Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Module - 09
Digital Control Implementation using Microcontroller
Lecture - 85
Practical Implementation of LLC Converters (Part - II)

Welcome to another session on the Digital Control Implementation of Power Converters using Microcontrollers. In the last lecture, we have seen how we have implemented a 2.5 kilowatt LED charger starting from the basic principles of how to address the power plant, the magnetic, and the feedback system. And in this episode, we will show you a practical implementation of a 6-kilowatt converter operating over a very wide output range from 200 to 1000 volts.

In the previous lecture, the system was based on a hybrid control system and the output voltage span was from 40 to 60 volts. In this particular lecture, we will show you a system that is of 6 kilowatts. And it spans from a range of 200 to 1000 volt using a very unique scheme of output bus switching which is implemented fully using digital control. So, let us have a deeper look.

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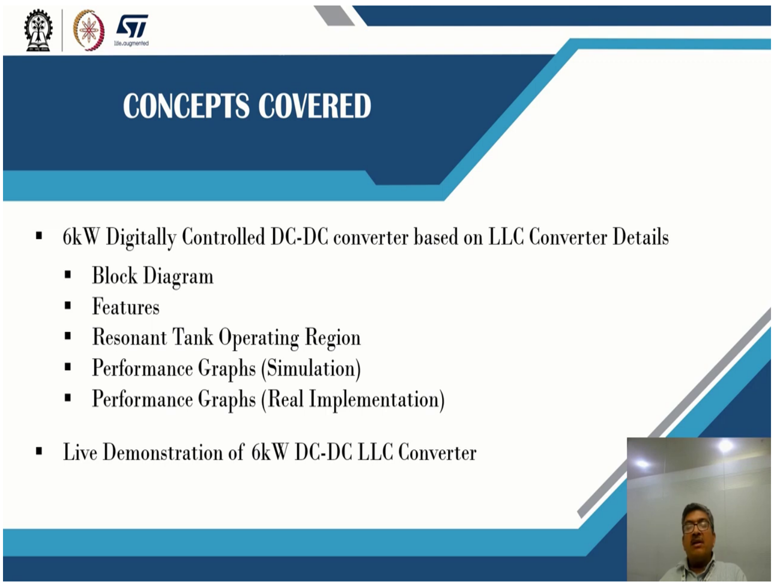

In this particular episode, we will cover the following topics. We will essentially show you the 6 kilowatt digitally controlled DC-DC converter based on the LLC operation. It will be again like the previous lecture, it is also full bridge LLC. We will show you the details in the later slides. We will start with the block diagram and how the system operates under digital mode. We will proceed to its features the detailed feature set that makes the solution very flexible.

We will also show you the resonant tank operating region which is one of the key design aspects for designing any LLC or any resonant converter. So, here in detail, we have shown the different gain curves the different simulation results that we have observed, and how the simulation results are matching very clearly with the actual results of the actual system. The performance graphs would be shown both in real-time as well as our observations that we recorded when we were doing our set of bench tests.

Then; obviously, we will move on to the actual live demonstration of the system using real-time loads. And we will show you based on how the user inputs from the microcontroller you can see the output voltage and the tank current and the regulation and the gate drive and the ZVS happening all under one oscilloscope screen, you should be able to see. And I hope you would find this session informative and would apply the principles and the learnings to your designs henceforth.

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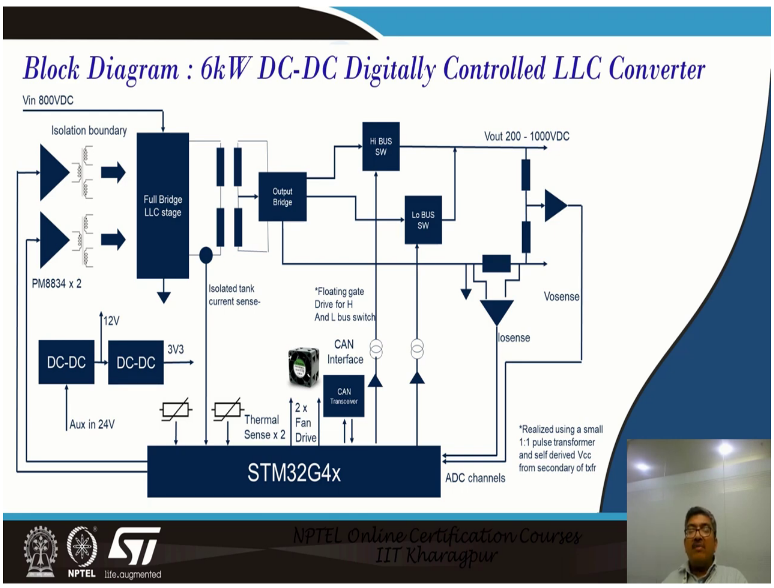

So, on this slide, you should be able to see the block diagram of the 6 kilowatt fully digital LLC converter. So, again this is a full bridge power plant that we have implemented. So, on the bottom left, we have the housekeeping supplies which provide the supplies for the gate drivers which is 12 volt. It provides 3.3 volt for the microcontroller. And it also provides an isolated 12 volt for the other functions like the output current sampler and the output voltage sampler.

There are some isolated voltages for driving the floating MOSFET structures that we will show in a later slide and also for driving the fans. On the top left side, you can see that the galvanic isolation between the power plant and the main MCU control stage has been provided using gate drive transformers. These are parts from a pulse electronics company based in the US. And these are 1:1 transformers with a very high volt second product.

These have close to a 250-volt microsecond of volt second product which allows it to be used from down to 65 kilohertz up to about 200 kilohertz in this implementation that we have done. So, here you can see there is a transformer. So, we have done this realization using two schemes one is with two transformers and one is with a single transformer. So, these transformers are wound on ETD 59 cores and two transformers can handle up to 8 kilowatts.

Possibly even 9 kilowatts, but we have tested only up to 6 kilowatt due to measurement constraints. And we will later see a very unique secondary side rectification structure that allows a very wide output range to be available from an LLC converter. Typically, an LLC converter works with a fixed output voltage or with a fixed input voltage, or with slightly varying output or input voltages. But typically when you try to operate an LLC converter over a very wide voltage range because it is a pulse frequency modulated system it also means that the frequency excursion must be very high.

If the frequency excursion becomes very high the efficiency starts dropping. The efficiency starts dropping in the magnetics, the efficiency starts dropping in the output rectifiers, the efficiency starts dropping due to increased switching loss in the MOSFET, and the efficiency also starts dropping due to inadequate dead time for obtaining ZVS. So, many things in combination start happening when the frequency excursion around resonance is increased to target a very high operating range.

So, the only way to maintain very high efficiency is to somehow limit the frequency excursion around resonance. That is what we have tried to achieve and we have used the

STM32G4 controller which generates the PWM, which accepts the output voltage and current samples. And the STM32G4 core can take decisions and perform all the digital modulation to drive the primary side edge bridge of the power plant.

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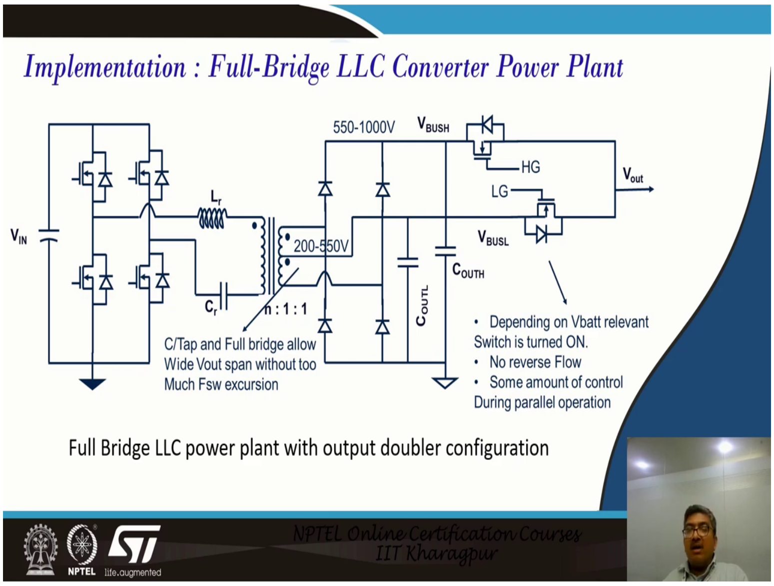

So, this is a more detailed block diagram of the actual implementation of the very wide range wide-range. Now, this LLC converter was designed to be used in electric vehicle charging stations. And electric vehicle batteries can range anywhere from 250 volts to 850 volts. So; that means if w consider discharged batteries and fully charged batteries, the total excursion the total voltage excursion or the total voltage span required at the output would be from 200 volts up to around 1000 volts without any human intervention.

Now, this system has been designed in such a way that on the left-hand side of the system, you can see it is a standard full bridge as I explained earlier, but we have done some tricks on the secondary side. If you look at the secondary side, the secondary side is a combination of a full bridge and a sorry it is full wave and the full bridge scheme. We are using the center-tapped full-wave scheme when this MOSFET is selected and this MOSFET is switched off when the battery voltage is restricted to less than 500 volts.

If we need something in the range of seven hundred volts we turn off this MOSFET and we turn on this MOSFET. So, when we connect the battery to the V out terminal, the MCU of the system can communicate with the battery and sense the battery voltage. For example, if the battery voltage is less than say 450 volts, it automatically decides that the low side or the V BUS low the low bus MOSFET has to be selected.

So, if this low bus MOSFET is selected and this MOSFET is the upper MOSFET the high bus MOSFET is turned off so; that means, these two diodes have no function and we are operating the LLC converter in a secondary center tapped mode. So, you can see this diode and this diode has gone out of operation only this diode and this diode is operating and this is the center tap.

So; that means, you get a voltage that is essentially half that of the full bridge configuration. So, depending on what the voltage of the battery is you can switch the mode. So, the MCU determines which mode to select either it will select the high bus or the full bridge mode or it will select the low bus or the full wave mode to charge the battery.

You see in this entire switching process we are not playing around with any parameter on the primary side. So; that means, its point of resonance and the point of operation or the frequency excursion are entirely in my hand. And I can limit my frequency excursion for obtaining a very wide voltage by essentially dynamically changing the rectification scheme from full wave to full bridge; from two diodes to four diodes.

This is done using high-side switches. You can if you notice the structure of the switches later from the slides or from the video you will be able to understand, these will never cross conduct and there is no possibility of ever any current back flowing from the battery to the power plant, because of the unique configuration of the high side switches on the two voltage buses. It might seem that the high bus and the low bus are sorted together, but no these two are mutually exclusive.

If the high bus MOSFET is switched the low bus MOSFET is switched off. If the low bus MOSFET is switched on the high bus MOSFET is switched off. So, these are high voltage low resistance MOSFETs that have been used to do the switching, and just by the addition of two switches and some glue logic, we have been able to achieve a very wide output range LLC converter.

We have not sacrificed efficiency, we have done both experiments using two separate transformers and without this scheme in which case the operating span was from 85 kilohertz to 180 kilohertz. And the efficiency was in the worst case from 91 percent to 97 percent.

While, when we adopted this scheme of using dynamic bus switching of the high bus and the low bus depending on the battery voltage, the worst case efficiency became 94.5 percent, and the best case efficiency became close to 98 percent.

So; that means, we have gained an efficiency of 3.5 percent over the entire operating span by using this unique scheme. Now, a 3.5 percent efficiency gain in a public charger spread over many thousand hours of operation reduces the total cost of ownership and the total cost of energy by a significant amount.

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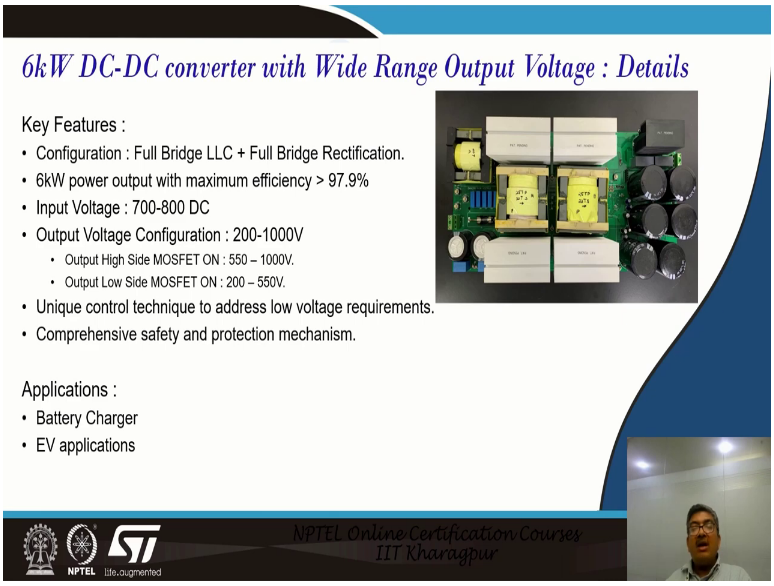

So, this is a real system a top view of the real system. We will show you in great detail later when we go to the lab and there is a dedicated slide also. So, as I mentioned earlier, this is a full bridge LLC and the full bridge rectification combination. It has a 6-kilowatt power rating with a maximum efficiency of over 98 percent. So, I explained earlier. So, the output voltage configuration can be set between 200 to 1000 volts.

In the final system what happens is the battery BMS; the car battery BMS communicates with the charger microcontroller over the can bus. And then the charger microcontroller decides which voltage bus to select whether the four-diode full bridge rectification mode or the two-diode full wave center tap rectification mode which directly provides you with a factor of two voltage scaling.

So; that means, the same operating point that you have used to supply 800 volts at resonance. For example, say at 120 kilohertz if you need 400 volts, you do not need to increase the frequency to 200 kilohertz to achieve 400 volts. If you are needing 400 volts instantaneously, what you need to do is you need to hunt and go back to the same operating frequency as 800 volts. If you just use the center tap you will you get exactly half the voltage which is 400 volts but still operating at resonance.

So; that means, your efficiency at 400 volts which was earlier poor because of very high-frequency operation has now increased because the switching frequency has decreased and come closer to resonance. So, this is the unique scheme that we have implemented and we will show you in detail when we do the lab.

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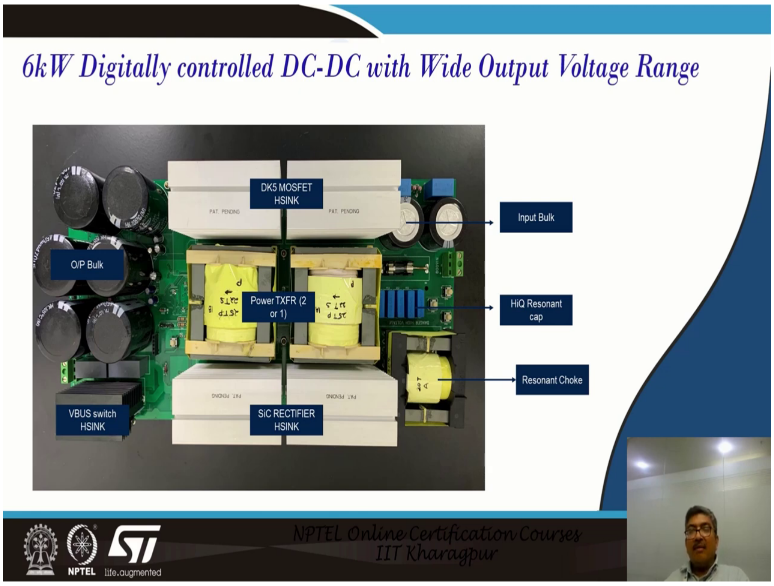

So, this is the board in much greater detail and close-up. So, on the right-hand side, you can see the five blue resonant capacitors here. It is very important to choose these resonant capacitors carefully because at higher power, it has a lot of reactants and as a result, they would have a lot of AC voltage appearing across them at very high frequencies typically from 80, 100, and 120 kilohertz.

You need to derate the AC voltage rating depending on the datasheet. And these are very specialized capacitors these are not DDC-blocking type capacitors. These are very specialized low-dissipation factor type capacitors only special types meant for resonant conversion must be used. On the bottom right-hand side, we can see the resonant choke.

Is the value of this around 70 microhenry? This has been realized on an ETD 49 core of n 97 grade from f cos. These are the heat sinks, these are the output MOSFET heat sinks. 900-volt devices are used here to run from an 800-volt DC bus. These are the output rectifiers of the output silicon carbide diode heat sinks. This small heat sink contains the dc bus select switch, there are two MOSFETs.

It is important to understand that these DC MOSFET. These DC switches are only static switches, there is no AC component here. So, there is no switching loss in these MOSFET. There is only conduction loss. And these are the output bulk capacitors again these must be very low ESR, high-temperature types. So, it can meet a significantly high MTBF rating because commercial chargers deployed in the field must have several hundred thousand hours of MTBF.

And again these two are the input bulk capacitors. So, these would also carry a significant cant amount of ripple current. The input is driven from the output of a Vienna rectifier or the output of a three-phase PFC and the input is the recommended input is from 700 to 800 volts.

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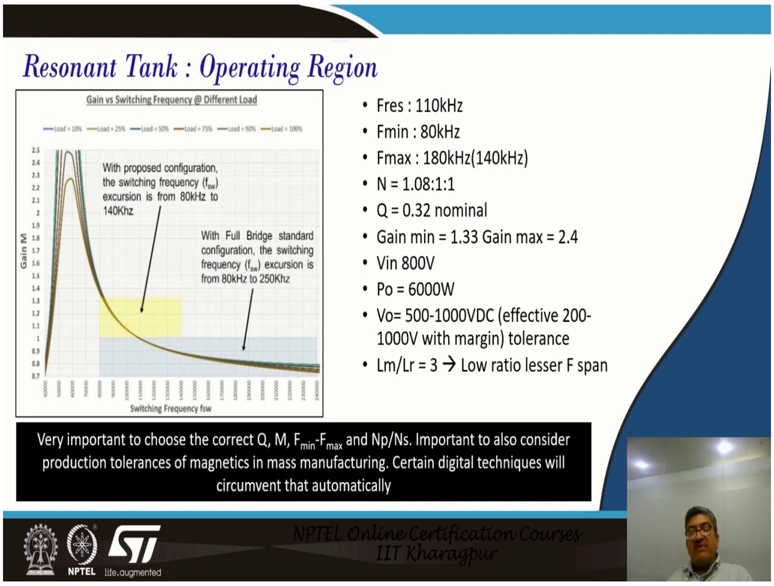

As I mentioned before in the previous lecture, it is very important to choose the correct amount of Q, M, the F max, and the F min, and the resonant frequency and the term ratio of the transformer. It is also very important to consider the production tolerance of magnetics in mass manufacturing. Certain digital techniques will allow us to circumvent that automatically due to the control scheme in the picture, but in this particular scheme let me show you what are the various parameters of operation of the magnetic components.

The resonant frequency of the tank is 110 kilohertz and the minimum frequency is 80 kilohertz. And the maximum frequency at lighter loads and the lowest voltages can go up to 180 kilohertz when we are not using the bus voltage switching scheme. And for improved efficiency when we are using the bus voltage switching scheme, the maximum excursion is from 80 kilohertz to 140 kilohertz.

So, there is a 40-kilo hertz difference or 40-kilo hertz reduction in the operating frequency span which results in almost an efficiency gain of 4 percent.

The trans ratio of the transformer has been designed at 1.08 to 1 to 1. And the maximum Q is 0.32. The Q and the M are related very closely as can be found out by the first harmonic approximation equations. And for each converter and the operating modes can plot your curves. And we suggest choosing the operating span in such a way along the gain curves that you have the lowest operating span of frequencies for the highest efficiency.

So, that is what we have chosen. We have chosen to operate just at the knee of the gain curve in the modified scheme that allows us to restrict our operating frequency from 80 to 110 kilohertz. And that causes a significant gain in efficiency over the entire operating span. So, once again reiterating; it is very important to plot the gain functions, and it is important to restrict the frequency of operation to a point that meets your target efficiency.

And it is also very mandatory to choose the ratio of M in such a way that the ratio of L m to L r will provide you with the adequate voltage span that is required to meet your application specification.

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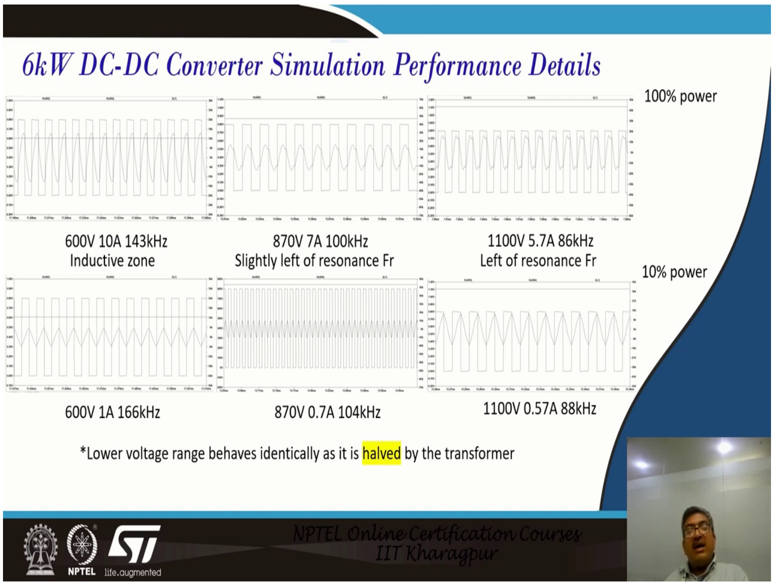

As with any converter, it is better to start with a few sets of simulations, just to understand that your rough calculations are at least in line with the design fundamentals. So, here also we have done some simulations and we have run simulations at 100 percent power versus 10 percent power. So, you can see the lower side there is 10 percent power. So, point 7 amps, 7 amps, 5.7 amps, and 0.57 amps; and again 1 amp and 10 amps.

So, at 600 volts 10 amps output. It is slightly in the inductive zone at around 143 kilohertz and when increasing to 870 volts and 7 amps it is at 100 kilohertz which is slightly left of resonance. At 1100 volts and 5.7 amps it is at 85 kilohertz which is towards the left of resonance. So, depending on which voltage band I am in I am operating either close to resonance much higher than resonance or l, eft of resonance. And you can see the frequency also changes.

When I am operating near resonance light load versus full load does not have too much of a frequency span, but when I am operating away from resonance in the inductive zone, seeing ng lighter load means I have to go even higher in frequency. So; that means if I have to go from 600 volts to 500 volts I have to go even higher in frequency, therefore, sacrificing my efficiency.

So, what I am doing now is in the modified scheme that we have shown you with the bus switching, if I need 300 volts I will not operate at 200 and 50 kilohertz. If I extrapolate this to the same mode of operation may be to obtain 300 volts, I should be switching at 300 kilohertz, but no I will not do that. To operate at 300 volts instead of going to 300 kilohertz, I will just drop the tap.

I will just use the low-side bus instead of the high-side bus. And I will still operate at 143 kilohertz as is shown here and I will get a significantly higher efficiency because I have reduced the operating frequency by half. So, once again if I have to operate at 300 volts I will choose the operating zone which is close to the resonant and then select the tap either the high side or the low side that will allow me to use the frequency which is closer to the resonant, resonant frequency and hence higher efficiency.

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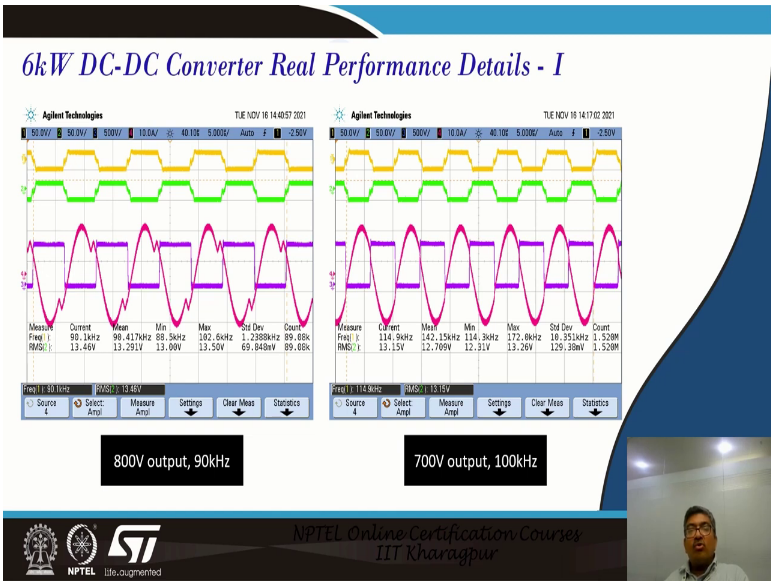

So, you can see from the simulations we are now moving on to the actual graphs that we have taken. So, this is working at 8 the 00-volt output we are operating at 90 kilohertz; at the 700-volt output, we are operating at 100 kilohertz. So, you can see that there is a very minute chafo10of 0-volt the difference is there is almost a 10 kilohertz change. So, this is what we will show in the subsequent slides as is the property of LLC converters it is; it is a pulse frequency modulated converter.

So, the output voltage is a function of frequencies, but as we will see the whole span of frequencies required for covering 200 to 1000 volts is only from 80 kilohertz to 140 kilohertz; instead of 80 kilohertz to close to 200kilohertzz.

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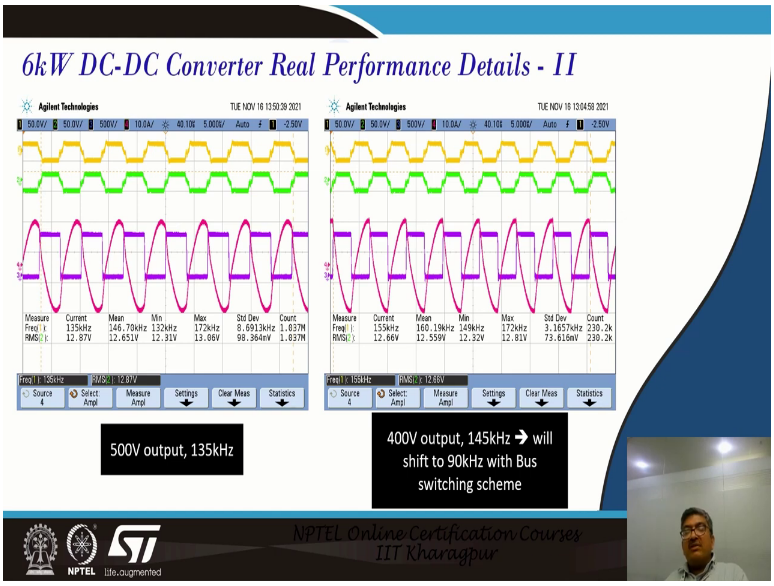

So, here we have moved from 700 volts now to 500 volts. Here you can see that frequency has increased even further it has gone to 135 kilohertz. So; that means, now if I want to operate a 250 volt; for example, I know that at 135 kilohertz I had reached 500 volt. So, for 250 volts I can also reach similar efficiency levels by operating at 135 kilohertz.

So, instead of using the high bus tap, I will use the low bus tap. So, I am still operating at 135 kilohertz, but I am getting an output of 250 volt instead of 500 volt. The same thing is happening here. When I am operating at 400 volts, I can go to 200 volts by using the same tap, or if I am operating at 400 volts output and I need 800 volts. So, I can move to the higher tap. So, both vice versa both moving from the bottom tap to the upper and the upper tap to the bottom is possible to maintain the same higher efficiency levels.

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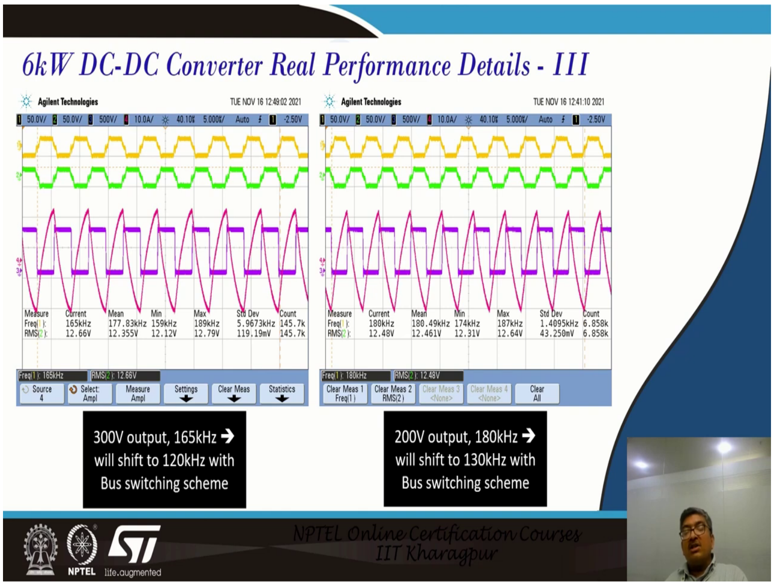

So, similarly, we are now operating at 300 volt where the frequency has moved to 165 kilohertz. It is perfectly possible to shift this frequency to 120 kilohertz with the same bus-switching scheme. If you analyze it closely it is just a matter of changing the tap or the output bus switch to reach a different frequency that is close to the resonance. Now, we have come to the end.

At 200 volt output, we are operating at 180 kilohertz, but this is not required if you getting for example, if you are getting say 92 percent efficiency at 180 kilohertz for the same level, you can easily shift this operation to 130 kilohertz by changing the tap. And you can achieve the same output voltage at a much higher efficiency point. And we have seen we will see in the later curves that the efficiency improvement is close to four percent at the extremities of the voltage.

So, this is indeed a very significant addition to the total cost of ownership of the charging system.

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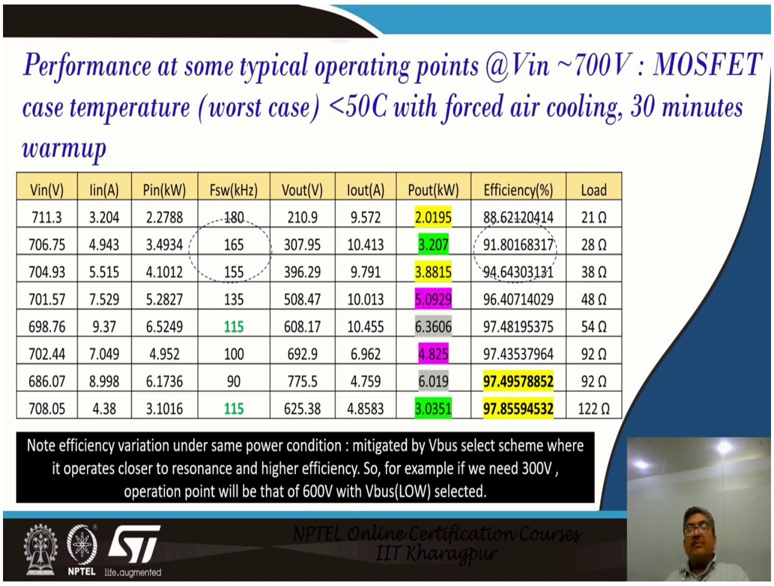

So, here is the tabulation of the efficiencies that we have found and that we can be able to show you also when we are doing the live session. These readings have been taken with a V input of 700 volts. And we have seen that the MOSFET worst-case temperature remains less than 50 degrees with some amount of forced air cooling after 30 minutes of warm-up.

So, here you can see that we have reached a peak efficiency of 97.9 percent with a 122 ohms load with a P out of 3 kilowatts, and with the pout of 6 kilowatts, we have 97.5 percent of peak efficiency. So, in the worst case, the efficiency we can see is in the range of 89 percent, but this is without the bus switching scheme. So, when we do the bus switching this will increase by 4 percent, and 3 percent to reach almost a flat efficiency curve as the other readings.

So, in this case, the efficiency varies from 89 percent at a very light load and 200 volts up to 97.5 percent at 6 kilowatt at full load. This will become almost flat, this will become almost flat from 94 percent to around 97 percent. So, a huge amount of efficiency increase happens from the lower part of the voltage spectrum.

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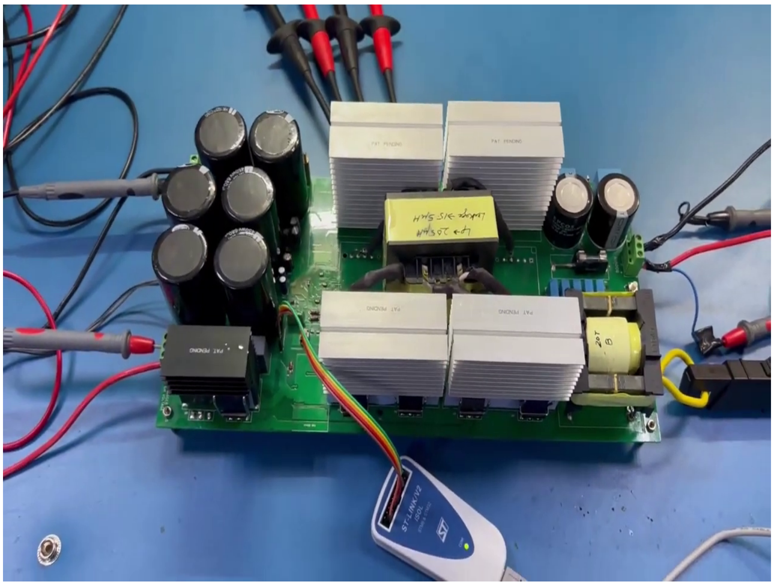

Now, it is time for the lab setup and we will practically demonstrate to you the 6-kilowatttt converter the full digital converter that we were just explaining in the slides. So, if I look at it very closely. So, you have seen the pictures already in the slides sometime back. So, this is the real system.

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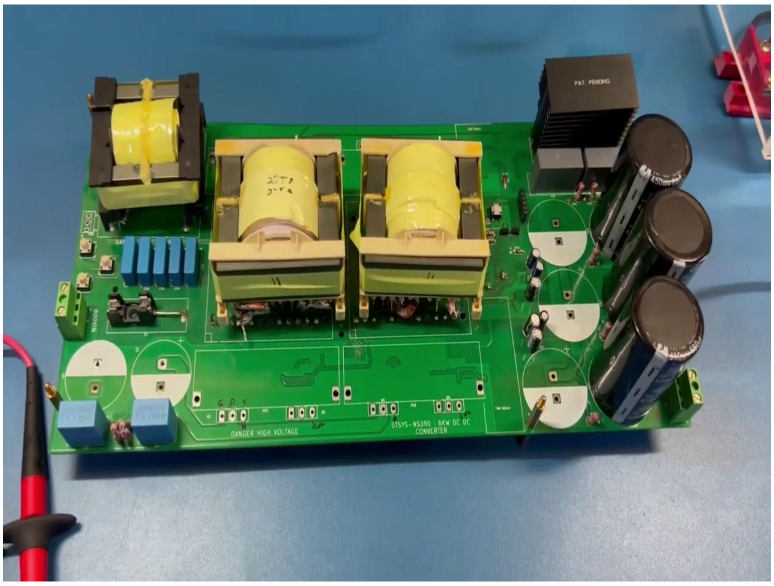

So, we have two systems here one of which is wired to our setup that we will use to demonstrate the operation. The other is a board that is also lying idle, but these are both working boards with two different schemes. If you remember, we explained the wide output range LLC operation sometime back with the particular scheme that we had devised. So, that depends on bus switching so; which means, we are using the center tap as well as the full bridge configuration depending on what sort of voltage we require.

For example, if you require an output voltage to charge a battery less than 500 volts, we use the center tap configuration because then the turns ratio is lesser. If we need to go to a higher voltage say from 500 to 1000 volts, then we use the full bridge configuration in which case the turns ratio referred to the secondary side is higher. Now, what is the advantage?

The advantage is for example if I need 400 volts, and in the normal scheme using the dual transformer I have to switch the half-bridge to the full bridge, the LLC the full bridge primary at 180 kilohertz; that means, I am losing a lot of efficiency because I have to switch at a much higher frequency. But, we have seen that if while operating at 800 volts, my switching frequency is close to 100 and 10 kilowatts or resonance, I can easily derive four hundred volts from the system by changing the tap or falling back to the center tap configuration.

Because nothing changes on the primary side; only the turns ratio the effective turns ratio we are changing by changing the output bus selection. So; that means, I can still reach 400 volts, but instead of switching very high up to 180 kilohertz, I can achieve the same 400 volts at 110 kilowatts. So; that means, in this case even though I was able to cover 400 volts, the switching frequency was close to 180 kilohertz; that means, I had a lesser efficiency.

But in this board with the modified scheme we can reach 400 volts just by changing the tap or by changing the bus voltage by changing the bus switch and I am still operating close to 120 kilohertz which is a round resonance. So, if you look at the tabulated results we have seen that the effective efficiency gain in the lower ranges can be as high as 4 percent. So; that means, earlier in this board when we were reaching a peak efficiency of 98 percent and a minimum efficiency of 90 percent.

In this case, the peak efficiency of 98 percent does not change, but the minimum efficiency which was 91 percent here or 90 percent here has moved up to about 94, 94.5 percent in this configuration. In any case, we will show you the actual operation in a little while. So, let me just quickly walk you through our laboratory setup.

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This is the Chroma high power high voltage high current voltage source. It is an AC-DC voltage source. So, we will use this system to power up our board.

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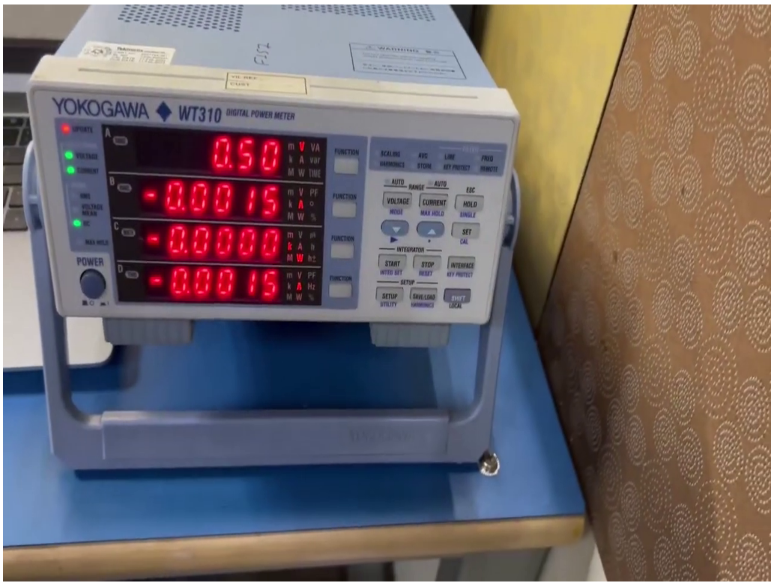

Here we have the input side power analyzer which inputs the AC or DC voltage the current, and the actual power.

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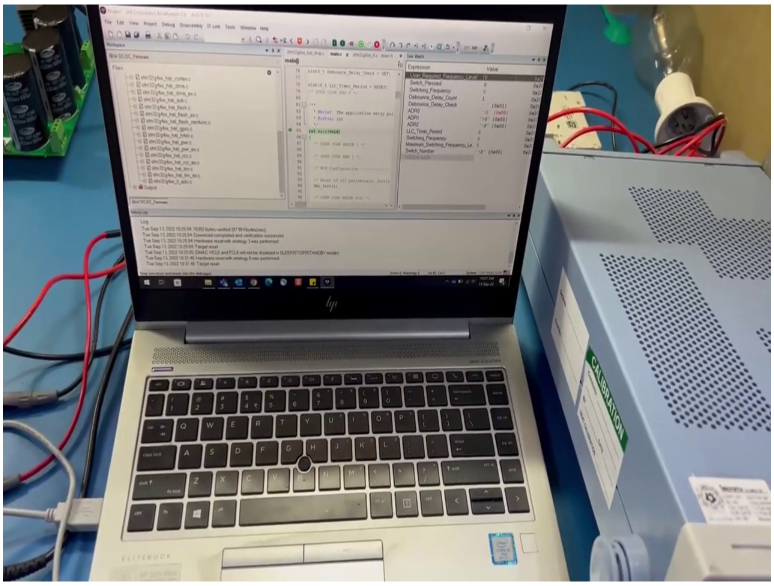

This is the laptop on which the STM32 debugger is running live.

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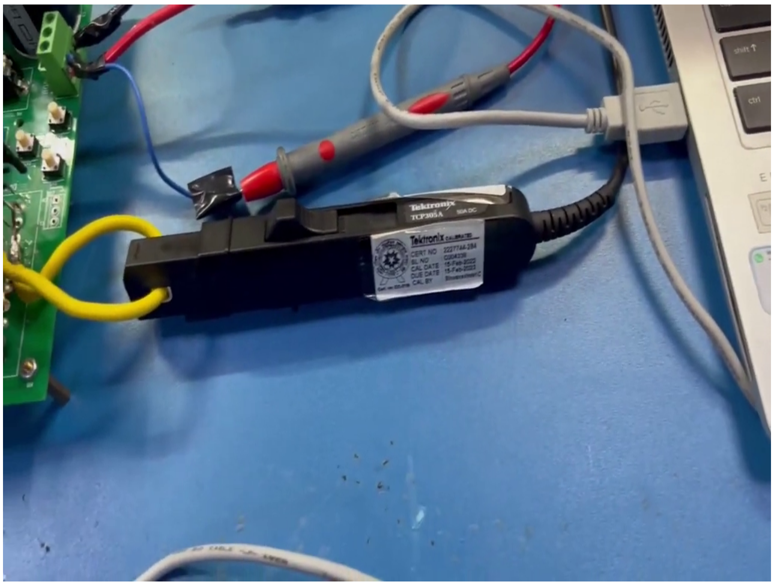

This again is the board. We have created an external current loop a physical current loop with which we have connected the electronics current probe, here we have the dummy board.

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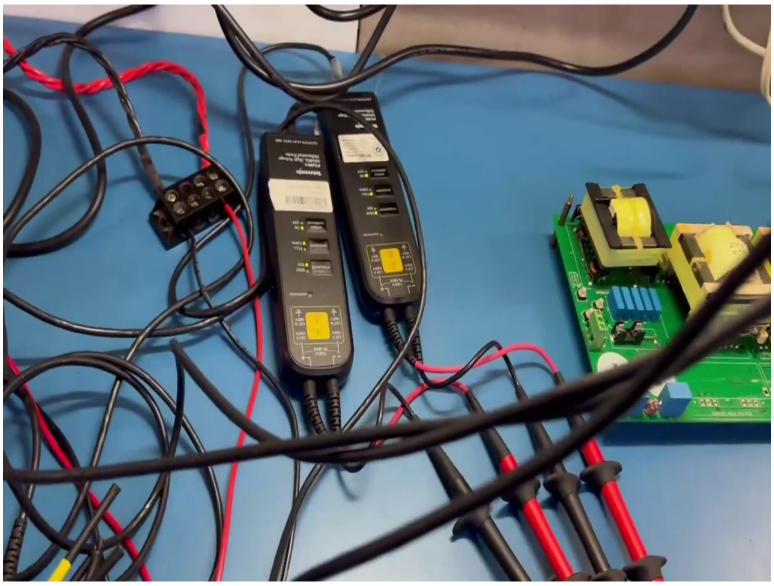

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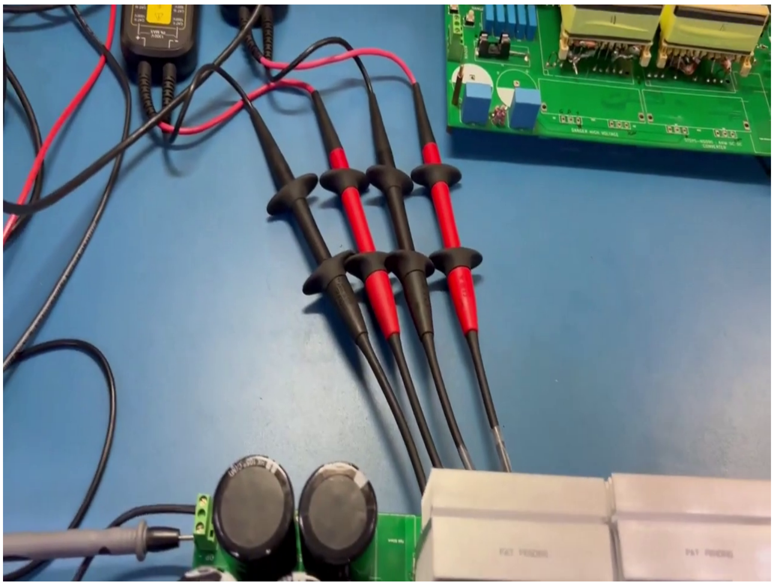

These are the high-performance differential probes used to measure very high-frequency signals in a very noisy environment so that we can reject noise. We have used the differential probes single-ended grounded probes will not work very well.

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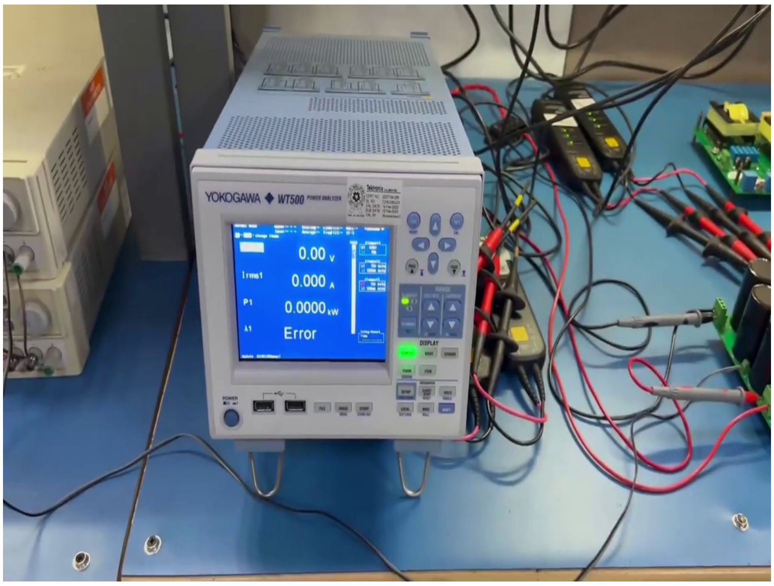

This is the output side power analyzer which is also from Yokogawa, it measures the output voltage output current.

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And this is the active load. It is a 6-kilowatt active load, now configured for 200 to 1000 volts up to 6 kilowatts. So, now, before we start I would just like to give you a quick explanation of the board. So, here you can see this is the main power transformer. So, you can see on the secondary side, three wires are coming out. So, the extreme ends of the wires of the windings; and this is the center tap of the middle wire.

So, when we are desiring higher voltages say anything between 500 to 1000 volts, we ignore the center tap we use the extreme two windings to run the output rectifiers in full bridge mode. And the output bus select MOSFET switches the full bridge mode output to the battery. On the other hand, if you require something between 200 and 500 volts we ignore the full bridge mode, but we take the secondary center tap configuration.

Again, the low bus switch MOSFET which is mounted here selects the center tap output and feeds it to the battery. So; that means, depending on the battery voltage my system controller can switch the corresponding bus and operate close to resonance unconditionally. So, now we will start up the system and will see how it starts up from a soft start because as you know an LLC converter when it starts up tends to charge up the output capacitors by which it might accidentally enter the capacitive zone which is destructive for the system.

Instead what we do is we run the system from, start the system from a very high frequency. So, that it never experiences the inductive capacitive zone. And it slowly ramps up the operating current by decreasing the frequency from the short start frequency. So, the output capacitors the output bulk capacitors here get slowly charged and do not pose a stress on the switching components.

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So, as you can see here you can see that the switching frequency is 270 kilohertz. This is the switching waveform and you can see a highly inductive tank current. So, this waveform is a tank current and these are the two bridge gate drive waveforms which are at 270 kilohertz.

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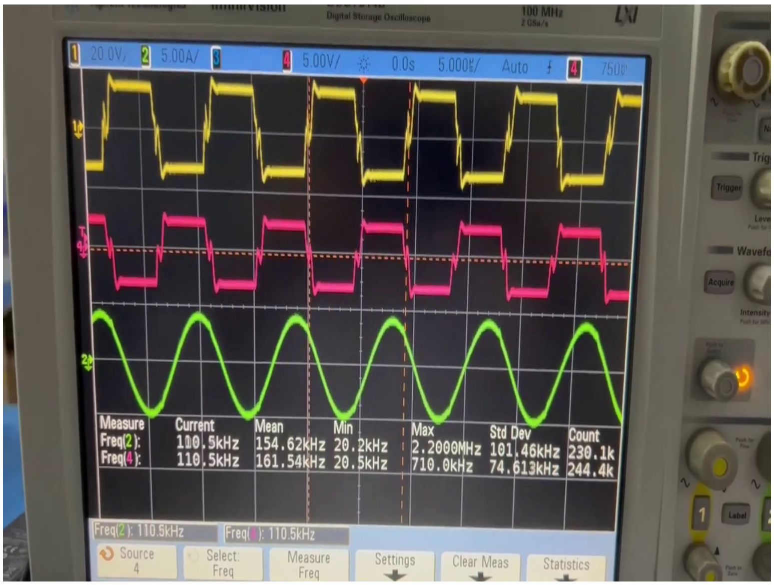

Now, we will run the MCU in a closed loop and it will switch it has happened very fast. You can see that it has switched and come back to its resonant frequency which is its steady-state operating frequency at the moment. You can see a very sinusoidal tank current. These are the gate drive waveforms and it's run close to 110 kilowatts.

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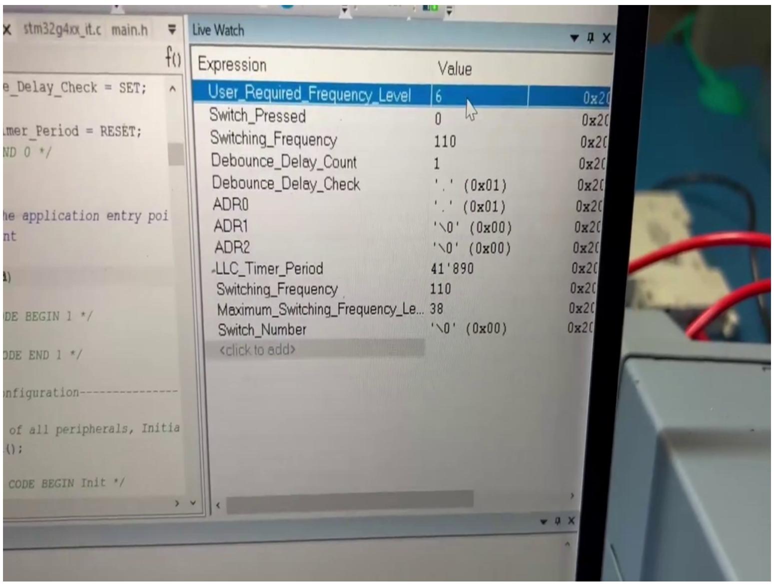

Now, what we will do is we will show you the workspace. This is the workspace and on the extreme right, you can see the watch window where we can have a look at the various parameters various variables within the code. So, as you can see if you note this cell it says switching frequency which is 110 kilohertz now. And you also look at the LLC timer period. So, because it is working at 110 kilohertz there is a corresponding LLC timer period that is visible. Now, I will ask my colleague to reduce the operating frequency by 5 kilohertz.

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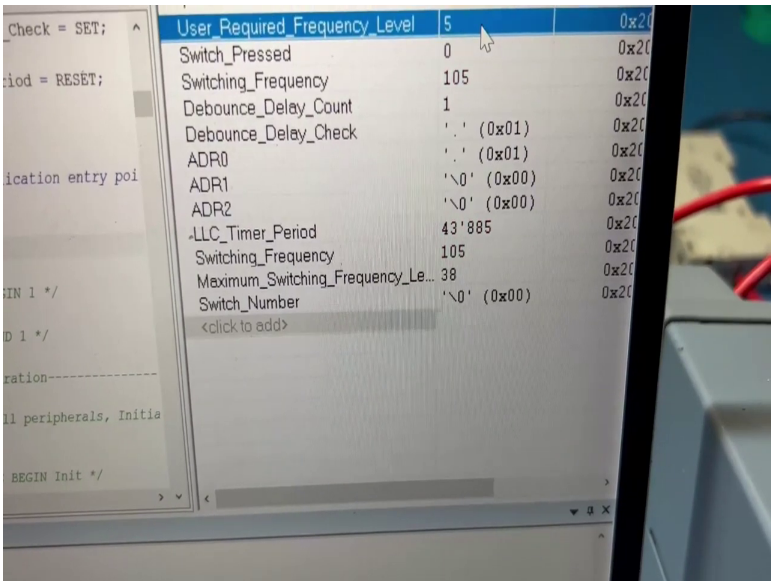

So, he has pressed the button and you can see that the LLC timer period has been updated. And so has the switching frequency which has now reduced to 105 kilohertz. So; that means, when it has reduced to 105 kilohertz it has moved slightly left of resonance. So; that means, we can expect to see the magnetizing current kink on the top and bottom side of the resonant current.

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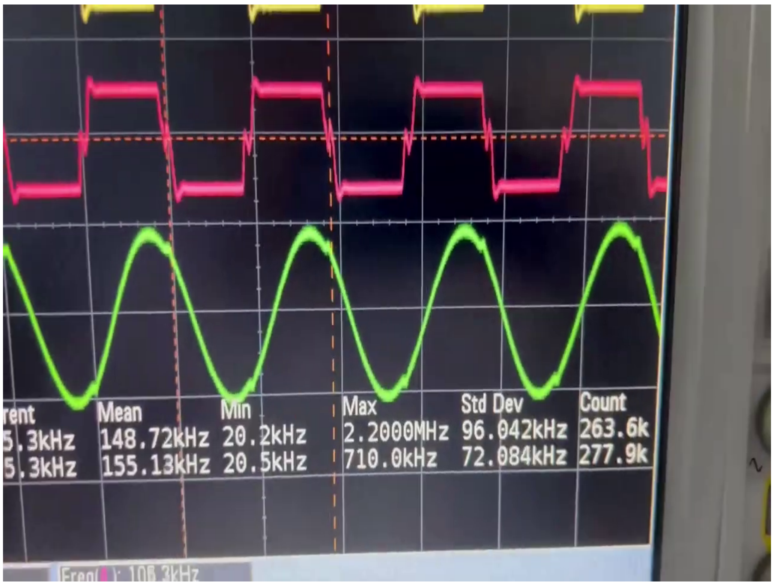

So, here is the resonant current. So, you can see it is operating at 105 kilohertz, and you can see the kinks that have started happening because it is now operating slightly left of resonance.

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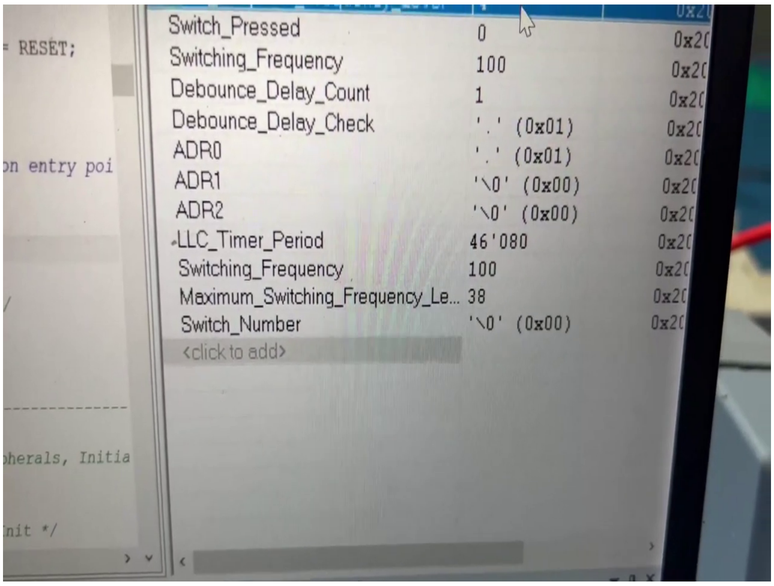

We will again decrease the frequency and we will come down to about 100 kilohertz. So, you can again see that the LLC timer period and the switching frequency update and the frequency come down to 100 kilohertz.

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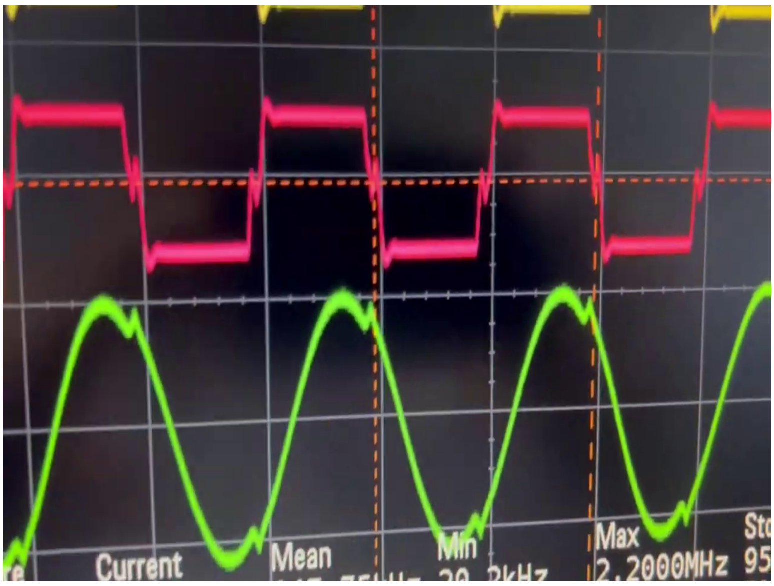

So, here we have 100 kilohertz, you can see it has moved further away from resonance, and here is the frequency at 100 kilohertz.

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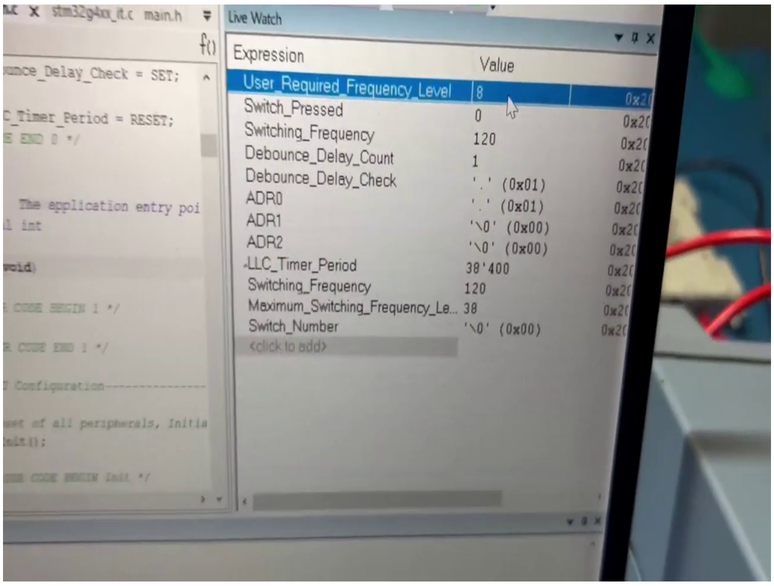

We will again go back to around 120 kilohertz where we will enter the inductive zone of operation. So, you can see that the LLC timer period has decreased, and the switching frequency has increased.

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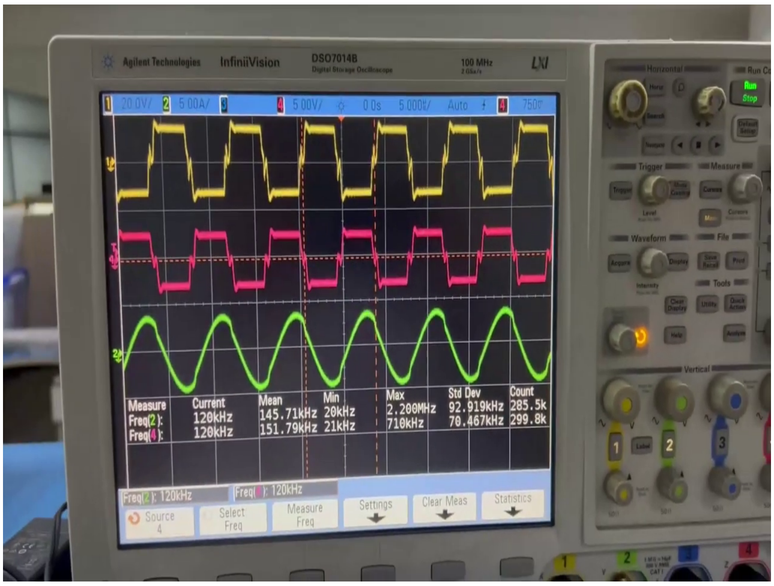

And we will now see or we will now expect to see the tank current waveform, its shape of it has changed it is slowly a triangular component or an inductive component is getting more prominent in the tank current waveform. So, this is the full digital implementation that you can see in runtime. And this is also the flexibility that you get when you are implementing something in the digital domain that these are very fast to incorporate and observe.

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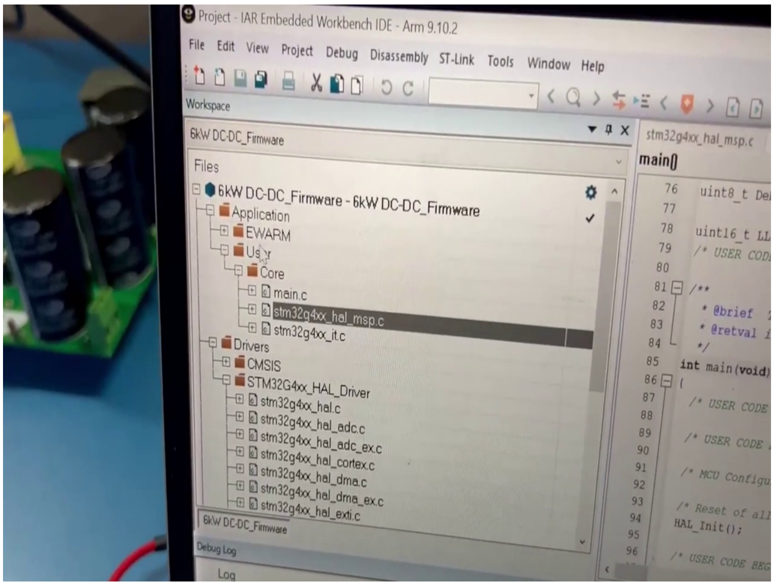

We will now have a closer look at the workspace. So, on the left-hand side, you can see all the relevant files that are required on the folder structure.

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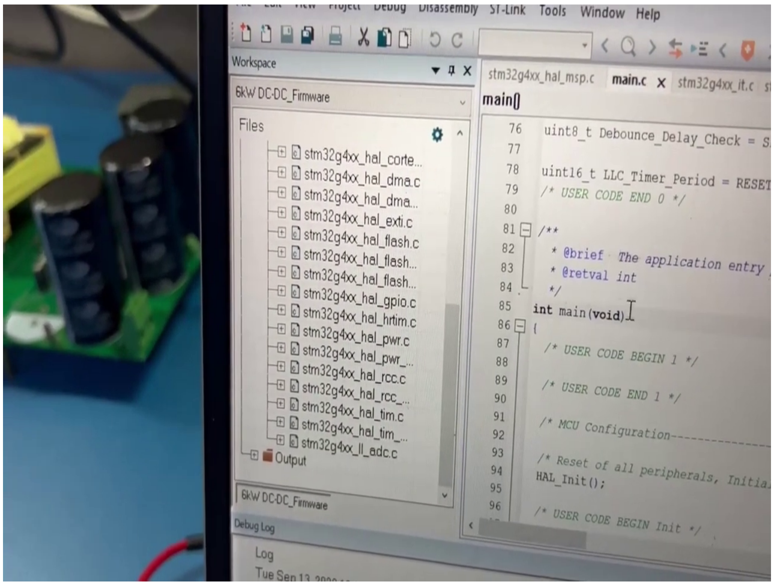

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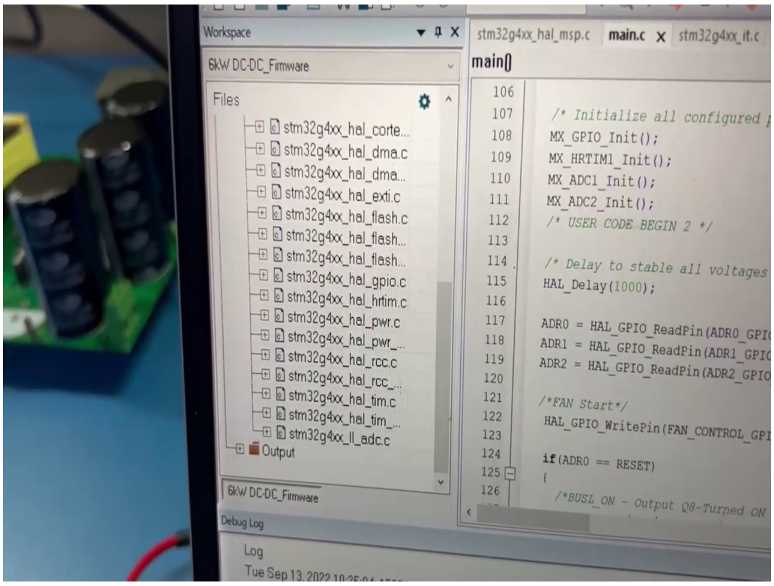

We have configured you can see the flash, we have configured the DMA, we have configured the ADC, and we have configured the timers.

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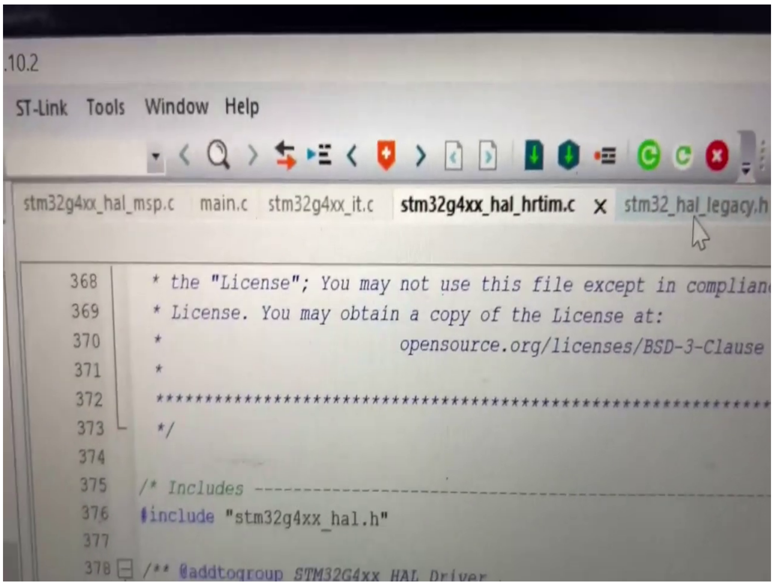

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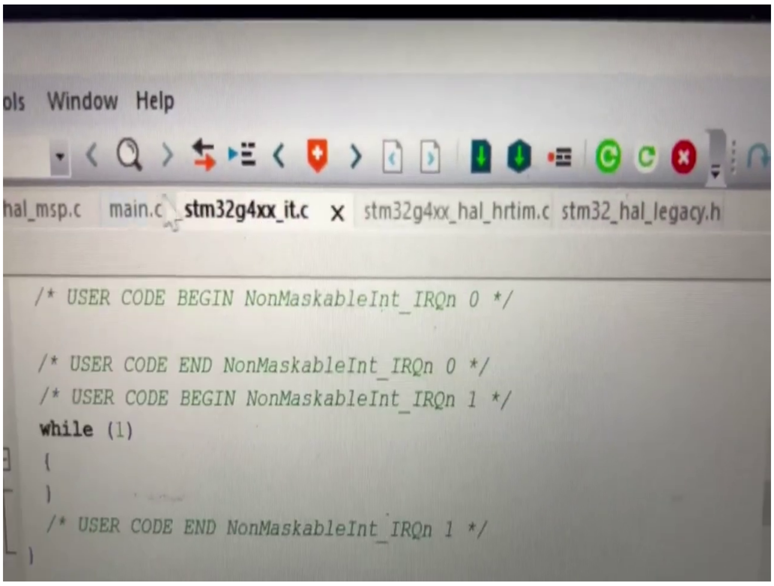

These are the various individual dot c files. It is the main file, you can see the interrupt configuration file, the HR team, hardware abstraction layer files, and so on. You can find examples of the code, and examples of many digital converter codes on the st dot com website. And if you are willing to you can download them and study the code and the code structure in greater detail.

So, that is all for the live demo session, hope you can follow the entire session. And this inspires you to design your LLC converters using digital techniques.

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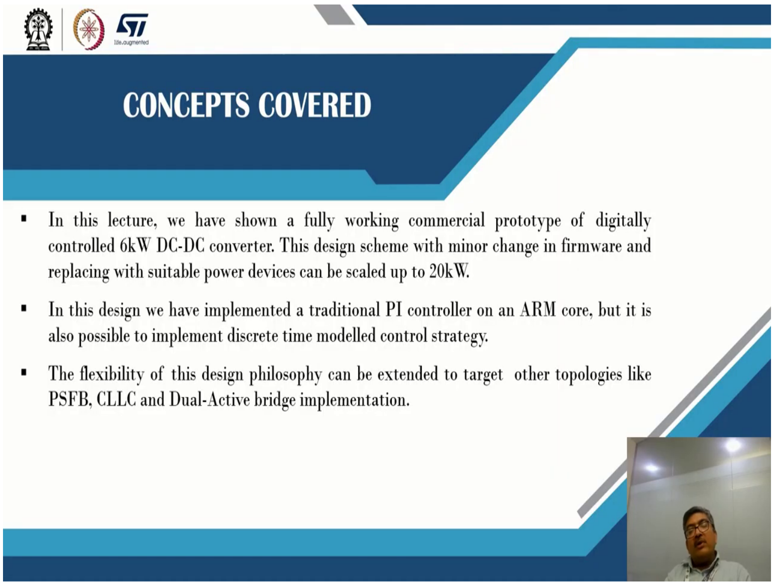

I hope you can carefully watch the live demonstration of the 6-kilowatt board that we just showed in our lab. We have shown a fully working commercial prototype of the digital control converter. So, with this scheme with minor changes in firm firmware and replacing the power devices with other power devices, you can address other power levels and this can be scaled up to about 20 kilowatts beyond that I think we need to use a different scheme or we have to use power modules.

In this design, we have also implemented a traditional PI controller on an arm cortex m core microcontroller, but it is also possible to use discrete time-modeled control strategies and hysteretic modes. Are any other modes that choose to implement quickly? The key USB of digital control is flexibility and quick turnaround amongst others. The flexibility of this design philosophy we can also extend to target other topologies like PSFB or CLLC and dual active bridge or any other topologies for that matter.

The full bridge structure if you replicate the full bridge structure on both sides the same powerful hardware board can be used for bidirectional unidirectional and multiple topology evaluation. In some cases, you might need an extra inductor or an extra capacitor, but that is minor compared to the other flexibilities regarding how quickly a prototype you can do using fully digital control.

So, there is no question of replacing components or trying them out in real hardware. Once the hardware is validated there are limitless possibilities. I hope this series of lectures and practical demonstrations have been useful for you and that you will take inspiration to design your LLC or PSFB or any other high-power converters using full digital implementation.

Thank you very much for your attention.