Design for Internet of Things
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Lecture - 15
Energy Harvesting - 03

If you have applications where there is a lot of waste heat that is available, then the possibility of applying thermoelectric generators is pretty attractive.

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What I have with me is a thermoelectric generator. It is a flat piece as you can see, with the two wires coming out one plus and one minus what is its thickness very very thin. There is one surface here, there is another surface here and in between there is something sandwiched these are essentially services which can withstand a lot of high temperature like ceramic and so on.

So, material is a very important thing, and some composite material will be there it can stand very high temperatures. Now, the idea is this high temperature if it hits this side, and you expose; you connect this high temperature side to a surface which is hot and this side is not touching then there is a differential between the two and the differential is sufficient for generation of some power on these two points here.

Essentially, what this actually means is there is a principle in physics, which you might have studied, and that is related to Seebeck Effect. So essentially you are talking about a hot side and a cold side, and some material which is sandwiched in the middle that material that is sandwich comprises of P and N type heavily doped P and heavily doped N, one giving you access in electrons the other giving you access in holes and then you have the combination of electron hole combinations which actually will result in flow of electric current.

So, this Descemet this P and N are all connected to the same surface, on the top side and on the bottom side. So how it is equivalently if you want to imagine how it is to be shown equivalently you can think about this picture.

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Which I want to flash here, see here, you have a heat source on top, you have a cold source on bottom here and you talk about P and N type materials, that means your material A and material B, and you are essentially looking at flow of electric current from the hot side to the cold side, this is the rate of heat flow from the hot side to the cold side, and this is the rate at which the heat is being rejected and the cold side.

QL, H to L there is a difference in the temperatures, which results in a flow of electric current from the two different materials which are sandwiched in the middle as. I mentioned one is P and the other is N, what actually happens is if you connect the load, you will get some electrical output. So, if you take apply a heat source on the H side on the hot side, and on the cold side you are rejecting the heat what you see is some load electrical output power output which you can actually visually characterize.

Supposing you connect a resistor supposing you connect an LED you should be able to see an LED glowing as long as there is a temperature differential here, or you can also drive a sensor you can drive an embedded system, you can drive an SoC which has a controller and other related components. So, all of that is possible provided you maintain this temperature differential.

So, this is a nice picture and this picture we got from this paper, Thermoelectric Power Generation Using Waste-Heat Generation as an Alternative Green Technology. Anyway, there is heat potentials and waste heats out there, in several factories where there are furnaces and all that. So, you want to tap from that and you want to drive your IoT sensors, and that is something that you can easily do in your labs.

Well, this paper also talks about several advantages of doing it this way. It talks about solid state device that provides direct energy conversion, from thermal energy due to temperature gradient into electrical energy which is based on seebeck effect. They are reliable, they are simple and compact. They are very small size and virtually weightless, capable of operating at elevate temperatures, suited for small scale and remote applications, environment friendly, they are not dependent on any position.

They are only dependent on the fact that there is a source for energy which is essentially the temperature differential, and they are flexible power sources. The problem with these tags is the low efficiency in conversion, that is only problem. And that is again brought out by this paper which says, power generator is relatively low conversion efficiency typically 5%, again there is a reference in this paper, which talks about that number.

And how do you calculate the the efficiency of the system? Well, efficiency is what you feed in QH and what you get out this is in the thermal domain. This is in the electrical domain. If you take the efficiency, it will simply be We by QH, which is shown here already in this equation. I will show you that directly here you can see this this expression simply says We equations We by QH which is essentially the equation.

So, now, you must know a little bit of theory in order to understand how this thermoelectric generation actually works, I mentioned that it is based on seebeck effect. So, let us see a few things associated with thermoelectric generators, particularly figure of merit, which is an important thing. So, let us look at those simple expressions which are out there. Now basic theory.

And operation of the thermoelectric is based on that as I mentioned seebeck effect, the idea is when a temperature difference is established between the hot and the cold of two dissimilar materials metals are semiconductors a voltage is generated. This is based on the seebeck voltage it is also called the seebeck voltage. In fact, this phenomenon is applied to thermocouples as well, in thermocouples which are using dissimilar materials is also the same thing is actually applied there also.

And you get the thermocouples that are extensively used for sensorsing temperature measurement, at temperature very accurate temperature, measurement means people use thermocouples based on the seebeck effect, thermoelectric devices can act as electric power generators. Actually, it is the same thermocouple, but here you are extracting the power, reducing that power and you can see as shown in figure one heat is transferred at a rate of QH, from the high temperature heat source.

Which is maintained at this temperature which is TH, and it is rejected at a rate QL, right is the rate at which it is rejected is QL to a low temperature sink maintained at TL. TL is the cold site temperature, based on seebeck effect the heat supplied at the hot junction causes an electric current to flow in the circuit and electrical power is produced, using the first law of thermodynamics.

The difference between QH and QL is the electrical power output We. So, very simple straightforward application of law of thermodynamics. Further it goes on to say it should be noted that this power cycle intimately resembles the power cycle of a heat engine, the Carnot engine does in this respect a thermoelectric power generator can be considered as a unique heat engine in a way good.

You can see that the electrical output is shown here, there is a ceramic plate which is here this is a heat source, the rate at which the heat is flowing is to QH, the temperature of the hot side is TH, QH which is the rate at which it is flowing TH which is the temperature of the hot side and the QL is the rate at which the heat is being rejected. TL will be the temperature at the cold side.

These are all the thermo elements which we made, which we mentioned and then the electric flow so, it is a beautiful, nice picture that the paper talks about. Now, the performance of this thermoelectric materials which are in between the two top and bottom surfaces can be given by this expression Z is alpha squared by k R, very quickly the Z is replaced with ZT dash.

You can think of multiplying this left-hand right-hand side by the T dash which is nothing but the average absolute temperature of hot and cold plates of the thermoelectric module. So, this expression one becomes 3 in this form. ZT dash is equal to alpha squared T dash divided by k

R and T dash itself is what? Very simple, hot side plus cold side divided by 2, which is the average.

This term alpha squared by R; which you see here in this expression alpha squared by R or here you must be looking at this alpha squared by R, what is this? That is the key point. The alpha squared by R is referred to as the electrical power factor. In general, a thermo electric power generator exhibits low efficiency due to relatively small dimensionless figure of merit. The unfortunate thing of why it is low in efficiencies.

Because this ZT dash, which is the average relative figure of merit, is that ZT dash which we said is typically, if it is close to 1, you are already good, but usually it is even less than 1 that is the problem. And if these that ZT dash becomes 2, 3 and all that it is fantastic, you will have very high the efficiency conversion efficiency will be so good, that it becomes comparable to other energy harvesting sources as well.

So, the problem is this is that ZT dash is less than or equal to one and that is the trouble case. The conversion efficiency of a thermoelectric power generator is defined as the ratio of power delivered to the heat input heart junction of the thermoelectric device and is given by this expression, which is out here, which I mentioned to you is the actual efficiency one to a numerator is more expressed in the electrical domain.

And this is the heat domain or the thermal domain. Limited by second law of thermodynamics the ideal efficiency of the electric power generator, the ideal efficiency of the thermoelectric generator operating as a reversible heat engine is given by this Carnot expression 1 minus TL by TH. And the power conversion the maximum conversion efficiency of an irreversible thermo electric power generator can be estimated using this expression.

Then what more can we say the, I think this is being emphasized here. So, let us look up this today's most thermoelectric materials such as Bismuth Telluride based alloys and Lead tellurite-based alloys have ZT value around unity that means, it is that ZT dash is around close to 1. However, if you have 2 to 3, then it will become competitive with other power generation sources.

So, the figure of merit of Z of a number of thermoelectric materials together with the potential power generating applications relevant to waste is shown in figure 6. So, you can see that different materials are shown, and the figure of merit is actually shown also. What you see is this picture here is essentially the datasheet of a company, this is the specifications of the TEG module, and you can see high temperature is 300 degrees Celsius cold side can go up to 30. So, you can heat up to this much.

Open circuit voltage is 8.4, matched load resistance is 1.2, match load output voltage is 4.2 match load output current is 3.4 amps that means under ideal conditions if you match the impedances, these are the outputs that you will actually get as a maximum possible power. So, you can get up to 14.6 watts and not anything more than that, these are absolutely critical for you to understand these graphs.

Now, what this is saying is the X axis is the hot side temperature and the open circuit output voltage is shown in the Y axis. You have three pictures, and you can see that if the temperature differential between the hot and cold are maintained high, then you get really good output that is obvious here. You can see cold side at 50, you maintain at 50 but you maintain the hot side at 150 let us say.

So, what will you get here, you can see that 150 hot side means, you go up like this, you touch this point, you get this point here? I am looking at the red because the cold side is fixed at 50 degrees that is shown here. Similarly, if the cold side is fixed at 30 you are able to maintain at 30. So, the same 150 you get much higher out open circuit voltage. So, this is telling you directly if your temperature differentials are good, you are able to maintain the temperature differential your open circuit voltage is also will be useful.

Same thing happens in the right-side picture, you look at the match load resistance. Similarly, matched voltage output again that has a bearing on the cold side temperature, match load current also has a bearing on the cold side temperature. So, all the time it is about temperature differentials match load output power also has a bearing on the cold side temperature. Power output is maximum here as you can see.

So, this is open circuit this is short circuit. In short circuit voltage goes to 0 and current becomes infinite, here current is 0 open circuit you get the highest output voltage. So, you must balance and get a proper output power which is appearing at this point. So usually this is the same way by which even solar panels actually shown. So, essentially the chart for output voltage and output power Vs output current under Th 300 degrees and Tc 30 degrees, high side is 300 and low side is 30 degrees is actually mentioned here.

So, this is about understanding the datasheet. So, we will now do a demonstration and then wind up this discussion on thermoelectric generators.

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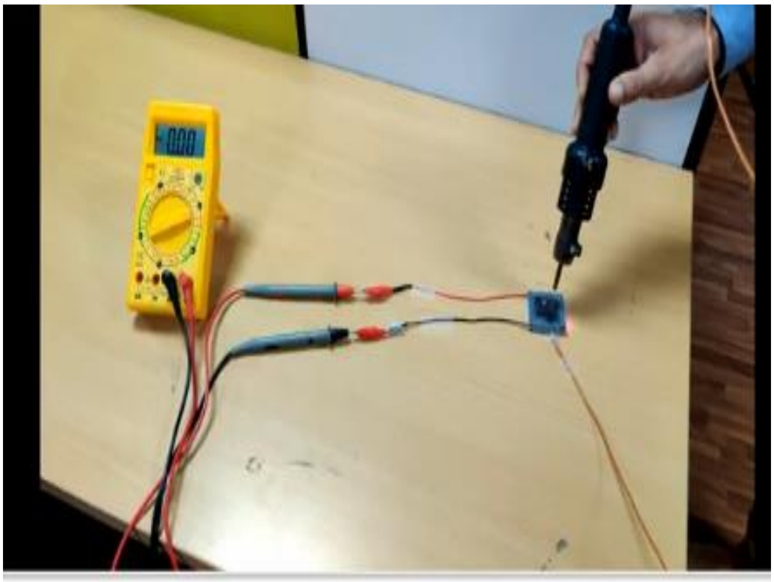

So now let me point you to a small video that was shot by our colleagues. What you see on the left side is a multimeter which is essentially measuring the open circuit voltage. Nothing but two probes, you can see here, these are two probes, which we have connected to the TEG output. Now here is the TEG top you can see that our colleague has held a hot air gun. This is a hot surface, it is trying to hit that surface, so that it will create a hot surface down this wire is the cold side that is mounted to the table.

So, it is fixed to the table and you are measuring the table temperature, in other words, the tag is placed on the table and you are measuring the temperature of the cold side. So let us see what is the temperature differential you will get. And for that temperature differential that you get what should be the output voltage that also you should know correct, then you will be able to go back and say more or less my way of measurement is; and also, that I am able to control the losses quite well and as per datasheet, I am getting some number.

If you are not getting that number definitely you are not maintaining the differential in a strict manner, you may be able to measure the differential, but you may not be able to maintain it. Then what will happen the hot will go and percolate to the cold, the difference will come down, and then the when the difference comes down the output voltage also open circuit voltage also will come down.

So, the whole game will be how much of output voltage can I sustain, in a in a steady state how much can I sustain that voltage? So that is what we will have to know. Getting a differential voltage maintaining a certain difference for a very short duration is not going to help in a practical manner. So, you must be able to see how to sustain that temperature differential. So let us run this demo. So let me press the start.

So, you can see the demo has started. A hot air gun is blowing hot air onto the hot side. Cold side is a wire this wire I will take and connect it to a spot measurement of temperature. There is a temperature gun which I can use, which I can point a beam and measure's spot temperature. And cold side also I will measure using the temperature gun. This is a hot air gun. This is a temperature gun. What do you see?

Hot side is at 49.4 degrees pretty hot and the cold one is at 33.4. So now you know that, and you are getting 0.8. Now that is not the point. The point is you have purchased a tag, and does it measure for the given data sheet? Are you able to get that difference in temperature is the question? Let us look at this picture. You can see that we measured the cold side of around 33 degrees or so.

So, I will take this as temperature of 30 degrees, that is this black line and now the hot side we got around 49 or 45, anywhere it was fluctuating between 45 and 49. So let us say 50 degrees, even if you take 50 degrees, and you take this black line, it is coming close to 1 volt. It is coming close to 1 volt, what we were measuring was about 0.8, sometimes even it went upto 0.85 and so on. So, you are getting around that range.

So, this demonstration tells you that you can apply these tags and actually get useful voltages for driving your embedded IoT nodes with harvesting sources, we deliberately did not take solar, because I am sure you will be able to do the solar part. This is something exciting, something interesting, please consult the data sheet every time you do a measurement, and you do a check, because data sheets hold a lot of value when you want to purchase a particular TEG.

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So, what we will do now is we will show you another energy harvesting demo. This is through the NFC system that I mentioned to you. What do you see here is this pulse, finger pulse sensor, and all the associated electronics. But let me point you to the document that is down here, this is the document of interest see you can make a pulse measurement by putting it on the finger.

And in the COVID times, this is the best you can do. You do not need to be in contact with the patient, you just come with a mobile phone, the nurse or whoever the caregiver can come with a mobile phone and read off the value. There you have to keep the NFC phone very close to the system here. And I want to show you how it is actually done, how the same pulse sensor is actually modified to power through a energy harvesting source.

And let us run through this document once. What does it have, we talk about the pulse sensor, it talks about the various parts, which comprise of the pulse sensor, the velcro tape, and so on. It talks about where all you can make a measurement, the structure the PCB that is associated with it, the colour coding of the wires. And how do you prepare the pulse sensor for making a measurement connected to a required microcontroller to acquire the data.

And then here you get the pulse sensor, which you can actually see on the right side is 64 beats per minute, which is clearly showing the value. So, all of this is something that you can actually do with this pulse sensor. It is not necessary that you need to put it only on the finger. You can also put it on the ear, so read this document it is freely available on the internet you can download this document.

And you can try see the way he has shown the instructions on how it should be clipped, and then the Velcro along with it and also the ear you can also put it to the ear. You can see on the right side here it is actually placed on the ear for making a measurement on the pulse. So, the idea is read this document, it is freely downloadable, you have seen the name out here. It is called Pulse Sensor.

You can buy it also at some low cost. It is called pulsesensor.com you can go to that website and see this is one part of the thing the other part is to see an actual demonstration. Did we how did we pull off this energy harvested pulse sensor measurement? Let us go to that. Let us see the different parts that we have put see this one is a NFC coil this is that 13.56 megahertz NFC coil, which actually is the receiver side the transmitter is nothing but the mobile phone.

And it is coming closer to this coil it charges it induces a certain amount of voltage output that voltage output is stored into a capacitor what you see this flat thing here is actually a super capacitor, it is all that energy stored there. And once the energy stores smart piece of electronic which will switch on the say the electronics down below and then once the electronic switch is on, the power to this sensor is also made available the whole system has sufficient power to make a reliable measurement.

All it here is a mobile phone, and which essentially is NFC enabled. Here is the finger of Vasanth and there is Abhishek who is placing the pulse sensor on top of it and they strapping it nicely using the Velcro and gives the NFC coil to place it on the palm of Vasanth and brings the phone closer to this coil, almost in close contact with the coil. And now the energy is getting pumped into the electronic embedded piece of electronic through the NFC system.

The NFC system is actually powering the system and charging the super capacitor. Now it has to be placed for a certain amount of time. This time is actually what you can actually measure even from the video, the amount of time required for charging the supercapacitor and making a reliable measurement. So let us see very soon you should be able to see the value there you are, you get the heart rate, which is 91.

An app was built also in the lab. And this app will actually make a measurement of the heart rate are nothing but the pulse of the human.

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So, this is a demonstration of what you can do with the energy harvesting systems particularly in the COVID times where you want to have certain amount of physical distance from the patients. Thank you very much.