**Design for Internet of Things**
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**Lecture - 07**
**Introduction to LDO**

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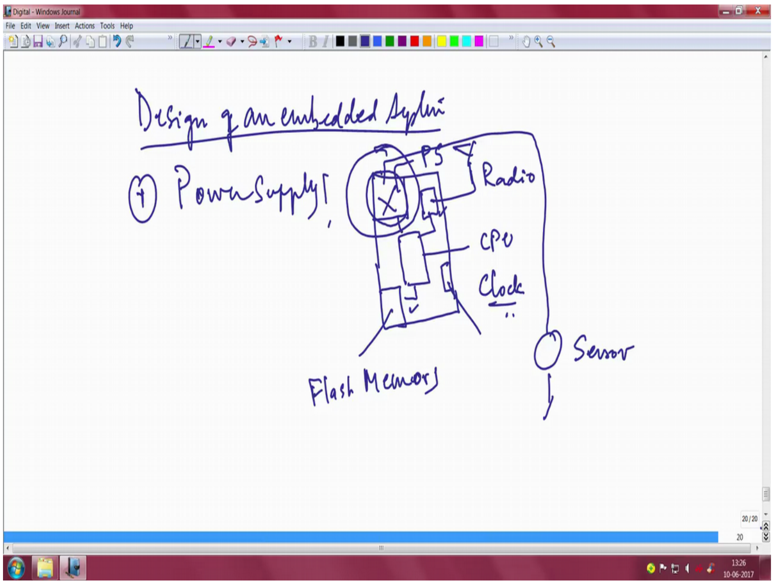


Design of an embedded block of an embedded system right. System and let us put down the design of the first block the very first black which is the power supply. The power supply block of the embedded system that you want to build for your IOT application this is the power supply block this could be the CPU there could be a radio right. There could be a radio sorry let me put it down clearly this could be the CPU. So, CPU here. So, CPU here and then the radio right. A low power radio, what about memory right. So, all of them are connected you need power supply for this, you need communication between the radio block, and the CPU block there is memory flash memory. And all these systems here either it is flash memory or radio or any one of the other peripheral blocks, all of them will work on the clock right. On a single clock, on the clock of a generated by there at the CPU.

It can also be analog to digital right. There could be an ADC converter analog to digital converter which essentially takes all the analogue sensor inputs, you can go through this you can have 8 ADC ports you can have 10 ADC ports 12 ADC ports and so on and so forth depending on the type of controller that you need for your particular application. Anyway you have multiple ADC ports which you can basically interface. So, this block we have to elaborate now right. We have to understand how does this how is this how should this power supply block be designed in a manner that it is able to provide stable power to this complete block not just the complete block, but also the other blocks to which this power supply this system this system is actually connected to right.

For example, sensors, sensors which are connected to the a DC block sensors need power right. So, let me put down a sensor a sensor needs power. So, it could be that this power supply has to make available power to this sensor blocked as well. So, this is the key. So, let us concentrate on this one portion which is the power supply block. Very good, let us move on and see what are the key requirements for this power supply block.

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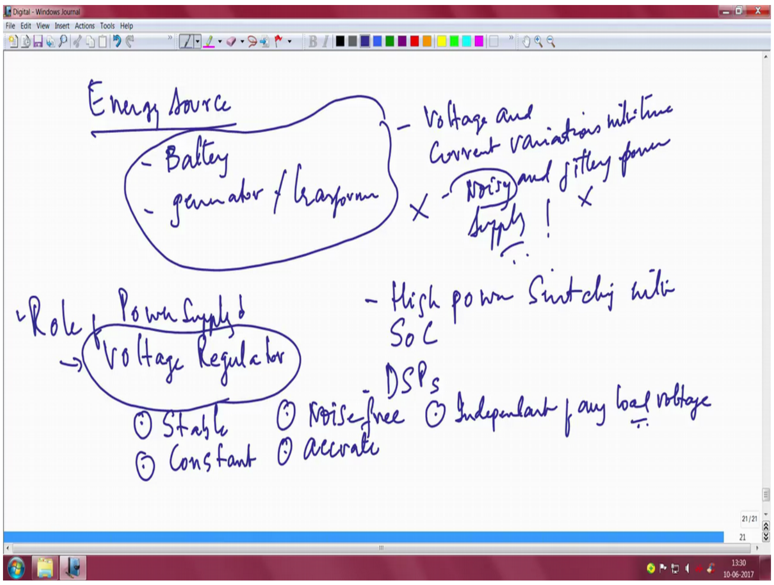


Keep the energy source to begin with, take the energy source to begin with. What is a problem with this energy source? The thing is another what is the, So, what are these energy sources essentially, it could be a battery, it could be a battery or it could be from some generator coupled through a transformer and so on and so forth.

These energy generating sources incur voltage and current variations. They incur a lot of voltage and current variations with time. Which means this essentially leads to very noisy and jittery power supply right. And this can be an issue, if this goes on varying these energy sources essentially have lot of variations. It is not generating lot of variations the then the system in in field indeed is doing a good power supply at all. And the question is why do these energy sources actually go through this voltage and current variations in time. The issue really is because of high power switching, that happens within this if within the SOC, system on chip, which has all the blocks that we showed previously. Or it could even be from DSPs digital signal process which seem to be switching at very high speed and creating lot of fluctuations in the power supply.

So, this power supply essentially if you look at the role, role of the power supply role of the power supply, when you say role of the power supply, we actually mean the role of the voltage regulator. Because you do not want to see in a noisy and in a jittery power in the power supply. So, you essentially want to have a power supply whose role which we are trying to define is an important role, implemented realized by this voltage regulator. The voltage regulator should ensure that the power supply is stable, constant, noise free, right. Noise free, accurate and basically independent of any load. Any load where and it basically it should be independent of any, essentially we should be able to provide you any sorry let us say independent of any load voltages.

So, whatever be the load voltage requirement, this power supply through it is regulator should give you all these nice features. So, one thing from my experience which is very critical.

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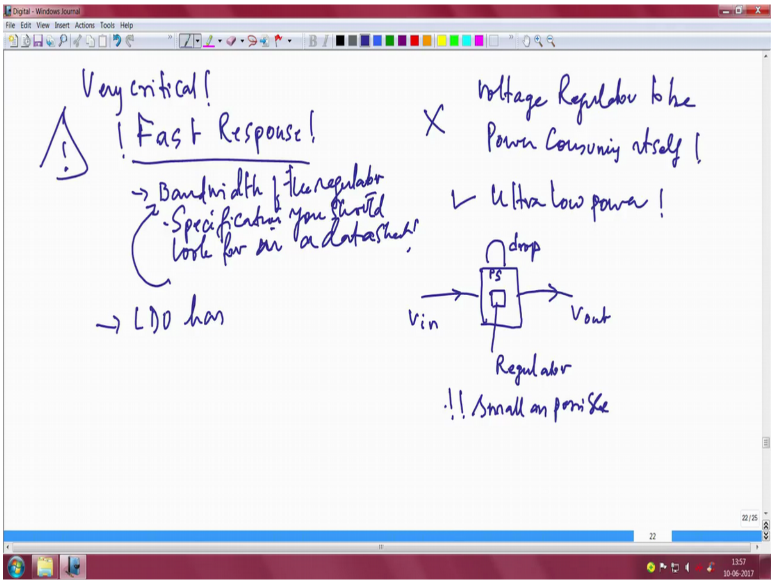

Very critical that you should actually realize through a power supply what you should realize to a power supply indeed is it is ability for fast response often ignored, but this is very critical very critical. So, I will show it with a band here. So, this is really important which means you should be worried and give a lot of caution to the bandwidth of the regulator.

This is an important aspect which you should look for which is an important specification. You should look for, in a data sheet very important. Another thing when you talk about the power supply, you will also have to be looking at what is the head room that you need in order to ensure that this power supply gives you all the features that we mentioned previously. Like stability it should be constant nice very accurate. So, on and so forth all these parameters all these requirements that we put together.

So, in other words you do not want the voltage regulator to be power guzzling power consuming itself. You do not want this to happen right. It should be what should happen it should be ultra low power itself. So, what does it mean it simply means that if you take the power supply block which has the regulator inside, will mostly worry about the regulator when you say power supply, will mostly worry about the regulator, with given input you get an output right. The drop across this, this is the drop the drop across the V in to V out should be as small as possible. This is important. It should be as small as possible yet it should give you the required power output that is important.

So, we can do it in many ways right. So, we essentially can generate let us say a 12 volt battery let us say you have a 12 volt battery source. You have a 12 volt battery source, let me write it a little more legibly let me choose.

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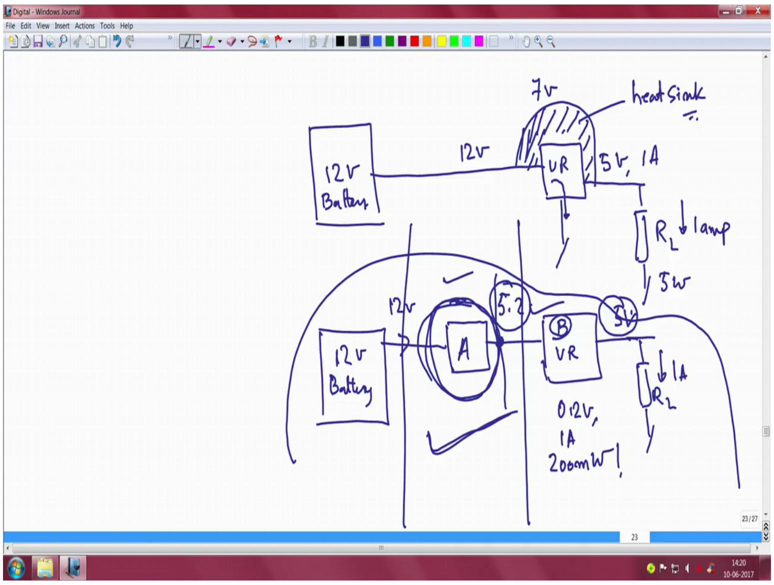


Perhaps you have a one volt battery you are interested in generating 5 volts and the output, and essentially you are going to give an input of 12 volts, you are generating an output of 5 volts. And output which means and let us say the current requirement is 1 amp for the load one amp is flowing through this.

You basically have 5 watts of power and you are dropping here 7 volts right. And all of this 7 volts plus the current is flowing through the voltage regulator is actually also passing through the regulator. Which means 7 volts one amp flowing gives you 7 watts a huge heat sink would actually be required to keep the regulator cool. So, this is not a good design right. What may be a good design would be you still have a 12 volt battery source right. You still have a 12 volt battery source.

By some other mechanism you bring it down to 5.2 volts, and here you generate 5 volts. This is back the voltage regulator essentially for taking care of the load. This block is an interesting block which took 12 volts give you 5.2 at the output. And here you dropped 0.2 volts. And change one amp was the current consideration of our load, it is now 2 hundred milli watts as compared to the high power that the previous system actually looked at. In other words, this drop is insignificant and therefore, no heat sink or anything would actually be required.

Now, most embedded designs, most embedded circuit is that you come across will essentially looking at these parts things like this.

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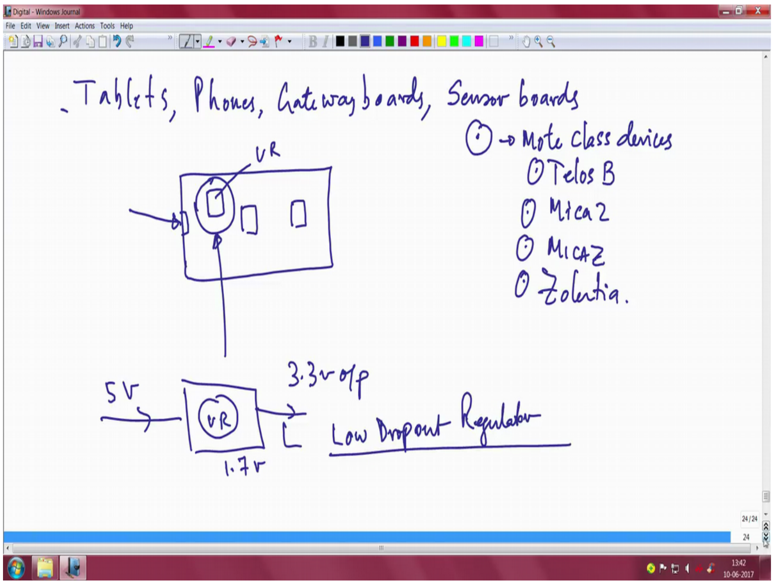


You take you take popular embedded devices like tablet us phones right. Popular gateway boards or any of the sensor boards, in the sensor boards issues like there are boards like the mote class devices, which could be like the Telos B Mica 2 nodes or Mica Z. I have to write this also Mica 2 mica z and so on, or Zolertia. All these are popular mote class devices, they more or less have some sort of they are all embedded systems right. Embedded boards which will have a CPU which will have a radio which will have flash and interface from the usb for the purposes of programming, but they will definitely have this regulator block voltage regulator block. And this block which will be part of the embedded design will essentially follow this kind of this part will actually follow something like this, where you will actually I am sorry it will not follow this.

But it will follow it follow this, but what will be implemented will be here this part you take something like 5.2 volts as input and you generate 5 volts at the output alternately you could be taking 5 volts as the input and you may be generating 3.3 volts at the output this is also a popular way yet you can see that the drop here is not significant it is only 1.7 volts and if the current is not very high the power dissipation by this regulator block it does not call for applying a heat sink of any nature.

So, let us concentrate on this voltage regulator block, and the popular name for that indeed is the low drop out regulator.

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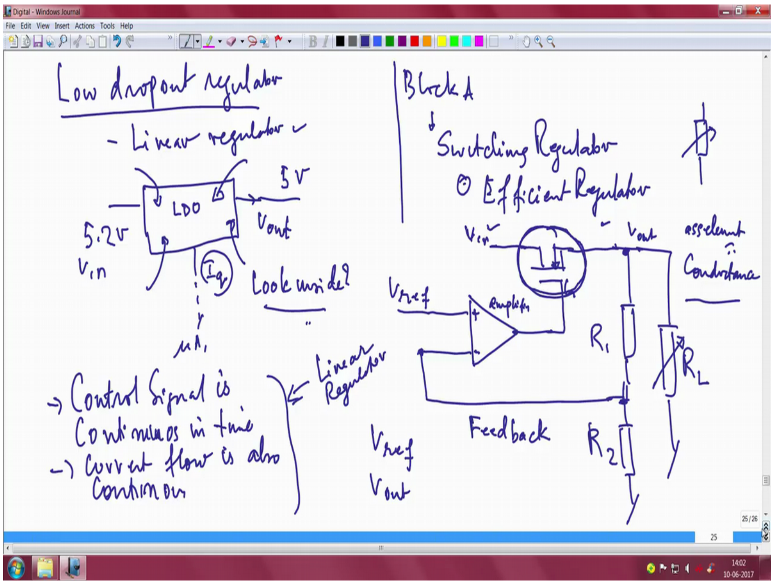


So, the low drop out regulator essentially low drop out regulator essentially is a linear regulator, it is a linear regulator. Recall I mention to you this block, this block which we never elaborated you have a battery which is 12 volt battery that you know, 12 volt is taken as input 5.2 is typically generated at the output for this example. And 5 volts appears here this block we did not elaborate, but I am going to mention at this juncture that that block that you see this block let us call this block A, let us call this block B right. This block A indeed is typically is switching regulator.

Why? The reason is why did you not use a linear regulator. It is no obvious right. If you do a linear regulator like the block I showed you here you need a huge heat sink because you are dropping 7 volts across the regulator, and you are generating 5 volts at the output for an input of 12 volts. I have assumed the load current to be 1 amp. This is not a viable option instead step it down to a reasonably close to what you need using this switching regulator and after that you do the conditioning right.

So, switching regulator is an efficient regulator. And it has certain functionality which we will address later. Let us just concentrate on story related to this part, where you get 5.2 volts at the input and you are interested in generating 5 volts at the output. The input output is just 2 hundred milli volts and it is 1 amp. So, you have 2 hundred mili watt just 2 hundred milli watt being dissipated across this regulator which is also called the low dropout regulator. The low dropout regulator as I mentioned is a linear regulator and it is importantly, it is a linear regulator and it has a fantastic feature, which we should not forget again from a data sheet perspective.

Let us take our standard example. Please recall we said 5.2 appears by magic because this switching regulator switch we havent expanded at the moment also written has block A here will be elaborated later of course, somehow appears and you are getting 5 volts here. So, let us start from this point, that start from this point 5.2 volts input. V in, V out they said is 5 volts what is interesting is this quiescent current right. The quiescent current is typically in micro amps clearly indicating that for the regulator to provide regulation and provide all the features that we said previously, the features the requirements that we said are it should be stable it should give you stable output constant noise free accurate independent of any load voltage fluctuations, all those features would be possible is all being done by it itself not consuming a lot of current, and that is what we call the constant current right.

So, this quiescent current is denoted by I q and this I q is indeed typically in the order of micro amps. So, that is an important feature of the of the regulator. How does this regulator look if you go inside of the regulator. How does it look and why is it important to look inside the regulator? Look inside how does it look inside. Let me draw the picture of a typical low dropout regulator inside picture. First thing is plus and the minus of a amplifier, amplifier can be constructed in several ways you can also think of an op amp as an amplifier.

Here we give a reference voltage V ref right. V ref somewhere you are going to give the. So, I will call this amplifier right. Somewhere there is an input which is V in and; obviously, there is a V out between V in, and V out. Between V in and V out is this active device, which is n MOSFET, is an n MOSFET it works in the depletion mode depletion mode and MOSFET is used here. Essentially you could replace this V in, V out this element for all practical purposes all imaginative purposes you could write this part as like this

Obviously, this is not going to be the complete story. V out you know that this pin is hanging here. So, let me write this equivalence a bit later and in fact, complete this picture take this point and connect it, take this point and connect it. Here and this indeed is the load right. This is nothing, but the feedback.

Now, you can replace this part. This part here this part here with a potentiometer. A variable resistor you could denote it with a variable resistor. Essentially this is a pass element right. This is a pass element, this is a pass element and here you are varying the conductance you are varying the conductance, of this pass element and when does that variation happen. That variation happens change in conductance is based on one simple comparison and that comparison is between V ref and V out, you have V in you have V out and we have the V ref the V out and the V ref are compared and the difference is amplified and fed to the gate input of this n MOSFET series element. Which basically increases the conduction from V in to V out. And thereby keeping this point always at a fixed atoms to keep the point V out always at a fixed point fixed voltage.

So, essentially you are doing that. Every time there is an increase in R L every time R L changes increase in you know when the current drawn increases, there is a change which is detected at this point, at the feedback point. And essentially the feedback point and the reference point are compared the error between them this is essentially an error amplifier the difference is amplified fed to the series pass series element gate of the series element which increases the conduction and get the V out back into regulation this cycle keeps going and the vice versa actually happens.

If it is if the current decreases. So, that way this system is keeping the whole the loop in control, a loop the control signal is so what are the features just put on them the control signal the control signal is continuous, continuous in time. Is continuous in time the current flow is also continuous is also continuous and these are 2 important features which basically define the fact that the regulator is a linear regulator. So, you have this important feature control signal is continuous in time, the current flow is also continuous in time and one can easily define the fact that the series pass switch connected between the input and the output is controlled the control signal given ensures that this V out is always in regulation.

Please note this circuit essentially means the simple circuit essentially has given home several things. That such a circuit that we drew is nothing, but the low dropout regulator which has features of being stable noise free constant accurate and so on. And just not that you also ensure that the LDO has good bandwidth performance right. Has a very good bandwidth performance. And this specification has also got to be looked up when you look at data sheets. So, that is a very important point.

Now, what was this block right. This was this block, let us see what is this block A this block A we glass over at the moment and will continue to glass over it for a while, but not before defining what that block is, that block indeed is a switching regulator, we mentioned this already.

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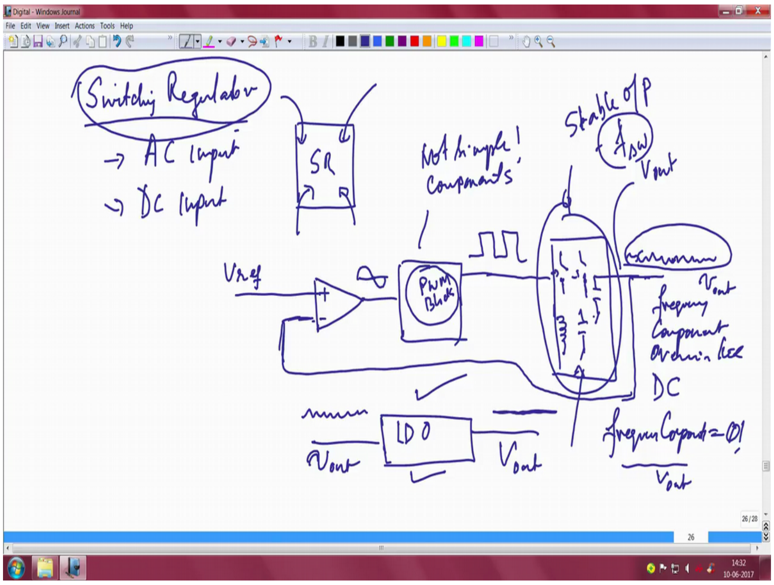

It is a switching regulator because if it is switching it can take AC input it can also take DC input.

This is important it can take AC as an input it can also take DC as an input. And how does it look internally when you say switching regulator when you say e side of this switching regulator. How does it look well not very different from what we have shown here, there is indeed an amplifier and there is an additional block, which is an interesting block which for completeness I will do it now? And you see that there is control there is still control only thing is the current flow is not continuous, and control signal perhaps is not also continuous in time.

So, let us complete this by showing a block diagram of a switching regulator, the story is the same you need a reference and you need another block which is also called the pwm block, where you get an analogue signal time varying periodic perhaps signal which then gets converted to some sort of digital pulses, which are fed to the energy block call it. So, I will call the energy transfer block, energy what may be a good name is a let us put down a good name for it energy yeah I will call it energy transfer block. This energy transfer block essentially has number of inductors and switches.

So, let me remove this so that I will be able to indicate inductors sorry switches could be active switches like MOSFETs right. As inductors has capacitors and so on ultimately leading to a V out with another capacitor all of them connected, which gives you not really a nice looking b C which we got here you can get a beautiful DC here sorry here it doesn't look good. So, let me put back V out right. The DC here is indeed pretty straight, with no perfect perfectly output signal, which indeed is noise free. Unlike that coming output coming from an LDO you may get a little bit noisy signal at the output which essentially you have to deal with right. You deal with is.

In fact, if you get this you should be lucky perhaps it may look DC like this perhaps sometimes even like this. And there is indeed a frequency component overriding the DC. There is indeed a frequency component, and I an and your and your whole purpose would be to make all the frequency components equal to 0. So, that you get you back a beautiful DC signal. So, question is how do you get from this fluctuating, we will call this as we will call this as V out written like this, and we call this as V out. So, how do you get how do you get how do you get V out as V out that is the question right. And it turns out LDO can actually do that as well. It can take fluctuating AC component riding over a DC and filter out the frequency components as much as possible and give you a stable DC output.

So, this is another important thing that LDO can do. Let us not get into more detail about the switching regulator, but indeed complete the discussion of this linear regulator. So, that we will see typical applications of this linear regulator in the course of this in the course in the course of time. And it is applications in the embedded world which is important when you design an IOT system. So, now, you recall this part we mentioned about one important thing that is very critical we said fast response how fast is this fast response we need to put down some numbers right. And everything leading to the bandwidth of the regulator.

And you must look for a specification in the data sheet which is talking about this this particular number. So, let me tell you a few things about that and then we will move on and look at some case studies on this LDO.

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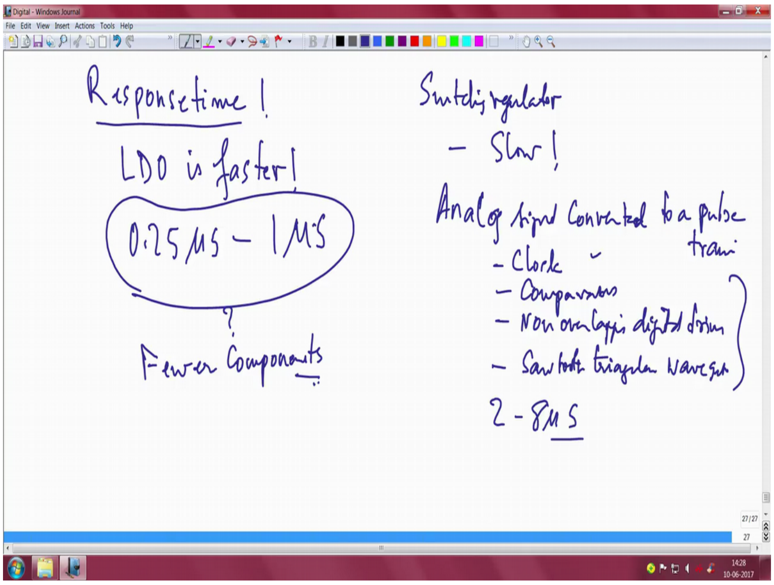


First of all, the response time it is easy to talk about the response time in comparison to the switching regulator already, which is nothing, but that block A which we said this is this block A, sorry where is that yeah this block this block is this block A. So, it is a little smugged. So, let me write everything here a right. This is the switching regulator which actually made things life made as made our life very nice because it really brought into this 5.2 volts.

So, you can actually talk about the response time together and you know handle it in one shot. So, that you really know why this is an important thing. Just now let us look at LDO is you say is faster. Now why is the switching regulator slower. That will be your switching regulator slow, why is it slow. It is slow because the analogue signal to a pulse train to a pulse is converted to a basically the analogue signal is converted to a pulse train is converted to a pulse train, I call it is converted. So, I think I should put it down correctly.

Before we go there yeah this block right. This is also getting feedback I didnt complete it. So, let me complete it by how will you connect it you will connect it for; obviously, from the load, this is the V out you have to sample the V out and connected right. Note every time when we show these pictures we are actually showing you wait I am let just let me where is the linear regulator yeah. So, look at what we do every time a feedback is a negative feedback, and therefore, the same should be here is consistent that way it is indeed a negative feedback. And actually given to the negative input of the linear amplifier which is essentially the error amplifier.

Now, the analogue signal here is converted to a pulse train right. And that is not going to be easy analogue signal, converted to a pulse train means, you need a clock you need comparators, you did you perhaps need non overlapping digital drivers of some nature. You need a triangular wave generator saw tooth triangular wave generator. So, all this means a lot of circuitry, lot of additional components, this block is not going to be simple not simple not simple. Although I have denoted it by this block it is not simple there are lot of components many components and many requirements clock comparators and so on and so forth.

Essentially, if you want this feedback negative feedback to remain stable, the bandwidth should be below the switching frequency right. It should be below the switching frequency of this, for stable output it should be below the switching frequency. These devices are switching at a certain frequency, in order to keep the output, stable the V out has to be stable, you have to ensure that the switching frequency of these components exactly is a decade lower, only then the negative feedback will be stable. You will only be able to get we will get be able to get a proper V out. In fact, the whole regulation will happen only if this condition is actually met which means you are not switching at very high speed means that the noise on this line is also not going to be it is not easy to eliminate this switching noise and therefore, you have this nice. So, you have this frequency compound dominant frequency component riding on top of the DC output.

of course, you could increase the switching frequency right. You can, but if you increase the switching frequency the switching losses are going to be high there is no doubt about that. And you do not want to end up with a lot of you know switching losses as well and if switching losses are high you will need to dissipate the switching glasses which might indeed you know turn out that you need components which are highly rated higher rated higher rated components plus you may also need a heat sink and so on.

So, really you do not want to do that moreover this negative feedback to be stable means you have to ensure that the system indeed is switching lower the switching frequency is indeed at least a decade lower in order to ensure that this negative feedback keeps the actual remains stable. So, that is that is really the key point. So, all of this means you have to put down some numbers right. If you take a switching regulator it responds anywhere between 2 and 8 microseconds. So, it is that is typically of what it will do as against something like 0.25 microseconds to about one microsecond.

So, it is really fast. Really, really fast. Why because it has very fewer components also. It also has very fewer components and how does it look how easy is it to vig up an LDO. Well very simple by the chip.

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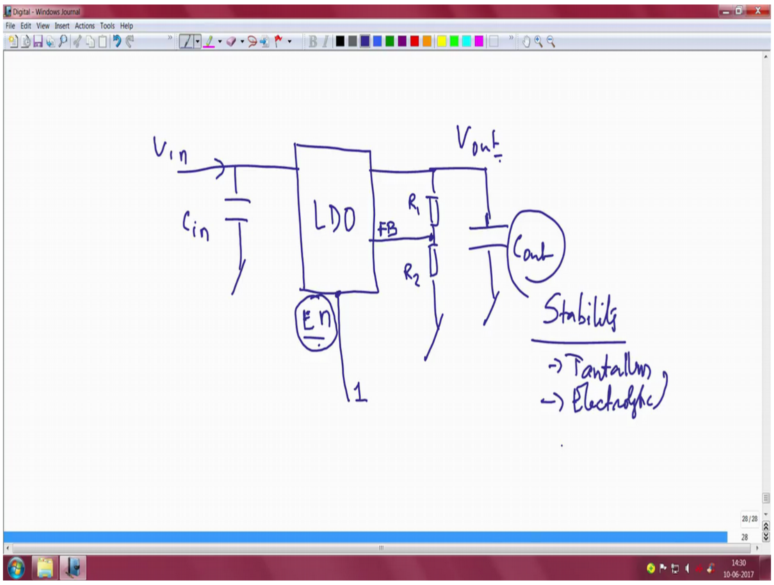


Give it a V in, there will be a V in pin connect an input capacitor to ground, call it C in connect 2 registers for the purpose of providing you feedback. And have an output capacitor, that is all this is V out. Looks simple looks very simple, but sometimes you may want to control input to output by using an enable pin, only if enable pin is one, the input actually switches to the output. Very useful in several power management algorithms, we will handle this one issue is one pin and how innovatively this can be used to ensure that you manage the power effectively.

So, what is the important thing about this circuit. This C out you have to choose this capacitor and this choice is indeed very critical, because it has the bearing on the stability of the regulator. So, the output capacitor is an important component here. Normally this is tantalum or electrolytic. We will discuss more about this LDO and issues of an LDO, if you make the wrong choice of an LDO for your embedded, IOT design how disasters the system can be not only in terms of response time, but also in terms of power consumption.

Just to compromise that you got a fluctuating input here, which we showed in this picture where we yeah. So, I did draw a picture yes this picture here we took a input DC, which had a certain frequency component and you wanted to generate a stable DC at the output we said an LDO can do this trick, and just because you want to do this trick if you do not choose this component in an appropriate manner, you would actually end up with a sub optimal design, of your IOT system. And therefore, we will have to look at a few case studies from very popular articles, of how researchers have really looked at tuning and choice of a LDO for a particular application.

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So, we will show you 3 experiments here. The first experiment is to understand this question what happens to the output voltage V out, when the load current increases different loads are connected they are switched and all that what actually happens when the load current changes you have to observe that right. So, this is a set up here essentially you can see this is the power supply on top of the power supply we have placed a DC electronic load, and this is the one that actually we are able to modify the I mean we are able to set the different output currents. Left side meter extreme left is the input voltage extreme left the second a multimeter you see is the input current, the after the power supply the first a multimeter that you see is the output voltage and the second multimeter to the extreme right. Is the output current.

So, you can see just first quick observation input voltage is 10 volts output is has to be 9 has to be 5 volts, that is what we are trying to say yes this is an LDO which is set to a 5 volt output and the output current has to be 25, but you can see 25 is at the input you get 24 at the output you may be surprised, but well we learnt from theory that there is indeed a quiescent current and the quiescent current drop is across the LDO that is why you get one milliampere less at the output which is fine absolutely fine all right.

So, now the current consumption here is 25 milliamperes all right. Now what we do is we increase the current let us see what happens when the output current I out when it increases what actually happens. So, then from hundred we moved to hundred and 25 milliamperes of output current and yeah looks like it still at regulation 4.95 volts close to 5 volts has been set and you can see that you have the output load is was at 124 and this was at 127 and now at 150 you see it is one forty 9 at the output 152; that means, as the load current increases the input current difference between the input and the output current also increases right.

So, you have see you can see that this is 3 milliamperes. Clearly as it is giving higher and higher and higher output power the LDO is also dissipating a lot of power across itself. That is a that is one of the things which we can demonstrate separately in in another experiment.

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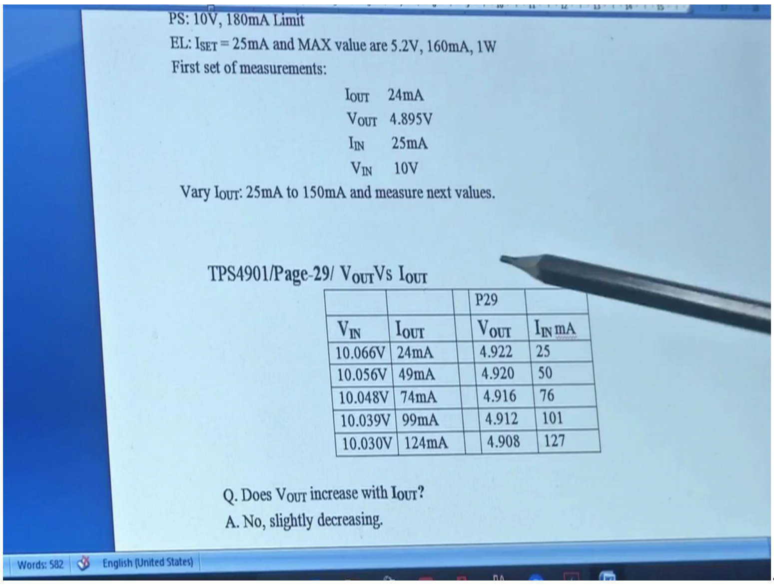


So, the big summary here is that V out is quite stable for whatever output load currents which are changing, the input the output voltage seems to be stable. Of course, if the output current requires 24 milli amperes it has to come from the power source and the that power source induced was the power supply the input current has to increase and therefore, you can see that the input current is the power supply is able to provide that input current.

So, this is a big summary that indeed LDO is able to maintain, it is regulation in spite of the load currents changing. So, the next question one can ask here is that what happens if the input voltage changes. You can see that again on the extreme left is the input voltage that this is a input current this is the output voltage. And that is output current meter on the right. Side of the power supply are all the outputs the input are on the left the input multimeters on the left side. You can see that as the input changes, now let see what loading we will do use an electronic load and then apply a certain amount of current and the value that we are trying to point into the DC.

Electronic load.

Electronic load indeed is set to.

25 milli amperes. So, 25 milliamperes the big summary indeed the big summary indeed is that when the current is fixed to the load current is fix to 25 milliamperes and the input

voltage is changed across 10 to 30 volts the when we change the input voltage from 10 to 13 steps of 5, you will see that the system continues to maintain output voltage regulation and the output power delivered also remains the same. So, that is the big summary there is a nice table which actually highlights that and we will have a look at the table.

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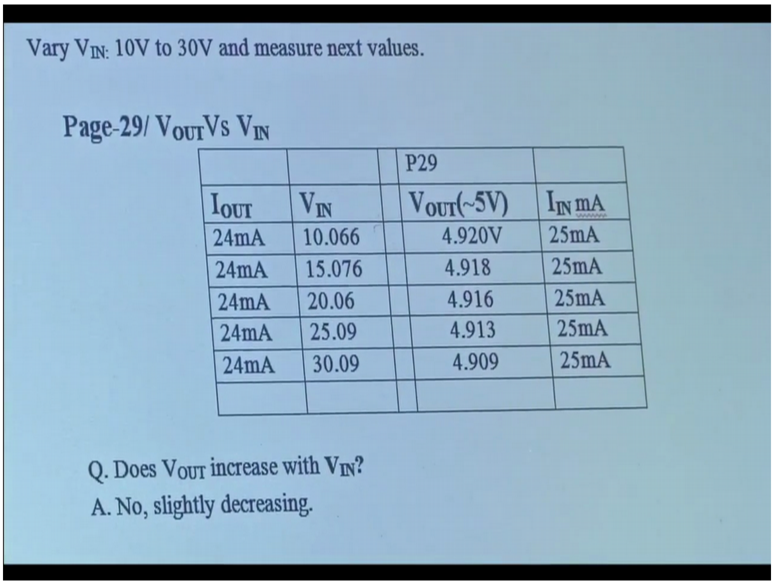


So, what we can do now you can see that the input has changed we have varied the input from 10 to 30 the output is weld into regulation and the. So, that essentially clarifies that in spite of change in input voltage systems are in stable the voltage regulator is indeed in (Refer Time: 62:20) continues to be in seem to be stable now let us what we will do is we will try to study the efficiency I expect that you will quickly be able to answer this question.

Ah. So, what we will do is we will keep changing the, I load current the electronic load which you see on top of the power supply is the one that we will keep playing with input voltage is fixed at 8 volts keep observing what actually happens right. You will study you will see that input is 8 the input current is a 50 milliamperes output voltages is 4.9 that is close 5 volts and the output current indeed is 49 milliamperes and it seems to be fine right. So, and the current is actually flowing through this load resistor.

Now, we will modify we will change the input we will we will make the output load current to 75 milli amperes and conduct the experiment for 24 to 20 hours sorry 24 to 124 milliamperes.

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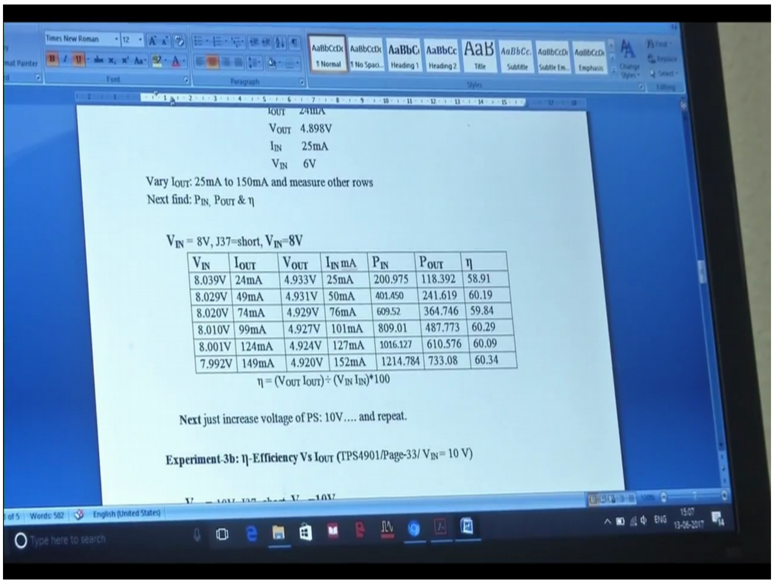


So, let us quickly looked at the summary of the results. So, now, you can see that the v input is you know maintained at 8 volts the load output load current has changed from 24 to 149. You will see that the efficiency the extreme right. Table column indicates the efficiency which is roughly ah.

Sixty percent.

Sixty percent right. It is maintaining at sixty percent.

Ok

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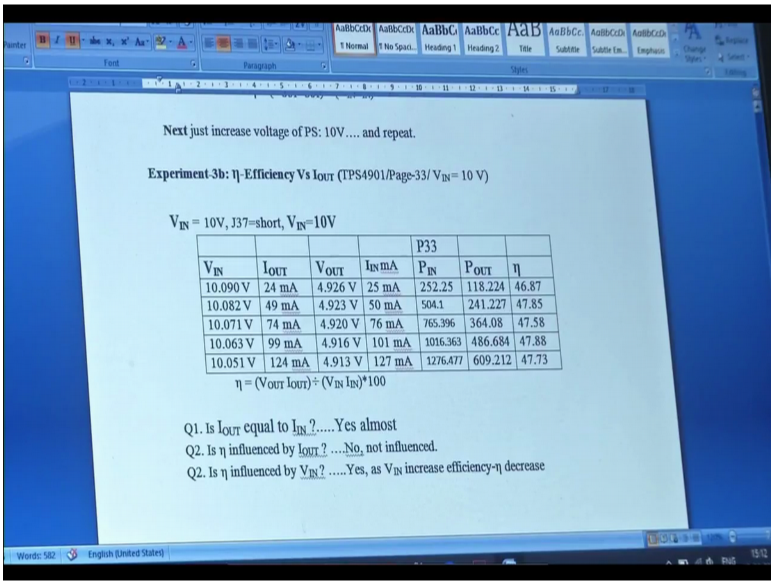


So, now what we do is we change the input from 8 to 10 volts and we again you know vary the output load current using that electronic load from 24 to 124 milliamperes you find the efficiency has dropped right. Now you can answer this questions is IOT equal to I in yes almost is efficiency influenced by I output the load current no not influenced is efficiency a influenced by input yes as V in increases the efficiency decreases. So, this is the big summary stop.

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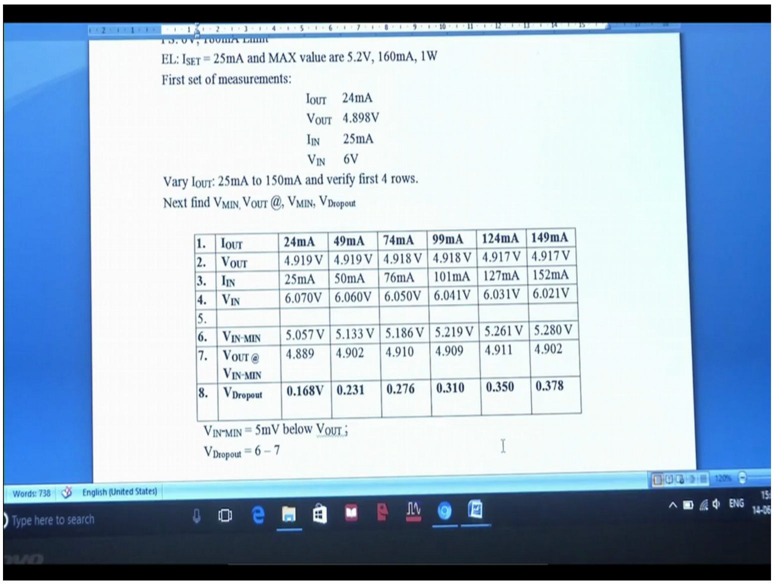

So, this table is essentially finding out is trying to evaluate the experiment can be done in order in a manner that we can estimate the drop. You can see that the load current changes from 24 as a load current changes from 24 to 149 milliamperes. The drop across the LDO also increases for lower currents the drop is low 0.16 volts and as you go on to draw higher and higher output load currents the drop across the LDO, also increases clearly indicating that indicating that the dissipation across the LDO continues to increase with the load current this is the big summary of the LDO.

Yes

Stop.

Thank you very much.