Design for Internet of Things
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Lecture - 13
Designing with LDO's, switching regulators and case studies Part IV

So, what we will do is I will before we go into the energy harvesting part it may be useful for you to look at a few case studies. One particular case study which I tried in my lab, I thought I should share that experience with you. So, let us see one actually the background is this.

We were trying to build an energy meter in my lab; the name of the energy meter is you can look up its called joule jotter. And in the process of building that joule jotter the power supply section as we have been discussing on power supply for a while now, is the most interesting part because I encountered some interesting problems there. And I will show you what exactly happened in terms of an oscilloscope snapshot and how we try to avoid that problem how you overcome that two actual we overcome that problem.

How we over how we overcame that problem. So, let me take your attention to one particular problem which I actually documented everything well for you.

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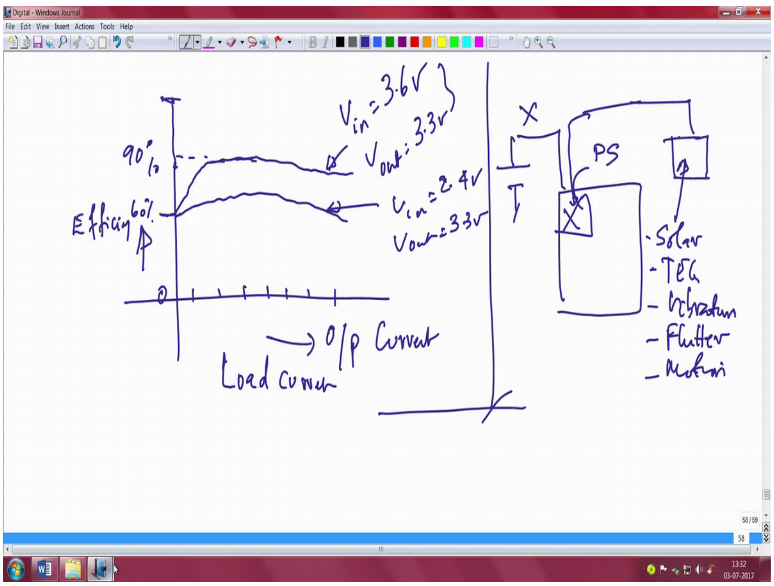

So, that we can directly I can directly show you that so, that comes from this doc file I have just put down the block diagram ok.

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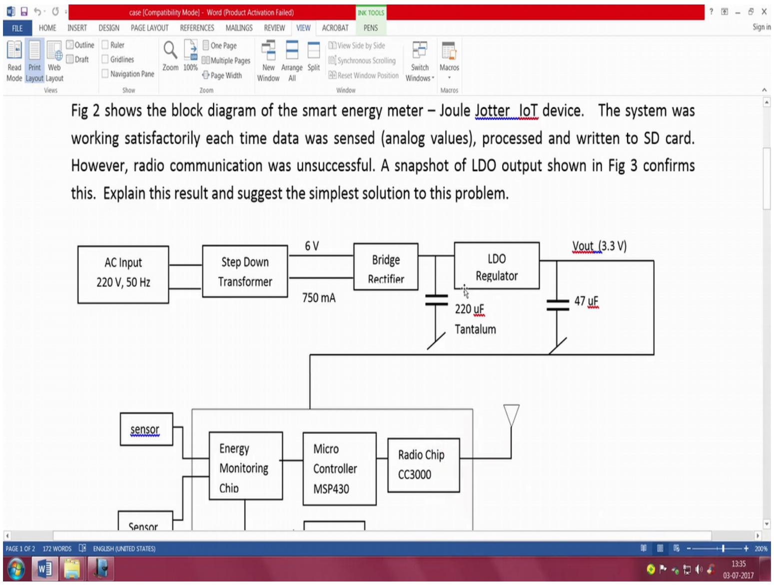

What we did was this is a energy meter which obviously, is monitoring power right it is monitoring the power quality, it is measuring the VRMS IRMS power factor and all that for which you need several sensors the potential transformer essentially takes care of measuring all the voltage related parameters. The current transformer we will take care of measuring all the current related parameters I output current, IRMS and all of that will come from the current transformer. So, before we get into running the system itself in order to measure we using the sensors like potential transformers and current transformers, the embedded system is be powered right.

So, this is the chain of the embedded system you have an a C input 220 volts 50 hertz step down transformer gives you AC 650 volts this transformer is rated for 3750 milli amperes, we have a bridge rectifier then you have obviously, a lot of ripple and all of that coming up and then you will see that I have put a 270 microfarad tantalum capacitor ,LDO which is the specification of the LDO is I have it clear it is essentially at it is TPS 7 a 47, it is a LDO which is TPS 7 a 47from t i I am not specifically fan of any co particular company, but we just use this because we found this to be the most suitable one, but there are LDO’s from rich take there are LDO’s from magazines are so many other companies which essentially make a LDO. So, you may have to choose based on whatever it you have or whatever specification that is closes to your requirement and then accordingly use it. Anyway it has an input minimum of 3 volts I have it here, I will just read out for you V in minimum is 3 volts V in maximum is 6 volts then V out is 1.4 volts minimum and V out maximum is 34 volts.

So, the input itself V in min is 3, V in max is 36 volt which means this regulator that I show you here essentially is a takes a very large input range and can also give you a large output range depending on what you are looking at. Obviously, this is an LDO right the input has to be higher than the output un like a boost converter where input can be lower also right because when you doing switching it does not matter what your input is it just had to you know if your building a boost converter then you obviously have a input which is lower than the output. So, never mind, it has a quiz in current off 0.58 milliamperes very important specification, but be careful be little more liberal here right you are not driving this LDO from a energy harvesting source, you are not driving this LDO from a battery driven source it is not.

So, you do not mind even if this IQ goes up a little higher, why because the a c here is a because this LDO is taking power from a 50 volt sorry 220 volt 50 hertz power mains. So, one milliampere is also fine not really going to be an issue for you. So, you can be a little more lakhs on the fact that its ground current quiescent current is a little higher. So, it is not really aspect that you should be worried about that is the point you should not really worry. So, much about I cube because it is not being driven the input to the LDO is not from a battery or from a energy harvesting source, that is the point I am trying to again take.

V LDO is 307 millivolt; that means, the drop across the minimum we d we drop out minimum I think it is the maximum it is not clear whether it is the minimum or the maximum, anyway the drop depends on the differential at the input output differential. So, anyway the drop he has mentioned is 307 millivolt which is I think this is the maximum drop it cannot be in it has to be the maximum. Accuracy of this is LDO is 2.5 percent remember we discussed this as an important parameter, noise in microvolt r m s is 4, PSRR at 100 kilohertz dB is 60 very good right 60 70 is a very good number you need that because you need a very stable ripple free DC for all your measurement using these very accurate sensors you will need them ok.

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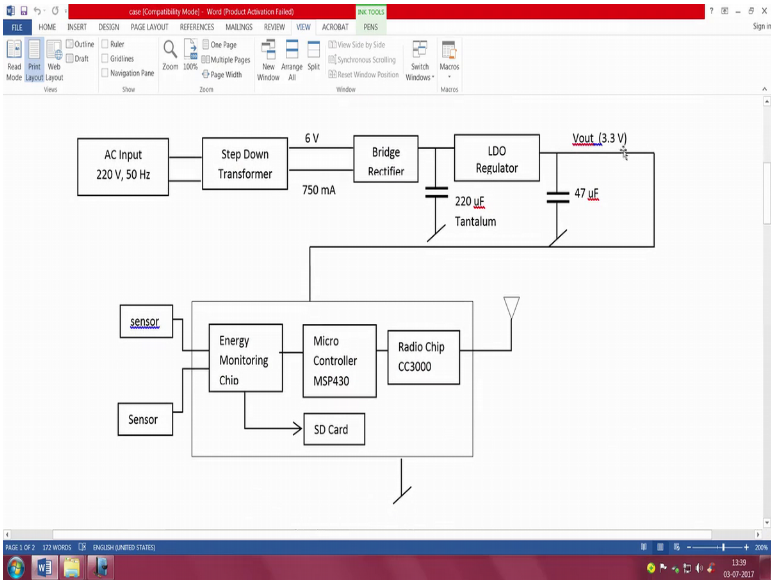

So, this is a very nice number, output capacitor is ceramic he says you can put a ceramic. So, just completing this story here how did the circuit work how is it (Refer Time: 06:46) together. So, you get 3.3 volt output here and as you know the LDO requires an input capacitor and an output capacitor these two capacitors where chosen with a lot of struggle.

And I will show you how finally we were able to overcome that problem before we go into that you have sensor and sensor here. Obviously, there is an energy monitoring chip from analogue devices it is called the a d 7 8 series. So, we use the analogue devices energy monitoring chip, microcontroller here is MSP 430, there is an SD card for storing a parameters and for storing the energy values that have the monitored the sensor values from the energy monitoring chip and then there is this radio chip called CC3000 which ultimately did not work very well for us we had to replace it with some other Wi-Fi model.

But nevertheless this being a at least a four year old effort CC3000 was one of the first Wi-Fi integrated chip for IoT applications and we were perhaps one of the first few to use this chip and also get into a lot of bugs with this chip lot of bugs lot of bugs. So, before it actually they improved this chip and then they brought out CC3300 and things like that. So, lot of things actually happened we will not going to the details, but anyway sensor one and sensor two; obviously, one sensor one is a potential transformer, and sensor two is a current transformer, current measurement can be in made in different ways you can use a simple peat a c t or you can use other types of sensing elements as well depending on what kind of accuracy are looking for you may want to use other kind of current sensing as well there is something called Rogowski coil right.

You can use a Rogowski coil based current monitoring; obviously, you will need a little bit of electronic a small amplifier circuit would be required so, but anyway. So, depending on what in this case we just use a simple are current transformer c t which I will show you as we go along in our building. Now the beauty is not there the beauty is ok.

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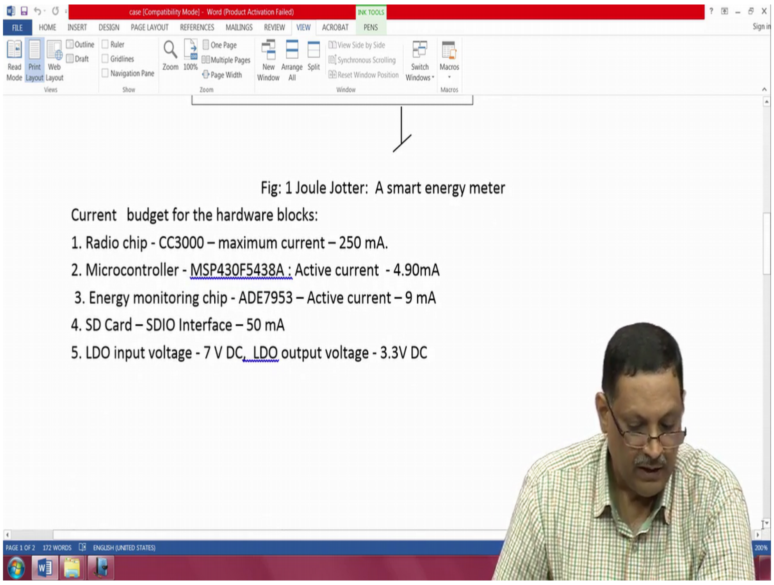

This is all fine good nice nice energy monitor and all that, radio chip I put down the specifications, maximum current is 250 milliampere, microcontroller active current is 5.5 milli in a closed to 5 milliamperes energy monitoring chip which is ACE7953 is 9 milliampers LDO see this is SDIO the SD card for logging all the data requires when you are writing up to close to 50 milliampere and LDO input was seen volt DC and LDO output as I mentioned to you is 3 volt DC.

We overcame and I cho go you gave you those values of two tantalum capacitors and we finally, choose these two those two tantalum capacitors because after lot of struggle because of this picture this is really the problem this is not really the solution look here carefully.

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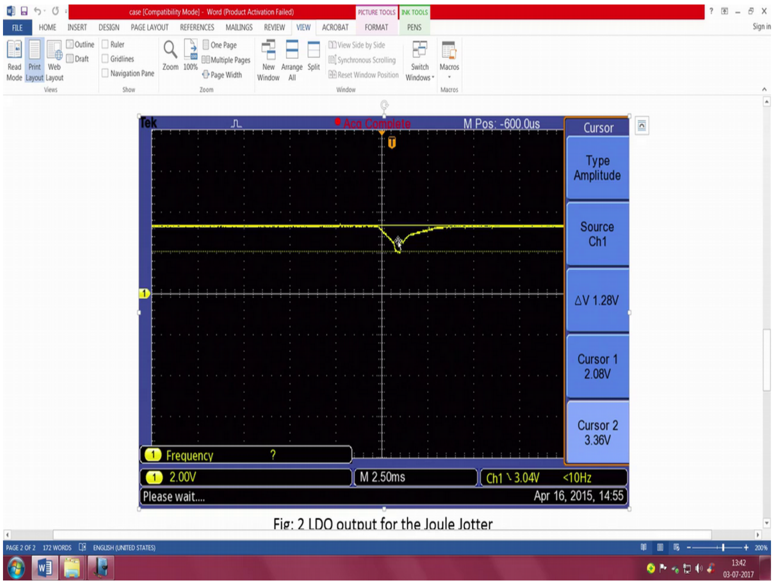

There was a dip in the if you look here, there was a dip in the output voltage and what is the problem when was this dip coming how did I measure that what is the problem statement let me read out the problem statement very carefully for you a snapshot of the LDO it says here confirms this, what does it confirm? The system was working satisfactorily each time data was sensed processed and written to SD card no problem every time you were sensing every 20 seconds or. So, we were sensing the h values we were sensing it and writing it into an SD card no problem.

However radio communication was unsuccessful a snapshot of the LDO output is shown in figure 3 confirms this explain this result and suggest the simpler solution to this problem, anyway the solution is the stability of the LDO where 220 microfarad tantalum input and 47 microfarad at the output actually solved the problem; and what was that problem how did you solve it and why and how did it work.

Anyway the solution to the problem is stability of the LDO it was really out of it was not stable and those values which I showed you actually brought in the stability and when you have problems of stability you will have problems of this nature, where the output voltage actually dipped to a2 volts from 3.3, there by the radio module was not working. Everything was working fine when you did a communication is they had a problem because communication requires a slightly higher power the CC3000 required higher power.

So, how much was that I did not mention its 250 milliampere you can see that. This 250 milliampere current which is required because this is a Wi-Fi transmission right it is a module which has a Wi-Fi chip on board, Wi-Fi technology on board that required a significant amount of current. This LDO is capable there is no problem only issue was stability was an issue because of the input at output capacitors, and because of that the output was dipping to 2 volts and I caught this on an oscilloscope exactly at the time when you wanted to communicate at 3 point this line indeed is the 3.3 volt line it actually dip down to two volts, you can see that each division here each large division here is actually 2 volts I have written it down here and this is obviously, going down to 2volts.

So, really we solved this problem by introducing the by bringing the LDO back into its stable point. So, this is really the whole story with respect to the LDO and nice case study which I wanted to share with you our experience on tuning the LDO for specific for us particular application. So, dear friends this is important look at the requirement of your regulator look at what kind of sensors you are likely to connect look at parameters from the data sheet please imp importantly do not get into too much of theory.

Obviously, you should know a lot of theory before you start using these be before you put your power management block of a IoT system, but look out for these critical parameters which I have mentioned which I have read out to you like accuracy noise PSRR and all that which we discussed actually right and accordingly plan your power supply section of your IoT.

I want to explain one more part in this power supply section which you will have to encounter sometime or the other. So, let us go back and discuss one more part which this is also very important. So, which is called also the charge pump which I thought will be useful before we close and move on to this part right. So, this is what we should be really looking at how to design our power supply with energy harvesting sources before that lets look at charge pump.

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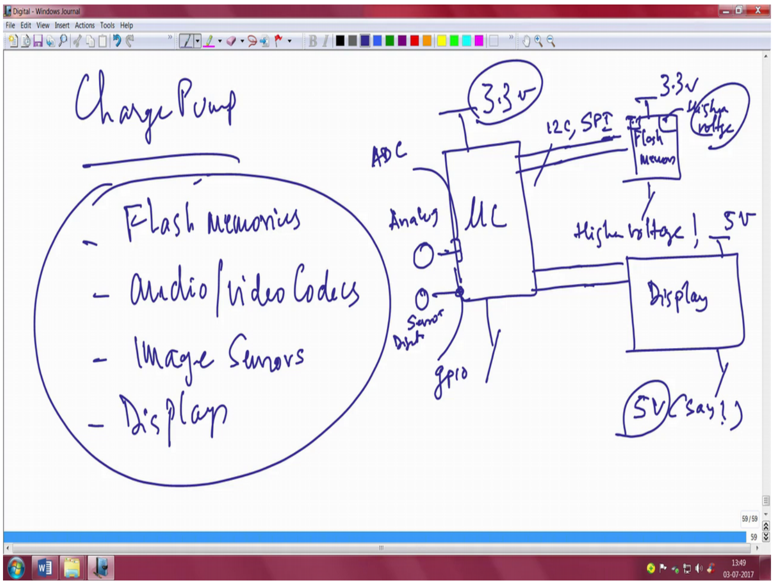

So, the point is this there may be many situations where you will have to a sometimes you will have to live with certain voltages which are actually available to you directly as you know just a minute let me pull out what I want to say. So, sometimes sometimes you will have to power let us say flash memories or you want to flash audio and video codecs you have to power flash memories writing for instance requires higher voltage right.

Audio video codecs or an image sensor for instance requires sometimes a higher voltage right sometimes even this displace right they all require a slightly higher voltages this is the requirement for your embedded system. Let us write on board you have the embedded system, let us say this is your microcontroller this is your rail voltage let us say this is 3.3 volts and there are certain sensors connected to it, if it is an analogue sensor this is an analogue sensor you will obviously connected to the analogue to digital port if the sensor is digital you would obviously connected to the g p i o this is also another sensor, sensor digital right.

Then you have a different buses you have I 2 c, you have SPI this is 2 wire and this is 4 wire and you have let us say other peripherals which are connected through this system it could be even flash memory flash can be available over you will have to connect over and SPI flash or an I 2 c flash and sometimes while writing to the memory location, you will need higher voltages, right.

Or let us say you have an interface this is an interface which essentially is connecting to the display and this display requires 5 volts let us say example say right I will say 5 volts. How do you generate from this 3.3, how do generate this 5 volts. Flash memory sometimes this may still require a rail of 3.3 in which means there is no problem, but when you are writing you will require let us say you want to write to this location when you right to that location; obviously, it needs a higher voltage right, how does it manage how does it generate this higher voltage from this 3.3 well that is a pretty straight forward trick I would not go into great detail, but I will show you a very very simple circuit.

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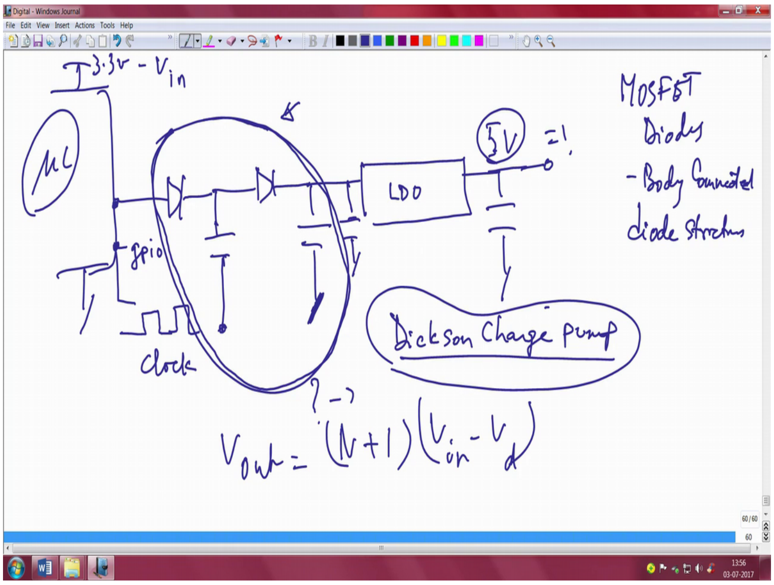

Let us say this is a microcontroller and this is your rail of 3.3 volts and this is ground, what you can do is take one g p i open and construct sorry let me right it well right take one g p i open actually what you should do is you should not you can of course, there is no problem and there are two ways of doing anyway, we will take one g p i o here and you generate a simple program to generate a clock this is g p i p please note this a general purpose input it is a digital port.

So, write a small program to generate a clock and fur this clock here to this capacitor, this I will ground not this and what you will get here is I will put my usual input and output capacitor and I will get I will I need 5 volts right 5 volts bingo you will actually get 5 volts here and what is the circuit I built here this part what is this very simple right go back to your fundamentals and look up you have actually built a Dickson charge pump.

Basically Dickson charge and pump charge and pump is charge pump. So, actually your built a Dickson charge pump. So, and what did you how did you generate this a Dickson charge pump how did you generate this 5 volts? Well ideally this 3.3 should a big have become 6.6, but that is not going to work that is not going to happen because you have diode drops. And therefore, you basically I am not added melt multiple stages as well I have just added one stage and with that I just did one multiplication, and I put back the final stage which is this another diode and this capacitor and then this is nothing to do with the this capacitors nothing to do with the charge pump, this what I have circled it actually is all that is required to create a charge pump and therefore, V out will be N plus 1 times V in minus V d, right.

This is N plus 1 always it will be N plus 1 this is the stage which on which you will store all the energy, and in this case you basically have a single stage here. So, you can see that if you substitute N as 1 here, you will actually get this one and this two their first and second V in minus this V in this is actually nothing, but V in, in this and the diode drops that you see here essentially is the drop that we will occur across this stage and the output should simply be this 2 times V in minus V drop V diode drop which will give you some voltage higher than 5 volts at the output, which you will take and then applied through an LDO and generate this 5 volts. That is it this is a simplest is the simplest possible charge pump that you can think of you can go on adding stages here essentially here I have applied this clock to this stage here.

So, let me rub it and apply this clock here you apply this clock here then from here in stuff grounding this you remove the ground from here and add one more stage and add multiple stages here, but; obviously, you will have to take different clocks right it cannot be the same clock you can apply this clock back at the other third stage generate one more clock and connected here generate another clock and gent and connected to the third stage and so on. So, you can go on cascading this I let you look up Dickson charge pump for you to quickly understand how you can build it, but I give you a very simple circuit by using your existing embedded system itself your microcontroller itself with its own rail you can you can actually build this and generate a stable 5 volt to connect to these display systems or image sensors or audio video codecs of flash memories and so on.

This flash memory also which is you can buy outside and connect it either through I2c or SPI internally will be doing this charge pump it will have a charge pump inside its on chip; because if I will writing you need higher voltage right. So, a in other words this simple circuit which I have circled here this simple circuit we will actually be implemented in silicon and then implemented inside this flash memory and how do you do that, how do you implement these this diode structures in silicon.

Well, you have a body connected MOSFETs, you can use MOSFET diodes, right. MOSFET diodes body connected are very common body connected I will not get into details, but just to note that body connected diode structures can be easily built structures can be easily be built in silicon and you can essentially build this Dickson charge from topology are quite well. In fact, there are many types there are cross coupled systems and so on we will not get into detail.

This in a sense means that your power supply section you will you can use an LDO under certain conditions, you can use a buck converter under certain conditions you mean require a charge pump under certain conditions the right depending on how you have to lay out your circuit, and this in overall you can also quickly build I have build this in the lab and I have actually tested it before I will let you know that this actually works.

You can choose components accordingly and build this a simple systems to get your embedded system, IoT device with different rail voltages requirements a very very effectively. So, this is the story on this devices let us now go back and reconnect to this picture that we mentioned that this power supply is an intriguing part and you can build it with battery as an input, you can build it with ac as an input you can build it also with harvesting sources as the input where solar tech vibration flatter linear motion and so on can be used.

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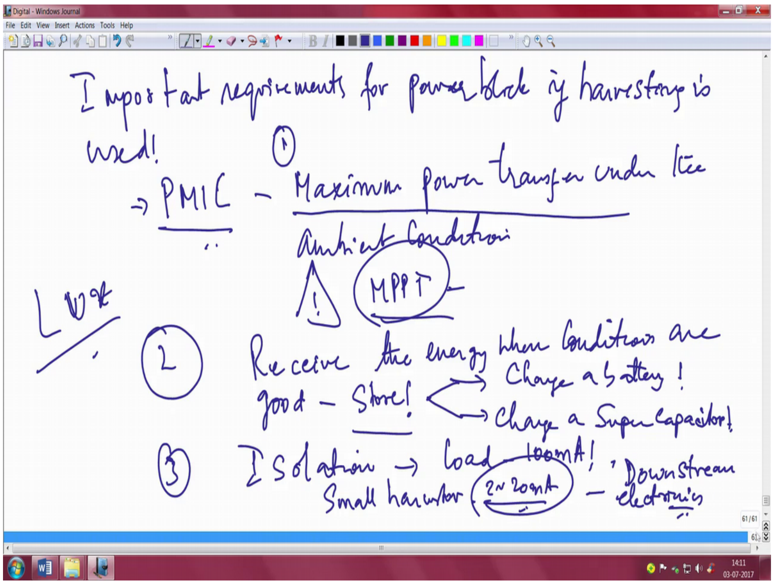

Let me now highlight to you some important requirements for power block for power block if harvesting is used this is the most important thing. So, let us go and focus on this is the important requirements for the power block if harvesting is used, as you know and harvester is a what is an energy harvester? It is basically nothing, but an electrical power source right I will ultimately you are interested in electrical power right you are not interest you are more insert interested in the electricity is essentially the purest form of energy right. So, that is what you are looking at because most of the electronics most of the IoT embedded devices that we are looking at actually run from electrical power.

So, you are looking at energy harvester which is nothing, but in electrical power source it basically operates by absorbing some form of absorption is there absorbing energy somehow energy in some form and providing you absorbs energy and provide energy right provide electrical energy. So, if you say absorbing energy in one case it is solar energy absorption, if it is take it is in terms of temperature differential right in the form of temperature differential nothing, but the thermoelectric effect nothing, but the thermo takes an nothing, but we use the. So, in one case it will let us get the physics right one is photovoltaic effect photo voltaic effect and the other is the thermo electric thermoelectric effect this is the physics behind generation of the electrical energy right.

So, again I do not want to get into the details of all of them, but what is important is, if you are looking at energy harvesting the power management from a power management I c perspective these are basically some basic requirements. So, I will run this out. So, that you just note that these are concepts from physics, but very importantly what are these requirements if you are talking of energy harvesting, I c which you want to build you want to be used an existing energy harvesting I c which is available out in the market. You want to use a solar panel, you want use a thermoelectric generator, you want use a wind energy micro wind energy, you want use linear motion all these systems are there already out there, how do you interface those energy harvesting sources to your embedded systems such that you will have a perennial working of the complete system that is the goal right you do not want to keep going and replacing batteries.

Or you may also want to do that I will do all the harvesting for charging array chargeable battery that is also another paradigm for example, if you are talking of let us say very critical operation like for instance you are interested in a variable, and healthcare parameter has to be monitored.

If you say that I use a solar energy harvesting means that only this variable should be worn during the time during the day you should have sufficient sunlight and only on the duck condition the variable actually is able to work, because that is a time when the energy is available. You obviously, do not want such designs it should be seamless it should work 24 bar 7 it should be able to do the monitoring for you and all that which means you have to put a battery.

Battery is fine, but you do not want to replace the battery for a long duration which means you may want to keep charging the battery you do not want to find a charging point where you are to go and you know consciously go and remove you available and then actually connect it and then actually you want to charge it, that is also not something which is very practical.

So, you must be able to wear it and (Refer Time: 30:02) it will harvest energy and then basically charge the battery which is intern use for driving the load. So, energy harvesting can be applied in many scenarios directly by harvesting energy you derive the electronic or harvest store the energy by storing the energy means charging the capacitor or charging the super capacitor or putting that energy into a rechargeable battery. So, that the battery keeps charging all the time. So, that is these are the two basic things.

Anyway, essentially if you talk about energy harvesting I see it should provide the necessary electrical interface to the harvested to ensure one important parameter is the maximum please complete it if you already know power transfer under the ambient conditions. See slowly from LDO to buck converter to charge pump we all mentioned many of these systems all of them made an assumption that there is an input voltage available input which is in is available. So, that you get V out.

But now you are changing your hat you are saying I do not know when V in we will come and I to do a few things in order to make it work. So, one thing if you do not know when V in is coming the second thing you want to do is if V in comes how to extract maximum from that V in how to get maximum power from whatever energy is available how do you extract it maximum. So, energy harvesting means maximum power point maximum power transfer, which means maximum power point tracking becomes an important requirement for energy harvesting power management systems sometime.

So, this is number one very very prime to a energy harvesting circuits and second thing is received the energy output when conditions are good received R e c e i v e right receive energy received the energy when conditions are good and store this store very important store this energy where do you want to store this energy; charge a battery charge a super capacitor both of them we will allow you to charge the energy charge what whenever it is available.

Then third thing which is a requirement would be to manage the power transfer you have to ensure that there is isolation, basically you have to look at isolation what do you mean by isolation? This is not really either galvanic isolation or any of the electrical isolation the isolation transformer for instance does a isolation between the input to the output so that you essentially when your operating at lower voltage is from high voltages this isolation allows you to create your own ground for instance and work in the lower voltage domains, it is not that isolation.

When you talk about ma power point I mean when you talk about energy harvesting, isolation means here in the context of load may require let us say 100 milliamperes suddenly, and what you are you have is a small harvester you have a small harvest. So, which gives maybe a let us say anywhere from 2 to 20 milliamperes based on the conditions which prevail at the by the harvesting sources like if it is there is a lot of sunlight you may get more than 1 lakh 50,000 lux, or even 2 lakh lux in bright sunlight or you may end up with the 200 lux, 100 lux if it is inside indoors right 100 lux, 200 lux is indoor solar panel 100 lakhs 200 lux indoor, 2 lakh lux bright sunlight and if there is a cloud it is down to 50,000 lux outdoor it is down to 25,000 lux outdoor cloud passing by 2 lakh goes down to 50,000 may even go down to as low as 25,000 as low as even 10,000 lux, 5,000 lux and then again go back and pick it back to two lux.

Sometimes when there is a lot of cloud when there is monsoon season the sun is not out you can even have 10,000 lux over a extended period of period during the da, which is very very low the same panel which saw 2 lakh lux l u x lux right l u x essentially is you will seeing a very small lux value. So, the energy is fluctuating input energy in the form of sunlight photovoltaic the sun energy call it or the light energy call it that is fluctuating.

And therefore, whatever is the input you should be able to extract maximum at the output that is why you need these MPPT and load, let us say requires 100 milliampere I give an example, but the input currents are fluctuating between 2 milliamperes and 20 milliamperes you must be able to essentially isolate the electrical load on the downstream basically I mean isolation downstream electronics ok.

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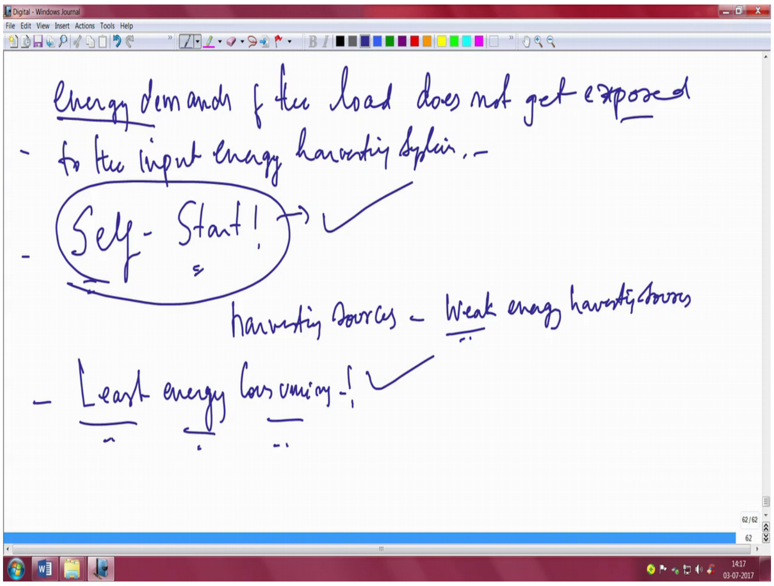

Downstream electronics has to be I isolated in a manner that the energy demands of the load right of the load energy demands of the load does not get exposed that is what we mean by isolation in this contex, does not get exposed to the input system input harvesting system you cannot say input system any more energy harvesting system; because if the load gets connected directly to the harvesting system there is no way by which the load is going to get that power right you have to do that isolation that is a very important things.

Another important thing I am tell you this is something that in the last many years researchers have spent a normal time and energy trying to understand what is a clever circuit in energy harvesting, what is that magic mantra, how do you ensure that energy harvesting circuits become very novel reliable. And all kind of let us say the hype the wow factor of an energy harvesting circuit really comes from one important parameter and that indeed is self start self starting.

So, many people's you will see in literature we says I will do a I am we will be able to do self starting. See what does it mean it simply means if you do not have a battery base system the whole electronics is going to work with just my harvesting electronics, let us say essentially means this is an application which is let us say doing ambient ma energy monitoring, where you are not really worried about the ones that I mentioned to you about a variable electronic.

This obviously, you have to put a battery and use a harvesting for charging the battery it is not that example, these are other example where you are essentially looking at ambient monitoring you want a sample let say every 5 minutes or 10 minutes or every hour, that electronic is completely energy harvesting based and that electronic you want to self start, because your starting with 0 energy to begin with some how you will need to kick start the whole electronics and kick starting the electronics to start working itself means that self starting is a very important thing and all the smart electronics all the wow factor for energy harvesting essentially hinges around this one important parameter which is indeed the able to do its ability to do self starting.

Why is this important because harvesting sources I do not have to say this, but I just want to derive home that you do not forget this important point. Harvesting sources are weak energy sources low grade right weak energy harvesting sources. So, you can be asking I have an energy. So, at the end you can say I am building this energy harvesting circuit and the other person can say is itself starting, have you solve the problem of self starting have you avoided that have you solve the problem of isolation of electrical loads which require higher energy, have a done that isolation effectively, does your circuit take care of that isolation very well, what is your input energy what is your source for instance when you say weak energy are you trying to look at energy which is for coming from Indore or is it out door and so on and so and so forth.

Finally this is a dream which we have discussed even in the other world, I just want to put back the same dream and the same story all over it itself should be least energy consuming right it is not a big deal, but this is a very important point. So, it should not be a power guzzler itself least energy consuming, which means you have to worry about the quiescent currents you have to worry.

It cannot be like the other examples where you can have 0.58 milliamperes, because you are drawing input power from let us say from the grid mains and you can afford to LDO for instant that LDO example which I mention to you in the last classes was actually taking 0.58 milliamperes you cannot afford that kind of currents because this is actually a harvesting and precious harvesting energy is being used. So, the electronic itself should be least energy consuming.

So, what are these big problems what are these big bullets when you talk about energy harvesting before we go into circuits, before we going to simulations is that it should do MPPT number one requirement, it should be able to receive energy when conditions are good and store these energy two possibilities of storing energy, it should do isolation of a different type essentially downstream electronics which where the emerging demands of the load does not get exposed to the input energy, energy harvesting system should be avoided, you should do that isolation it should do self starting and it should be least energy consuming itself.

Now we will launch ourselves into different energy harvesting is we will look at those simulation circuits and we will look at building those circuits and I will also show you a practical examples as much as possible for you to say how can I build this power block of my IoT system such that it can have an energy harvesting at its input energy harvesting source as its input.