set voltage this enable pin going below the set voltage of 1.2 they actually give you output of 0 there are also LDO's which have a sort of hysteresis in it is functioning; that means, it requires point any. So, it requires 1.2 volts to switch on.

But to switch off you have to lower it less than point for volts. So, you can see that 5 volts when harvested switches on in spite of energy harvester putting the energy slowly into the capacitor in meanwhile capacitor discharging also slowly down to whatever required voltage maybe even comes down to 3.9 from 5.5 volts to 3.9 or even 3.5 for instance or even as low as 3.5, because the rate at which energy is being consumed expended is much greater than the rate at which the energy is being replenished right by this harvester it continues to work because till the point this point becomes 0.4 volts this regulator we will continue to work satisfactorily.

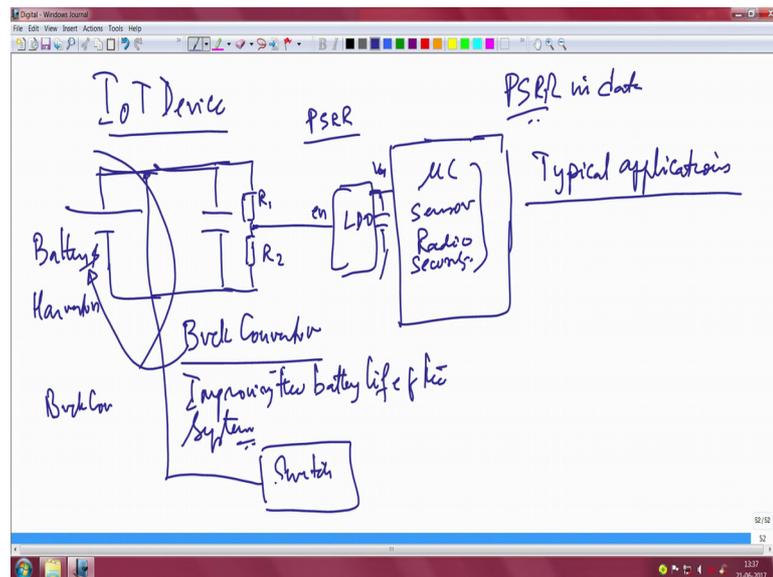
So, that is the good thing about this particular regulator which is TPS 780 so much about this design, so much about this particular regulator that we have with us here. Now I

should also tell you other specifications of this regulator. So, we will discuss about this set which means you can use it for. So, we set you can use this effectively for DVFS and keep managing provided your load is also to work across DVFS now. So, do not confuse the example there the  $V_{set}$  can be used for DVFS applications if your load microcontroller whatever you have chosen even in the bearing project if it is able to work from two point two to whatever example that I mentioned across the range of this one right this works from 2.2. So, I mentioned that here to support that if it is able to work from 2.2 volts to 3.3 volts.

Please go ahead and implement DVFS as well and use the microcontrollers pin to actually said things for you and how do you do that? Produce straight forward for you to do that I will replace this a real with the new  $\mu$  microcontroller and I will ensure that I give a 1 or 0 through this microcontroller. I now I am the master and the controller, I now decide what should be my rail voltage whether it should be this is the  $V_{cc}$  right whether it should be 2.2 I want to do a few things or whether I want to do 3.3 is also left to me based on this general purpose input output which is called the GPIO I can trigger the GPIO pin accordingly I can either pull it low or I can pull it high and decide what should be the rail voltage of the microcontroller based on this  $V_{set}$  as a system.

So, the power supply design for the controller is critical because the LDO has not just functionality of giving you good stable output voltage and having a very low dropout voltage between the input and the output, but also this kind of nice functionalities of using it like a switch so that harvesting SY systems can use using it for doing DVFS also nice for saving power and battery driven embedded systems.

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So, if the picture is very nice that if you want to build your IoT device which is driven from a battery based system, from a battery based system you want to do several nice things or from battery slash. So, I will say battery slash because harvesters are also important you could use this enable pin of the LDO very effectively to drive the output load.

So, this is the battery source this is the power source and this is the LDO and of course, you are embedded system which comprise of let us say block such as microcontroller. So, there is a microcontroller block, there is a sensor block right and there is a radio communication block there is something for security, then things like you know encryption engines and so on all of that can actually which you will which you will actually the building can actually be triggered based on the output using this features of the LDO.

But if you also have situations where the LDO is the input actually comes from a noisy DC buck converter, this is now replace with a buck converter you may have to look for another important parameter which is referred to as the PSSR of the LDO. So, much about this LDO's that we now have to understand the other type of regulator which is the buck converter and let us spend sufficient amount of time understanding the buck converter with respect to this battery, I will want to connect how buck converters can actually do magic for us in terms of improving the battery life of the system.

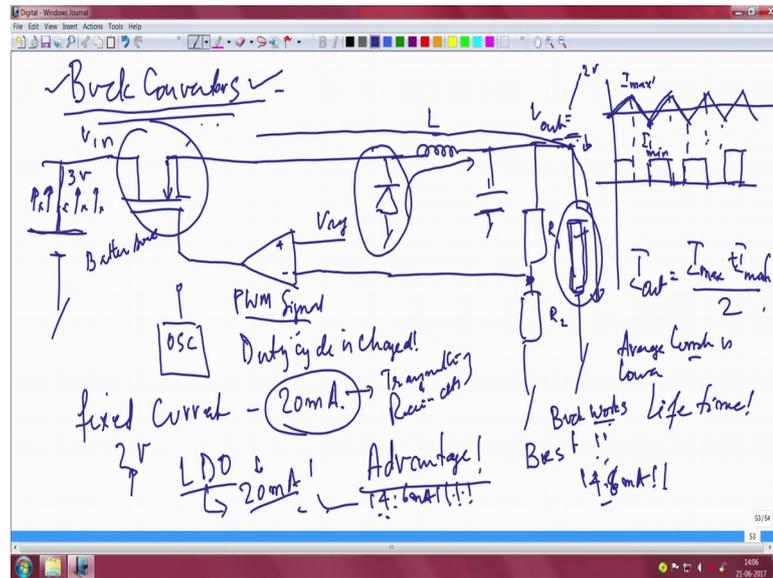
So, let us spend some time on this part at the more understanding the buck converters in great detail. One last parameter which I thought would be very useful that we discussed, but we did not see is he does not seem to mention about PSSR, other data sheets will indeed talk about PSSR in the data sheet it is of no concern because it appears that this expects that the input is very clean coming from a battery source.

Typical applications you must look at the typical applications that they have in mind and perhaps they know that the input is perhaps not coming from a buck converter, but actually coming from a battery source and therefore, it is more or less very clean there is no other loading of this battery to other systems which are switching loads they are not doing anything.

And therefore, it is just being fed directly to the LDO as an input and therefore, the system is pretty clean in terms of the output that is available, but so; that means, PSSR has not been taken into account if you do not know the PSSR of this LDO, and you have switching kind of loads which are coming up this is not the right LDO at all now you know that if I do not have a spec I am not going to use it because they have seem to have hidden information about that perhaps it is in a detailed document which you may have to look up so.

It is important that because this is a data sheet which has several chapters. So, in somewhere in this data sheet you may have to look out for the parameter on PSSR with this let us now move over to the other type of regulators which are called the buck converters buck converters.

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So, let us see buck converters and try and see how we can actually use these buck converters also in the power supply block of the IoT device. Remember this picture we drew last time we mentioned quickly that there is no difference really no major difference between the way you draw the block diagram of a LDO and that of a buck converter there is a usual series pass element here and then there is the reference and you are trying to compare the reference with these two feedback resistors.

Now, energy is actually stored in this L value in this L inductor and then there is the diode here it could be typically sort key diode which allows you to do the following what does it do in the forward direction when this output capacitor when this inductor has to service a given load it has to give you a bucked output let us say this is 5 volts, and what you are getting here is 3 volts how it works? Essentially this duty cycle is controlled is switching this switching is controlled here by this input voltage here and the series pass allows you to transfer the energy and store it in the inductor here and then sources the load by giving you a three volt output.

Now if this three volt output actually is changed because of the. So, how is that coming that is we just becoming because of the fact that you are switching this series pass element by this oscillator and there is a square wave generator which will allow you to generate back this you know it gives you a PWM signal the essentially there is a PWM

block, which will allow you to produce an output voltage which is 3volts by this very efficient and intelligence switching of this regulator.

Having get said only that much having said now if by chance the under any a dynamic condition this 3 volt actually goes down which means this conduction of this series pass element has to increase, then this is given as an error input and again the conduction changes of the series element and the way the conduction changes is because is essentially achieved by changing the duty cycle; duties are let me write it here essentially the duty cycle is changed in order to provide the necessary to get the output voltage back to it is a regulated output the way it works in first cycle the inductor charges and then the system is switched off the current comes down, but there is a circulating current which essentially circulates like this in the forward direction it is going like this through the load through the load and then returning back. So, the load is getting power in this direction and in the other direction the circulation happening through this short key diode and again the load is serviced to by the circulating current which is through the inductor right.

So, in other words the current increases goes to  $I_{max}$  and then the current decreases goes to  $I_{min}$ , and that way it keeps fluctuating between  $I_{max}$  and  $I_{min}$  based on the load requirement load based on the voltage that you have set at the output and I usually error amplifier is output controlling the PWM signal right the PWM signal is actually taking care of ensuring that the point comes back to regulation. So, if you see carefully what actually is happening you are I out here is the cracks of the story I out is  $I_{max}$  plus  $I_{min}$  by 2 right.

The average current is lower is actually lower right average current is lower, now take a situation where this load requires let us say a fixed current always of some number let us take 20 milliamperes of current that this load requires and this load can actually work from 2 volts. You have 5 volts here and you need only 2 volts at the outputs. So, this equation this thing will be that  $V_{out}$  you required you need to set it only to 2 volts.

This load, so irrespective of what this voltage is the load current always is fixed to 20 milliamperes. This is a situation where many transmitter receivers transmitters and receivers circuits actually required this fixed current of 20 milliamperes. So, trans we have essentially require this 20 milliamperes of I mean I am require a fix current this

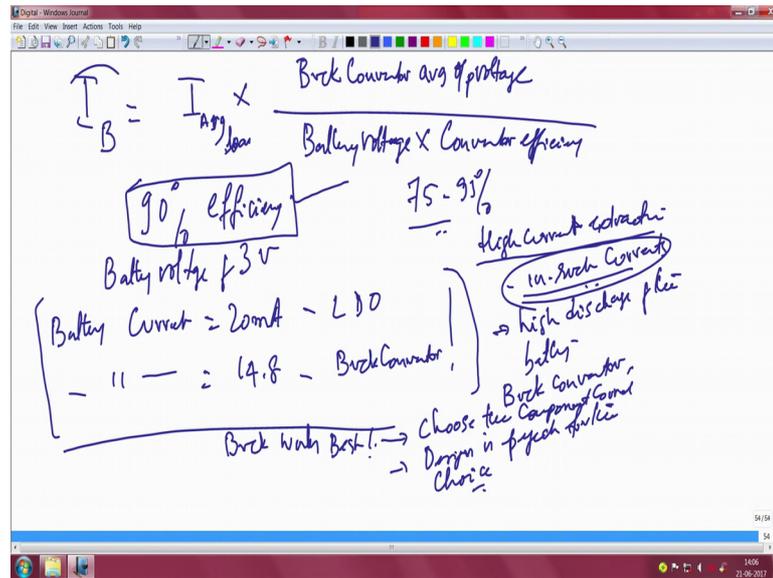
irrespective of the voltage. So, whether you give here 3 volts or whether you give 3.3 volts or whether you give 2 volts the current flowing through this we will always be fixed at 20 milliamperes. Now this is where you take the advantage you actually take advantage. What you do this is a situation where buck works the best in any of your designs buck works the best buck works best do not use an LDO in the situation do not use an LDO, when you know that the load current required irrespective of the voltage of operation is going to be fixed it is not recommended unless it is an analogue sensor ok.

If it is an analogue sensor the story is different it cannot tolerate switching noise and all that, but if it is a load which requires current fixed current irrespective of the load voltage the output voltage that you are applying, go for buck converter because buck works best here. Why because let us say this 5 volts is actually coming from let us say for simplicity I will make it 6 volts right instead of 5 I will make it 6, the reason I am making it 6 is because I am let us say connecting it in to a battery source you have 6 volts battery right 1.5 volts cells also can be used 4 of them, if you multi if you a put 4 of them you will get 6 volts or you can get a 6 volt battery source as well both these systems hello you have to connect to a battery source.

Now, if you take linear regulator if you take an LDO, this element is on all the time right it is on all the time why because it requires 20 milliamperes. So, constantly because of this LDO you will be it drawing 20 milliamperes all the time, battery survives for some life some lifetime we will not worry about that life time because that is a standard thing right you connect a load and then there is a load requirement and the battery has to source that load requirement all the time. Now you see the beauty that supposing I do not draw continuous current from this, I draw current then I switch off I draw some current and I switch off I should draw the arrow the other way right.

So, let me draw the arrow I draw some current and I switch off, I draw some current and I switch off, I do this all the time then what is the average current. The average current indeed is not 20 it is actually 14.6 milliamperes that is the beauty. 14.6 milliamperes how did I do that? Well there is a very simple expression for that.

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You can just try the I battery is nothing but the I average current delivered to the load I average. So, I average delivered to the load I average. So, let me I average A v g delivered to the load, load into buck converter average output voltage divided by battery voltage into converter efficiency, if you do this substitution if you take an exam. So, in this value that I give you fourteen point I said- 14.6 I think we will come to 14.8.

If you do this calculation by assuming that buck converter is 90 percent efficient efficiency is 90 percent, and you will see that no actually I think I you should make some assumptions we will not take 4 batteries we will take we will take 2 batteries. So, let us make it three volts let us make it 3 volts.

So, I just to match this number I am making a right I have just substituting we need can be anything just for a proper substitution and proper understanding, I will say V out is 2 is volts now everything we will fall in place. If you take a buck converter efficiency of 90 percent and battery voltage of 3 volts and bad current load current is 20 milliamperes right you will see that what actually comes out is in the case of LDO it will be 20 milliamperes from battery, LDO case and the same thing will be 14.8 case in the case of buck converter.

What an I opener this little thing is, that in there are many many situations because of high efficiency of the buck converter due to it is switching ability you actually have a huge amount of savings in the load currents source current as well as there is actually a

huge savings because of the a switching the battery is able to sustain longer the load the source currents are much lower yet load currents are a met the load things that is actually getting 20 milliamperes, but actually what is being drawn is only 14.8 milliamperes in that sense. But there are problems right you may get high efficiency unlike LDO's buck converts efficiency will be anywhere from 75 to 95 percent efficient, they are issues of you know the fact that you can have high current extraction, high current being pulled current extraction from the converter which actually is called the in rush you have problems of in rush currents which can create a high discharge of the battery.

You may be worse off if you do not. So, all these what I am trying to say is if you do not choose if you do not choose the right buck converter or you are the design is not a very optimal thing, you will actually have you will diverse of then an LDO if the in rest currents are significantly high and how do you know that.

Well there is no simple way by there is indeed a sub standard design, will actually shall I say a sub standard design will indeed have that problem, you have to only go by choice of the regulator and you also have to keep in mind that this load that you have chosen we will always required this fixed current of what about 20 milliamperes and it is not going to give you any say let us a transient, it is not going to switch off and switch on and do all kinds of crazy things, which will you know introduce this rush currents in rush currents.

So, you have to design you have to choose and go by the principal that buck works best I like this keep this in mind buck works best only if you choose the component correctly and design is fine design is perfect for the choice. These are the key things that you have to keep in mind.

So, let us see I will draw another picture in the coming in the next slide where this configuration actually is called asynchronous buck converter, that will be replace with a synchronous buck converter where we can get rid of this diode and we can actually replace it with one more tra MOSFET and well that is another version of the buck converted itself, but this indeed is the overall story of a buck converters.

Thank you very much.