Digital Control in Switched Mode Power Converters and FPGA-based Prototyping
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Module - 09
Digital Control Implementation using Microcontroller
Lecture - 84
Practical Implementation of LLC converters (Part - I)

Hello and welcome to yet another session on Digitally Controlled Power Converters. My name is Ranajay Mallik and I am from ST Microelectronics, Noida. In this session, I will walk you through how to practically address the design of high-power LLC converters using a mix of analog and digital hybrid control, as well as a fully digital control scheme with a very wide output range.

I hope after this session and the viewers would be confident enough to start working hands-on with high-power LLC converters. In fact, as the sessions progress, we will walk you through two designs, one 2.5-kilowatt design, and another 6-kilowatt design which has been developed from scratch here in our lab in Noida.

And we will walk you through the key waveforms, and the key characteristics, and physically we will demonstrate to you how the board works under both hybrid as well as digital control so that you will be able to have a first-hand view of how real-life high-power LLC converters work. And we are sure and we also hope that you would start working on high power converters, which is much more confidence and a head start that you should get from following this course.

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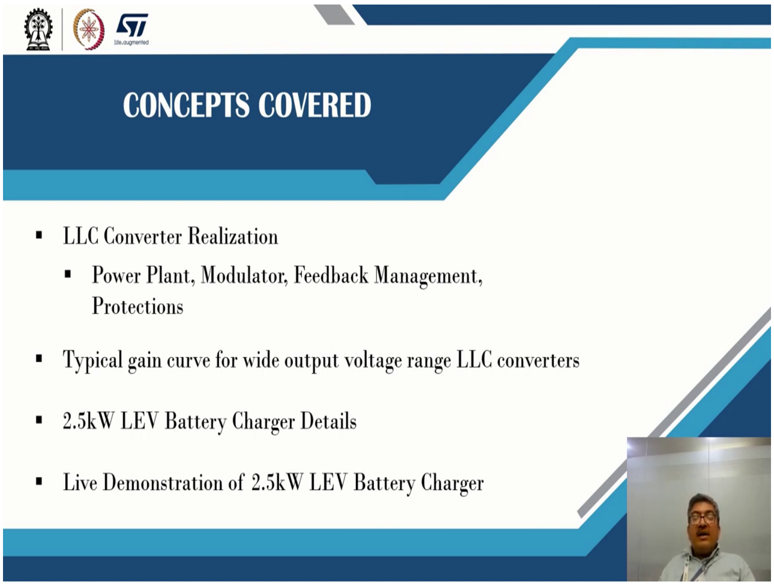

So, let us proceed. In this particular episode, we will cover four key aspects of LLC converter design. For example, if we have to look at LLC converter realization in great detail, we have to cover 4 aspects invariably.

So; that means, any LLC converter design depends on the power plant design, the modulator design, the feedback management, and the overall protection schemes that we have put in place. The power plant is the most important block here, which is the most visible block and the block that is subjected to a lot of stress.

So, this includes the input filter capacitors and the input bridge which is either half-bridge or the full bridge MOSFET or the IGBT or the SiC MOSFET stage. Then we have the resonant tank, the resonant tank is the most important part of the energy transfer block of the power plant.

So, that includes the resonant capacitor, the resonant inductor, and the main transformer. Then we reach the secondary side, and the secondary side would house would have the main rectifiers. It can be either discrete diode rectifiers in half-bridge half-wave or full-wave configuration or it could be also synchronous rectification using MOSFETs to reduce the losses.

And then we would have the output filters, those also carry a lot of stress, the output filter capacitors must be suitably rated for you know having very low ESR and having a wide temperature range. So, that it does not degrade during service.

So, once the power plant has been realized and characterized, we have to next move on to the modulator. The modulator is that block that provides the pulse frequency modulated signals, provides the requisite dead time, and contains the error amplifier which takes input or information from the feedback management system. And tells the power plant at which frequency to operate so that the regulation of the output current or the output voltage is maintained.

Then we have the feedback management block and the feedback management block is nothing but the output sampler stages because if you are developing a constant voltage output we would need to sample the output voltage, which is at an acceptable level for the error amplifier. If we are doing a constant current source we would also need to take the output current sample.

And if you are doing, for example, a battery charger, which needs a constant voltage, the constant current system, then it is imperative to take the feedback from both the output current and the output voltage.

Now the output signal might have a lot of noise, and the error amplifier must receive a noiseless sample of the output. So, it is very important to properly buffer the output signal samples. So; that means, we might use a resistive divider, or we might use the shunts, but everything that is done must be properly buffered, must be properly routed so that we do not pick up noise in the process. And we feed a clean signal back to the error amplifier so that it can direct the modulator and the power plant in a proper manner.

And finally, we need to have a lot of protections; there are some inherent protections that every converter must be provided with. For example; an LLC converter must never operate in the capacitive zone. For example, an LLC converter during startup must have a proper startup sequence, because during startup the output capacitors are short-circuited.

And the feedback loop would force the power plant to work at a frequency much lower than resonance, which would cause it to fail and destruct. So, these inherent protections must be a very essential feature of the LLC controller or the overall system control or the modulator and these things have to work together. So, that the startup or the shutdown of a high-power converter is done properly to prevent catastrophic failure.

Then we would also need to figure out how to prevent eventual fault events. For example, output short circuit, input over-voltage, and output sudden load disconnects. So, any sort of anomalous operations that can happen must be properly taken care of in the form of derating or the form of system shutdown so that catastrophic failures leading to expensive repairs do not happen.

We must also take care of the thermal issues and we must also take care of providing sufficient protection for the system to work unattended. So that means, the system must be able to either fall back or shut down or go into such a safety mode that despite what happens, due to any external trigger or due to anomalous conditions in the mains or due to the conditions in the load the system must never fail.

So, all these things come under the control of the main system controller, which can be either designed using traditional analog methods, using discrete circuits or can be implemented using the digital control blocks using a microcontroller. So, we will as we proceed we will see all these features and how they are implemented.

The most important aspect for designing the magnetics of an LLC converter for example is the gain curve, we will not go into too many details on the details of how to derive the gain curves but we have already we are already aware of the fact that the LC tank circuit gain curves are a deciding factor on how to address the operating range of the LLC converter.

For example, if you are working on a very wide output range LLC converter, it is very important to choose judiciously the portion of the gain curve where my LLC converter would be operating. Because wide output range LLC converters because by virtue it is a pulse frequency modulated scheme, and the output voltage is a function of the operating frequency.

If I need a very high operating voltage, then my operating frequency must be very low. If my operating frequency is very low and if I am entering boost mode, I have to be very careful that I do not enter the capacitive mode. Similarly, if I want very low voltages I have to increase the frequency; that means, I have to move away from resonance deep into the inductive zone. In this case, my losses would also increase. So, we have to find a trade-off in the operating gain curve, in the typical gain curve of the LC tank.

So, we have a trade-off between the operating frequency excursion and how much voltage pan we can achieve. So, we will show you later on that in certain cases it is possible to also target or also achieve a 1 in 1 is to 5 voltage span by using a certain scheme, which will demonstrate subsequently in some chapters.

We will finally, show you a real-time demonstration in the lab of a 2.5 kilowatt light electric vehicle battery charger, which is a mix of analog and digital control we will call the hybrid control.

So, we will show you in real-time how the system behaves, we will show you in real-time the tank current, and the gate drive waveforms and we will also show you depending on the operating condition, how the MCU sends the control signals to the main modulator. And how the tank characteristics change the tank current, the operating frequency, the output voltage, and how that changes in response to commands received from the microcontroller.

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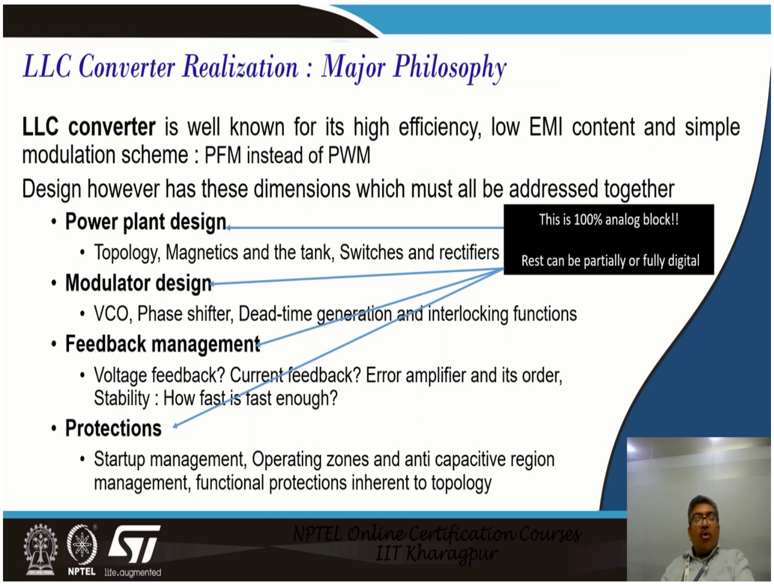

So, moving on we are all aware that LLC converters are very well known for their high efficiency and hence a very low EMI content due to soft switching. For a simple modulation scheme, we use pulse frequency modulation instead of pulse width modulation.

So, here the duty cycle remains very close to 50 percent symmetric due to cycles, 50 percent plus 50 percent for the two arms. And we vary the frequency of the waveform to provide regulation of the output voltage or the output current. As I mentioned earlier there are four characteristic dimensions, which must be addressed together.

First of all, is the power plant design. So, once we have chosen the topology, whether it is a half bridge or full bridge, we have chosen the magnetics in the tank after thorough calculation. Once we have selected the proper switches and the rectifiers it is possible to first make the power PCB or the power part separately on a properly laid out circuit board and independently test the power plant.

All that it takes is a suitable set of gate drivers and the power plant ready and the signal generator to generate the frequency span of interest. This way you will be able to characterize the power plant and debug it before you start applying either the analog control or the digital control to finally, work the system in a closed loop.

We must also have or we must also pay significant attention to the modulator design. For example, the modulator can be either analog we will show in some subsequent slides, how an analog modulator and a digital modulator behave. So, the modulator contains the VCO; VCO is the Voltage Controlled Oscillator that eventually generates the square wave pulses. The VCO gets its information from the output voltage sampler and run amplifier.

Then we have the phase shifter. So, the phase shifter generates 280-degree phase-shifted outputs for driving the two arms of the LLC converter, we have the dead time generation. We will see in the later slides that the dead time is very important for ensuring high efficiency and 0 voltage switching for which the LLC converter is well known over the entire load span. So, insufficient dead time can be a cause for losing efficiency and sometimes even destruction of the system.

And not one single dead time setting is good for the entire operating range over line and load. So, that is why digital control comes into the picture here, with analog control it is not so easy to provide a lot of ways to adjust in the dead time that we have provided. Some controllers and some analog controllers do have the feature of providing adaptive dead time, but the digital controller is hands down here because in a digital controller, we can always predict and we can always control the dead time dynamically depending on the instantaneous load condition.

This is one major advantage that we have using digital control, the flexibility of adjustable and continuously adaptive dead time which greatly enhances the efficiency over standard techniques. And then we have to also provide interlocking functions as I mentioned here, interlocking functions provide accidental turn-on of wrong MOSFETs.

So, only in the full bridge case, only the diagonal MOSFET should conduct, while in the half range case, only the top and the bottom MOSFET should conduct at this time. So, these violations do not occur. So, there are a lot of interlocking functions meant to provide catastrophic failures.

Then we have feedback management. So, what feedback do we need? If it is a constant voltage converter we need voltage feedback, if it is a constant current converter like in the case of led lighting we need current feedback. So, it is an error amplifier, and depending on whether it is a voltage mode control or it is a current mode control, it is a slow system or a fast system.

We need to provide either a type 1 or a type 2 or a type 3 compensator and a read amplifier eventually we also need to discuss a bit of stability. Now, stability is also a function of or rather the transient response and stability is a function of each other. So, if the system is too stable; for example, the system will be very slow if the system is very fast the system might not be stable.

So, we have to find a break even, we need to find a compromise, we need to find an optimal point an optimal bandwidth in which the system operates so that we have acceptable stability, acceptable ringing, acceptable overall undershoot as well as unconditional stability at the same time. And eventually, we have to provide a lot of protections, as I had also mentioned earlier like startup management and operating zones.

For example, it is a disaster if by any chance my system moves into the capacitive zone of operation in an LLC converter, which is not permissible, and the anti-capacitive region. For example, which is basically beyond the capacitive region. So, this is the protection that has come into the picture in recent controllers and this prevents the LLC converter from entering the destructive capacitive region. And eventually, we have to also provide the functional protections inherent to the topology.

For example, we have to provide for short circuit protections, we have to provide for reverse voltage reverse polarity protection, and we have to provide for sudden load disconnections as I mentioned earlier. These protections must also be provided if it is to be made unconditionally stable and the system does not fail when it is operating under harsh conditions.

Thermal management also plays a very key role and often the temperature of all the heat sinks are independently monitored so that if some heat is sink due to an ambient temperature rise or due to abnormal operating condition. If the temperature of the heat sink is increasing beyond the preset limit, the power is either folded back or the power is either derated or the system is shut down again to prevent costly catastrophic failures.

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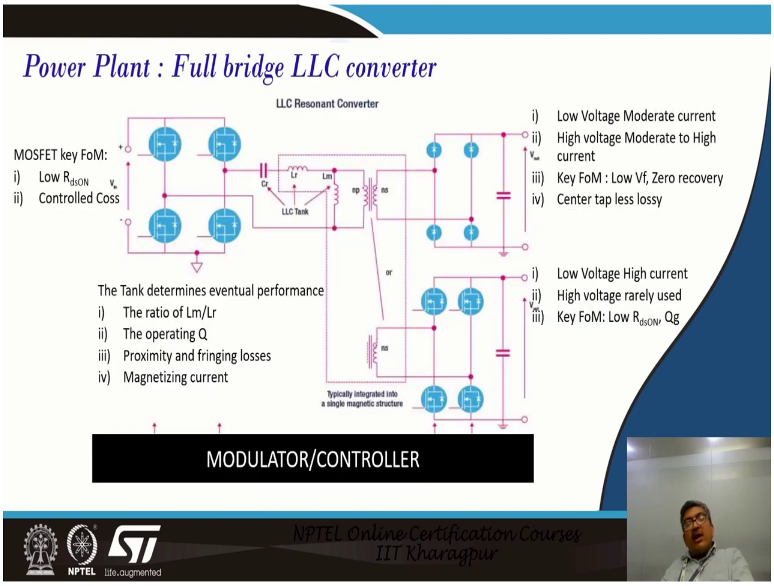

So, now let us look at the power plant of the full bridge LLC converter. We have chosen a full-bridge LLC converter here, but the same logic applies, the same justifications apply when we are targeting even half-bridge LLC converters.

We are showing you full bridge LLC converters because the demonstrations that we will show you, the actual designs that we will show you the 2.5 kilowatts and the 6 kilowatt systems in the demo sessions, are all implemented using full bridge LLC converters. So, if you look at the leftmost part here, this is the h bridge this is the full bridge MOSFETs.

So, the key figures of merit must have a very low R dsON and we must have a controlled Coss. Low R dsON ensures that your conduction losses are at the minimal, white-controlled Coss which is the output capacitance, and output drain capacitance of the MOSFET this ensures that you have ZVS over the entire operating span of your LLC converter, which has to be finalized during your design itself.

So, if certain generations of MOSFETs very controlled Coss, which means that over the production batches or production tolerances the Coss does not vary much. So, if the Coss is very controlled, it also means that in your production lot when you are manufacturing 10000, 20000, 1, or million pieces of converter your performance as efficiency or switching behavior remains uniform.

Then we come to the magnetic spot. The magnetics and this capacitor, and the resonant choke form what is called the tank circuit. And the resonant tank eventually determines the eventual performance of the conductor of the converter as far as the output voltage span the regulation and its efficiency are concerned. The most important thing to look at is the ratio of Lm to Lr.

Lm here is the magnetizing inductance, and Lr is the resonant inductance. In applications that require a very low voltage excursion. For example, in constant voltage applications like a data center converter or a computer power supply, say which is operating at only 12 volts, only 48 volt we can have an Lm to Lr ratio of maybe 6, 8, or even 9, very high Lm to Lr ratios provide you with very high efficiencies and very low magnetizing currents.

But the drawback is you cannot have too much excursion in the operating voltage. Then we have to also look at operating Q, the operating Q is also a function of the reflected load resistance from the secondary, the value of the resonant capacitor, the value of the leakage inductance or the resonant inductance, and the magnetizing inductance. It is a complex function, but we can, we can figure out the optimal Q and the optimal M from the basic FHA and the FHA derivations.

And we can plot some gain curves as I mentioned earlier from which you can choose the optimal region in which your Q and M will lie. Then we have to also look at very carefully the proximity and fringing losses that happen within the main magnetics or the main transformer. So, with the improved generation of MOSFETs, we are now operating at 150, and 200 kilohertz, and at these frequencies, the copper losses become trivial with respect to the AC losses or the magnetic losses, or the proximity and the fringing losses that are associated with the core and the winding structure on the magnetics.

So, when I mean what I mean by magnetic structure is the windings and the way the mind windings are placed on the central limb of the magnetic core, the typical magnetic core is an EE or an ETD core which has a central limb that is gapped. And the area where the gap is there is a tremendous amount of flux emanating from the gap. So, this flux, this tremendous amount of flux interacts with the nearby copper winding.

So, unless the copper winding is done in a particular fashion and unless a leads wire configuration is used, the losses can far overpower the normal copper conduction losses and you will see a reduction in efficiency.

So, these days finite element method tools and there are specific companies who are providing the services for high-quality magnetics design and this can as much as you know provide you with a 1 percent gain inefficiency. Magnetizing current again is a function of the Lm to Lr ratio, but in certain cases, as I mentioned earlier, if you have to operate at a very wide output voltage range we have to invariably choose a low Lm to Lr ratio. In this case, under certain operating points the magnetizing current increases, providing you with somewhat lesser efficiency.

But then we will see how to mitigate the overall efficiency loss by using a certain scheme in the subsequent slides. These are the secondary side we can use either discrete diodes as rectifiers or we can use the synchronous rectifier scheme using four separate MOSFETs.

The bottom scheme is much more complicated, but the top scheme is used for either low-voltage moderate current applications up to 40 amps or high voltage low to moderate current applications up to 15-16 amps in which we are using either Schottky diodes for up to 200-volt applications or silicon carbide diodes up to 1000 volt applications.

So, both Schottky and silicon carbide Schottky diodes have 0 recovery, which greatly helps in increasing the efficiency when the converter is operating away from resonance, especially when it is operating into the deep inductive region. The key figures of merit for these rectifiers are very low forward voltage drop which is very intuitive and also 0 recoveries. There will be some charge in the junk stored in the junction of these diodes, but it is mostly capacitive charge and this one has no effect, whether it is working on higher temperatures at higher commutation rates or higher frequencies.

So, it is only, it is only the capacitive loss due to the junction that comes in which is only a few milliwatts compared to the few watts that would have happened if the recovery time was not 0. The bottom scheme of synchronous MOSFETs of synchronous certification is used in applications where low voltage and high current are involved.

For example, if you are targeting a 5-kilowatt converter at 48 volts; that means, you need to have 100 amperes of average rectified current which is not possible to be handled with high efficiency using discrete rectifiers.

In those cases, we use high current MOSFETs which are very low on-resistance as rectifiers, and a separate controller called the synchronous rectifier controller is used. It is either a separate analog ic or it is managed by firmware or software inside the microcontroller in the case of digital applications. Here also we have to judiciously apply the scheme because the most common way to use this is up to 10-15 percent of the rated full load, it is the body diode of the MOSFET switch conduct.

And when the load exceeds this lower threshold, then only the MOSFETs come into the picture to provide a much more reliable operation over the entire load line.

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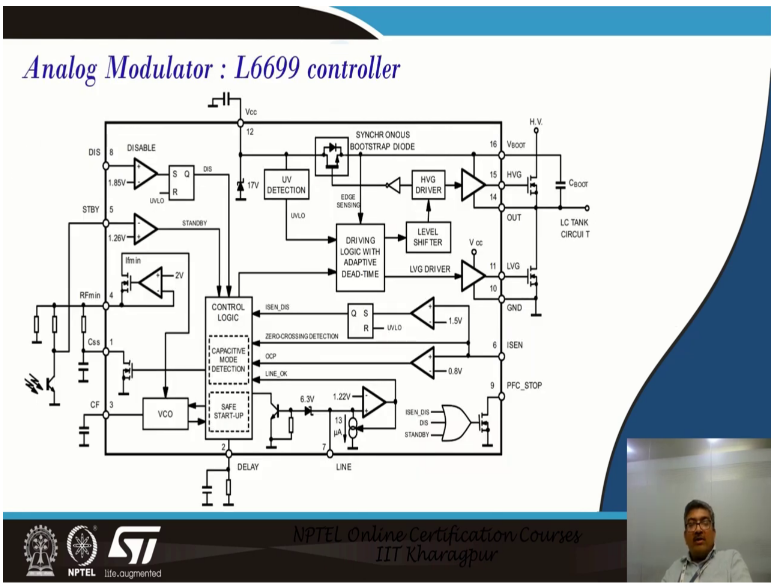

Let us look at one analog modulator and one of the most common modulators that ST offers is the L6699 controller, it is a half-bridge LLC controller, but you can also always connect an external gate driver to drive also a full bridge. Here as I mentioned, this contains all the blocks of a modulator, you can see at the bottom left there is the VCO.

Then you can see there are error amplifiers inside, you can also see there is a bootstrap and the gate driver stage which can drive MOSFETs with a DC bus up to 600 volts. Then you have the interlocking logic, then you have certain protection outputs like signals for stopping the PFC.

Then you have a proprietary block that takes care of additional protection functions like not entering the capacitive zone or something that also handles the over-current protection or something that also helps you to go into standby mode when you are operating at very light loads.

So, I suggest that if you have to have a very deep understanding of how typical analog modulators for LLC controllers work, you should have a look you can have a look at the L6699 data sheet available on the ST website here all the major building blocks for a very robust and the stable, but the fully analog implementation of an LLC converter up to 2 kilowatts or even 3 kilowatts can be realized using the L6699.

When we show you the demo later on, the 2.5-kilowatt system is what we have done we have used another variant of the L6699 which is called the L6599 which essentially contains most of these functions. We have used this device in addition to the microcontroller to provide a CV and a CC loop to design the 2500-watt light electric vehicle battery charger.

So, we have used this and with some tricks and some added logic, we have used a mix of microcontroller and analog modulator to realize a 2.5-kilowatt converter.

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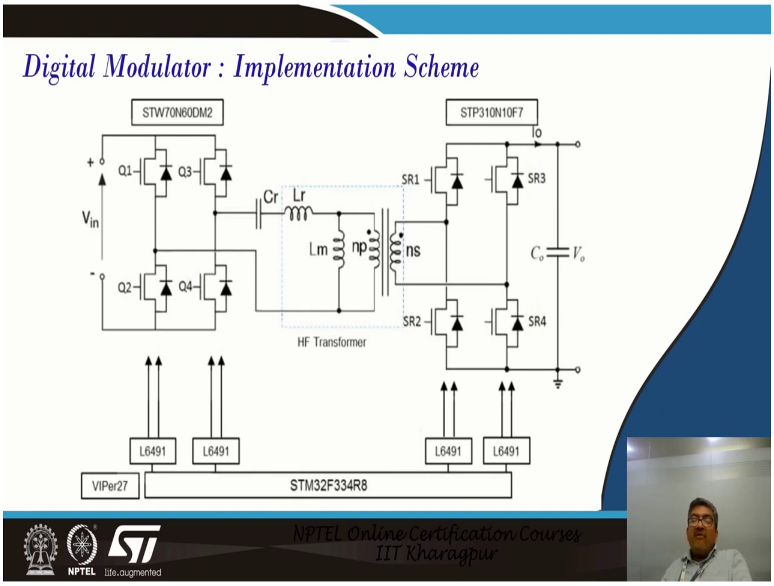

Now, let us look at a digital modulator implementation scheme, which will use a microcontroller to do similar functions to the L6599 or the L6699 controller that I described in the last slide.

So, here you can see it is the same block diagram. So, here is the full bridge power plant, here is the magnetics here is the secondary side synchronous rectification stage. So, what is joining these stages logically is the STM32 IC or the microcontroller which provides all the modulating signals that are required for the primary side and the secondary side.

It also contains all the building blocks all the ADCs and all the sampling systems required for taking a sample of the input voltage, taking a sample of the input current, taking a sample of the output voltage, and taking a sample of the output current.

And basically, using calculations in the core inside to calculate the suitable frequency and the suitable dead time required to run this power plant most optimally. So, here you see, I have added a great deal of flexibility. For example, if I want to try with a different frequency, if I want to try a different modulation scheme, if I want to try and stop the system at a particular operating point it is not so easy to do that on an implement that on analog control. But here I can easily assign a breakpoint like you have seen in the MCU in the MCU course.

For example, if you want to halt the system and operate the and see the operation operational behavior on the power plant at a particular point, you can stop, I can observe, can make changes on the fly, and have a reliable system operating in no time. This is not possible unless you make a significant amount of component changes, which means soldering and desoldering new components in the process errors might happen, in the process, you know short circuits and solder bridges might happen in the PCB.

So, all that things we have avoided. So, once you have validated this entire power plant and once your system has started working in the open loop you can keep on building up your code just by changing the firmware here without having to do no changes in the related hardware. So, this is one big advantage, the advantage of the flexibility and the advantage of trying out novel topologies and novel control techniques without spending much time on designing the analog controller block, which was shown in the previous slides.

So, here once the hardware is ready only the software changes will allow you to achieve what you are trying to do in a minimal time.

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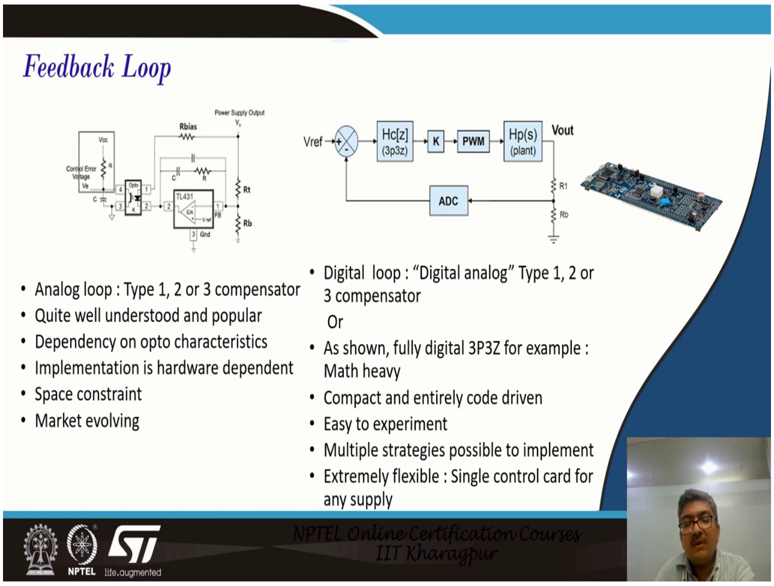

So, let us have a look at the feedback loop, which is typically used in both analog and digital controllers in analog systems the industry uses mostly a variant of this scheme that I have shown here. This scheme that I have shown here is based around the TL431 controller which works very nicely as a type 2 or a type 3 or even a type 1 compensator.

Realization using discrete op-amps is also possible and depending on whether you want to do only constant voltage or only constant current or constant voltage constant current you would need either one or you would need another error amplifier to address both voltage and current. But usually, the voltage and current samples or the feedback are taken from the secondary side, which is the isolated side which means that the user the end user, or a human being might have access to the output terminals.

So; that means if I have to transfer the signal from the isolated side to the error amplifier or to the modulator, which is on the main side I cannot have a galvanic connection so. That means I have to use an optocoupler in its linear region to transfer the error amplification signal or the feedback signal from the primary to the secondary or vice versa. But the problem is while we understand the behavior of the system very well, it is also quite popular, it is also a big drawback that the linearity of the optocoupler depends on its edge.

So, as the edge of the optocoupler increases as the operating hours of the optocoupler increases its linearity degrades and there is something called the current transfer ratio of the optocoupler which also becomes unpredictable over some time. So; that means, your control loop itself would become unstable after several years of operation. So, when you are building high-reliability systems, optocouplers are not the most popular choice it is a simple choice, but it might not be the most reliable choice.

The implementation again of the control loop is fully hardware dependent. For example, if I want to change from type 2 to type 3 or type 3 to type 1 if I want to introduce one more pole or insert one more 0, it is not so possible to do so easily possible unless you are adding external hardware components.

And often it might see it might seem that there is a space constant in the existing PCB, and we cannot add any more components. So, this means for this design, while it is very flexible while it is very simple to understand, while it is widely popular any change needs a change in the hardware and it might not be always possible to do the testing on the fly or to do the testing instantaneously.

These drawbacks have been removed entirely by the market evolving to digital control. So, here I have shown the block diagram of basic digital control. So, the digital loop comes in two forms: one is a digital analog control; that means if I am implementing a type 1 compensator or type 2 compensator, here it is also possible to do in code, we can involve we can do a P or a PI or a PID control entirely in code.

We can implement a type 1, type 2, or a type 3 compensator equivalent or we can also implement fully digital control like the three poles 30 scheme that we have shown here. So, that is entirely in the digital domain, it is quite a mathematics-heavy, but it is very compact and entirely code driven.

So, once you have understood, once the system has become popular like in the lectures that we have seen over the last few weeks, the actual implementation once understood provides you with an amount of flexibility that is unprecedented.

It is very easy to experiment and multiple strategies are possible to implement on the fly. The flexibility and the compactness are one single USB and as I have shown here, in most cases it is one single control card that is used in multiple systems. For example, you can have this you can have a wide lineup of products, but all your products will have a universal control card in which only you need to provide the proper code for the proper for the particular product that you are trying to put out in the market or put into production.

So, this flexibility is completely new, the market is evolving and we are striving to make digital control as easy to understand for mass manufacturers as possible.

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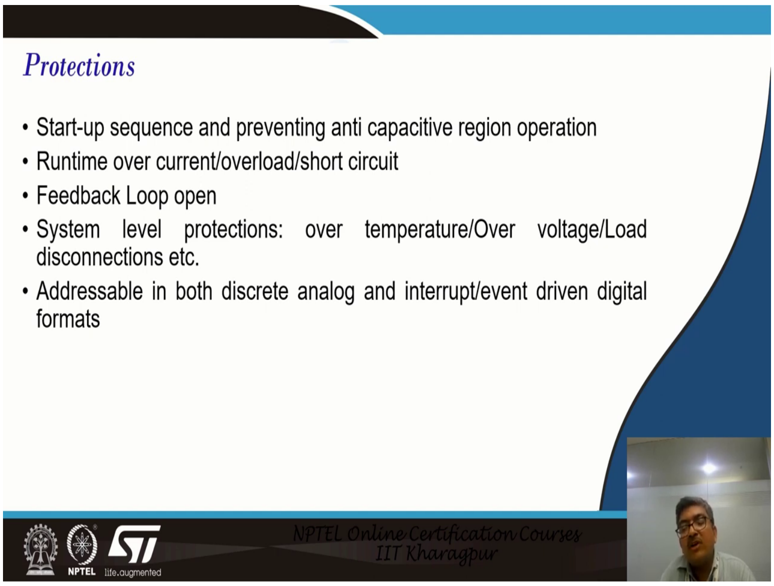

Now, once we have done the design of the other three parts, it is also very important to look at the protection schemes I mentioned in the first slides. The startup sequencing and prevention of entering the anti-capacitive region operation either during startup or during operation is very important. We must also take care of runtime over current, overload and short circuit effects that can happen, these are very common things to happen.

And often when this happens it is not the heat dissipation that causes failure, it is mostly because of entering into the capacitive region because when you are causing an overload or when you are causing an over current the operating frequency tries to shift to the left-hand side of resonance to maintain regulation, which becomes very detrimental to the reliability of the converter.

Many times due to component aging or shock or whatever the feedback loop might become open. When the feedback loop becomes open there is no control over the power plant. So, this is some fallback system that must be taken care of.

System-level protections that must be provided are over-temperature protections, over-voltage protection, certain load disconnections etcetera. So, these things can be taken care of either using discrete analog circuitry using op-amps and BJTs and comparators and discrete gates.

You could also implement this in the digital domain, you can implement it on a microcontroller that will also function as the housekeeper in the form of interrupts. So, even driven digital formats. For example, we could connect the temperature sensors to the various ADC channels, which have been configured as ADC interrupts.

For example, if the temperature rises to a certain level the NTC thermistor of the temperature sensor provides you with a voltage above the threshold that has been programmed and you can generate an ADC interrupt which will tell the MCU that over temperature condition has happened. And the MCU can take steps in either cutting down the output power or shutting down the system to prevent a catastrophic failure. So, all these sorts of protections must also be built into a reliable controller.

And once you have a system MCU in place, it is only a matter of writing a few lines of code to implement as many channels or as many new forms of protection as you want to put. For example, you could add 5 sensors, you could add 4 fans, and you could add 2-3 relays to disconnect your system. It is only a matter of implementation and writing a few lines of code to whatever extra features you want to add in real-time.

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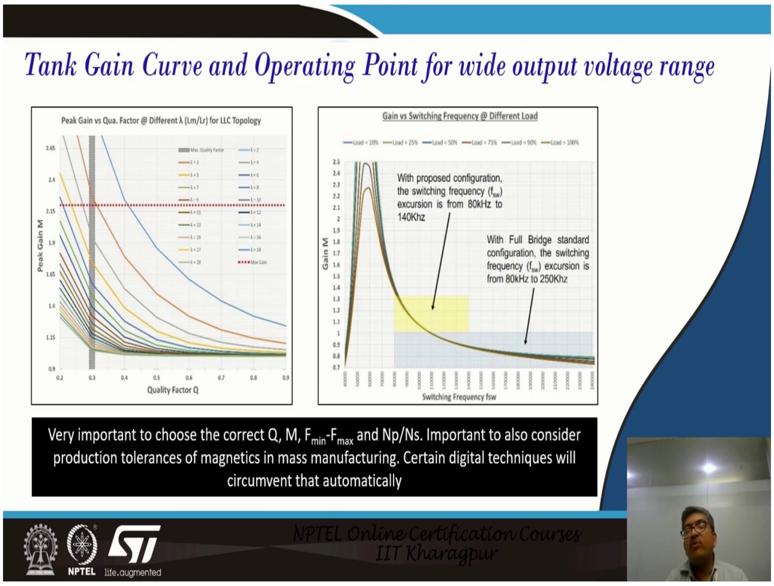

Now, that we have finalized or we have seen how the overall system blocks operate in an LLC converter, it is very important to understand how to choose the resonant tank for a particular LLC converter operation.

For example, if your LLC converter as I mentioned before if it is of a narrow range. For example, if it has to supply only 12 volts or only 48 volts, or only 72 volts, then you must keep the Lm to Lr ratio on the higher side. While on the other hand if you have to work at a very wide span of output voltage, for example, 1.5, or 1.6 times span.

For example, in the particular case that you are going to show, in that case, we have a battery charger that provides output from 40 to 60 volts from an input bus of 400 volts which comes from the PFC controller.

So; that means, here even if the input is constant, the output must change over a span of 1 to 1.5 which is from 40 to 60 volts. So, what we have done is we have chosen a very low value of M, which allows the controller or the converter to operate in this region, to operate in this region to achieve maximal control yet not lose efficiency.

Because if I am operating close to resonance, I am operating at a much higher operating at much higher operating efficiency region. On the other hand, if I have chosen a larger M for example, I would have to operate over such a large span, see over a span of 2, 2, and half times I would have had to operate. That would mean I would have lost efficiency on the lower voltage side, which is the case when the battery is most discharged and is demanding the most current.

So, this gain curve allows you to choose which operating point you operate on and you have to do a few iterations you also plot the actual region so that in worst cases you can set a lower limit of your operating frequency so that you never enter the capacitive region. Which is the most detrimental mode of operation for LLC converters.

So, it is very important to plot these gain curves from the FHA analysis equations you can choose to operate on the steep region or a moderately steep region or you could choose to operate in the shallow region. So, it is entirely up to you how much efficiency your system needs, what your target efficiency needs, how much, how much control, and how much tight control you need over the regulation.

So, again this is a set of curves you can plot from the FHA equations which give you a nomograph, basically what is your M which is the turns ratio which is the Lm to Lr ratio versus the operating Q that you can get. So, from the curve, you can choose that for a certain output power level and a certain voltage span, and a certain gain span, this is the amount of gain and this is the amount of M that I need to provide for a certain amount of Q.

You can go for a lower Q, but it is better not to go for a higher Q because if you go for a higher Q you might end up losing regulation as well as efficiency.

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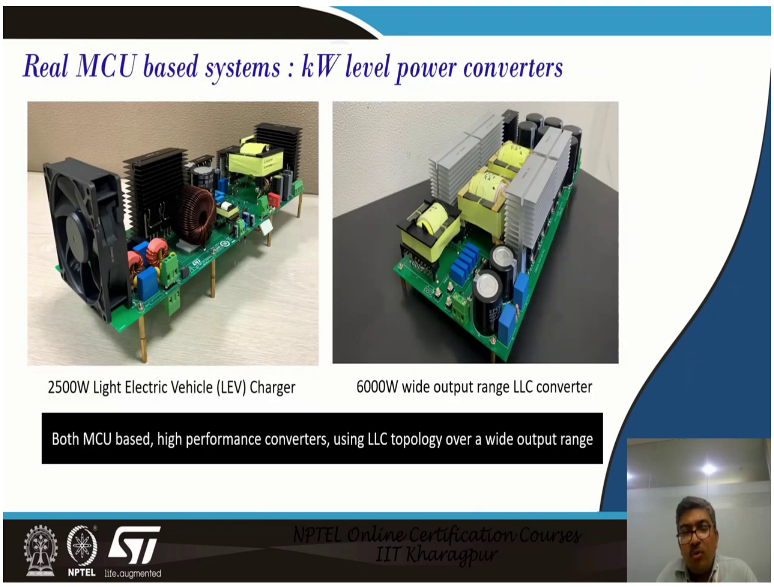

So, these are the two systems that we would show you later on as we progress into the sessions. These are real MCU-based systems; these are kilowatt-level power converters. On the left-hand side, you can see a 2500-watt light electric vehicle charger that provides an output of 40 to 60 volts, and the maximum power and maximum current output are 42 amperes which makes it 2500 watts.

And on the right-hand, side you see we have a 6000-watt, 6-kilowatt wide output range LLC converter, it is just an LLC converter so; that means, it has to be felt 800 volts DC from a PFC. And the output which is meant to charge electric vehicles ranges from 200 to 1000 volts. So, you can see that we have addressed an operating voltage span of 5 times. So, from 200 up to 1000 volt it is a 5 is to 1 span, on an LLC converter this is fully digital.

And we will also see the details of its tank parameters, the simulation results, and how it matches the simulation and the real-life operation figures. Similarly, we have done here, here you can see this is the full design, this is an integrated design that contains both the PFC and the LLC stage here, the LLC stage is on the right-hand side we will show you more details.

So, this again is operating in a span of 1.5. So, from 40 volts up to 60 volts, it can operate and we will see that the efficiency is in the range of 93.5 percent plus that is an end-to-end efficiency, not only in the LLC stage.

The only LLC stage efficiency is close to 96.5 percent, which is very good and it has been done by judiciously choosing the active devices, the output rectifier, and a very careful design of the magnetics.

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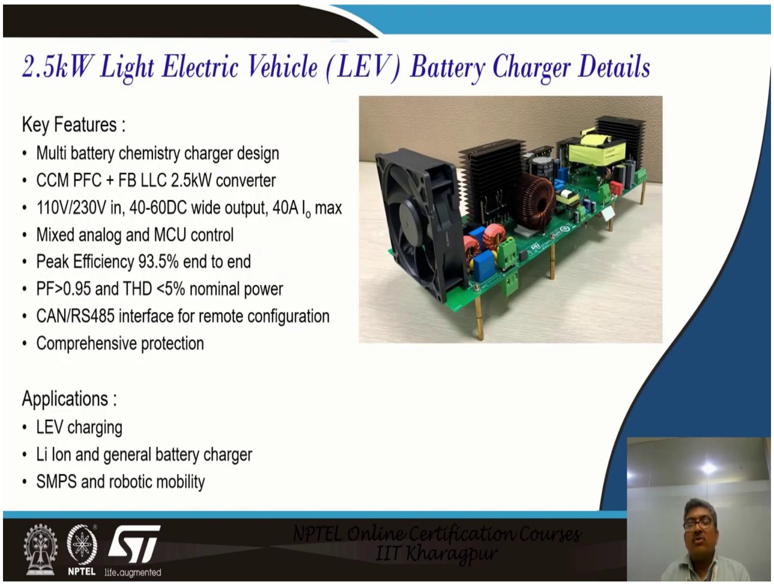

So, this is a closer look at the charger that I just mentioned in the previous slide, it is multiple, and it is a multi-chemistry battery charger. So, it can charge lithium-ion batteries, it can charge lead acid batteries, it can charge nickel metal hydride batteries.

The good part is you do not, you do not need to have separate hardware for separate battery chemistries, it is only a matter of code because the fundamental function of the system which is to transfer power is constant. What is changing is the charging profile of the different battery chemistries; lead acid batteries would have a different charging mechanism. The lead acid batteries would have another sort of charging mechanism; the nickel metal hydrate would have another sort of charging mechanism.

All these charging profiles are possible to be changed in a matter of minutes by doing a very small change in the code of the resident microcontroller. So, what we would like to highlight here is the hardware is ready. So, you have information on the input voltage of the output current. All you need to do is process this information after due communication from the battery and tell the power plant how to behave depending on what the demand from the MCU is or from the battery.

For example, if the battery is deeply discharged, let us consider the case of a lead acid battery of 48 volts which has been deeply discharged. So; that means, a deep discharge lead acid battery might be it is at 44 volts, a deep discharge battery is never supplied with full power, we do a trickle charge.

So, my system knows that if the battery is a lead acid battery and it has reached 44 volts; that means, it is very deeply discharged. So, I must pump only a few amperes of current to slowly revive the battery. As the battery starts slowly reviving I reach about 50 volts which now means that the battery is trying to relieve itself, the battery is recovering.

And when it has reached 50 volts I can now decide that my power plant must supply the full 40 amperes required to charge it in boost mode. So, these decisions or a matter of setting the correct parameters in the code. The entire power plant behaves as per the command sent by the microcontroller.

So, the microcontroller gets its information from the output voltage and the current sampler, which we mentioned in the block diagram, and depending on that it is only a matter of fine-tuning the code whether you want to charge lead acid or a lithium-ion or any sort of battery chemistry that you choose to.

So, this is implemented using a CCM PFC and a full bridge LLC and it can take 110 or 230 volts in and a very wide output of 40 to 60 volts out; that means, it can cater to 48 volts battery of any chemistry again ranging from 40 volts up to a maximum 60 volts. This is by changing the turns ratio of the transformer in a different design can be modified for 36 volts or 72 volts. It has a peak efficiency of 93.5 percent end-to-end with a very high power factor of 0.99 in most conditions and a THD of less than 5 percent at nominal power.

So, it also has CAN and RS485 interfaces for remote configuration and has comprehensive protection. So, you see protection is something that any end product should have as a basic feature to prevent expensive repairs or warranty claims from the field.

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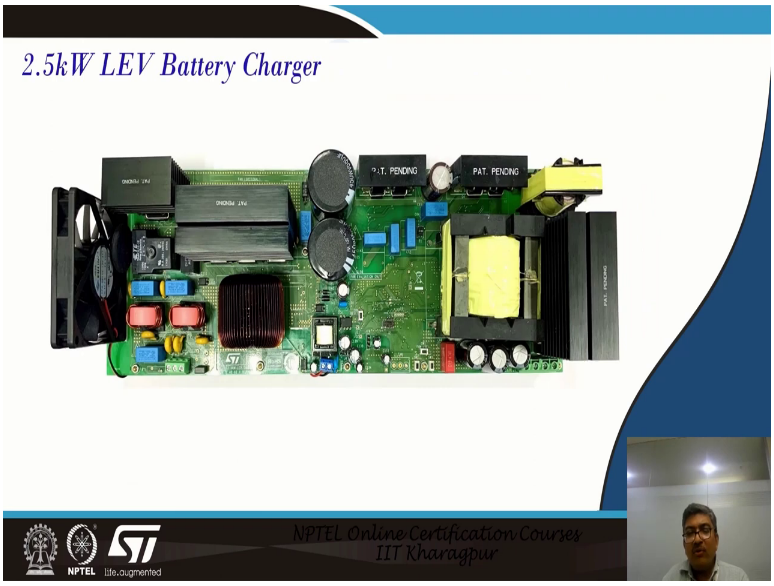

This is the top view of the same converter, on the left-hand side from the middle part of the board, the left-hand side is the PFC stage is the right-hand side which is the LLC stage.

So, these are the two heat sinks where the bridge MOSFETs are connected. We have used a special package of MOSFET for this; we have not used a standard leaded TO-247 or a TO-220 package. Instead, we have used the surface mount package and we will see in a later slide that the efficiency is so high that a very small heatsink is enough to dissipate all the heat. And we will see that the temperature rise of the silicon die has risen by only a few degrees above ambient.

This means it is a very high-efficiency converter, this is the main transformer and this is the resonant inductor which we have kept separate. The ratio of these two is 1 to 4. So, this is around 45 microhenry, this is around 180 micro henry. The biggest heat sink here is that of the output rectifier diodes because that is what carries the highest amount of current close to 42 amperes at full load and this means multiplied by the diode drop of close to 1 volt, this will have the highest loss component.

These are the output filter capacitors which are special very low ESR types because the output ripple current must be handled by these capacitors these blue capacitors here, are the very high-quality resonant capacitors, and these must be very carefully chosen if you have to have a very high-reliability product that you release to the market.

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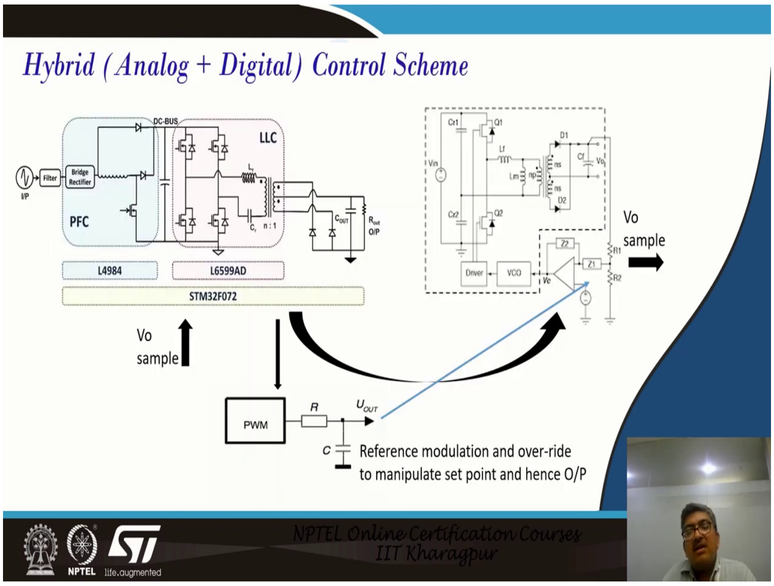

Understand the hybrid or the mixed analog plus digital control scheme. So, in a nutshell, the overall controller is realized in this fashion. So, there is this full bridge stage, which gets its pulse frequency modulated signal from the controller as I explained earlier. For the L6599 controller, on the secondary side, we have the two rectifiers from which it is fed to the load and we have samples of the output voltage and current, which comes to the STM32 microcontroller as well as via the error amplifier to the L6599 IC.

So, by default what happens is, when the system is started it starts at a very low voltage of say 40 volts. Now what happens is, if my demand from the battery is say 50 volts, I cannot pump current into the battery because my system has started up at 40 volts. So, what happens is instead of changing any other operating parameter, let us have a look at the right-hand side error amplifier. Any standard converter would have a modulator here in this dotted line and they would have an error amplifier.

An error amplifier has 2 inputs, one is the output sample through a voltage divider and the other is a reference. So, I can change the output voltage either by changing the ratio of the resistors which means a physical change in hardware has to be done either I have to change I have to increase the upper resistor or I have to decrease the lower resistor. Or what I can do in software is I can use; excuse me another tertiary PWM from the STM-32, which I low pass filter and obtain a DC, or I can use a DAC.

A digital-to-analog converter overrides the reference of the error amplifier with this additional DC voltage. So, what I will do is, suppose the error amplifier reference voltage is 1 volt, corresponding to 1 volt which provides you with an output of 40 volts. And believe and let us assume that it is linear. So, at 1.1 volts it would provide me 44 volts at 1.2 volts it will provide me 48 volts like that. So, I need 50 volts so; which means, I need something around 1.25 volts.

So, what I will do is I will ramp up my PWM at the same time keep on reading my output voltage sample till it reaches 1.25 volts. So, that is my set point. So, I have changed the output voltage without basically changing any hardware parameter, instead, I have just played with the reference. The output voltage is a function of the reference voltage into the error amplifier transfer gain given by the ratio of the resistors.

So, I have to keep keep the ratio of the resistors constant, but I have only played upon the reference voltage dynamically. So; that means, I have used a tertiary PWM followed by an RC low pass filter to average the PWM into its equivalent average DC value, which modulates the voltage reference to provide me with the required voltage.

So, this becomes a programmable power supply from the lowest to the maximum output provided by changing a tertiary PWM which modulates the reference of the error amplifier of the analog modulator.

So, this is why it is called hybrid, because at the core if I remove even the tertiary PWM or if I remove even the microcontroller the power plant would still keep on running, but provide me with only 40 volts of voltage. If I need more voltage, I need to provide the reference or the reference of the error amplifier with a voltage beyond 1 volt to reach my set point.

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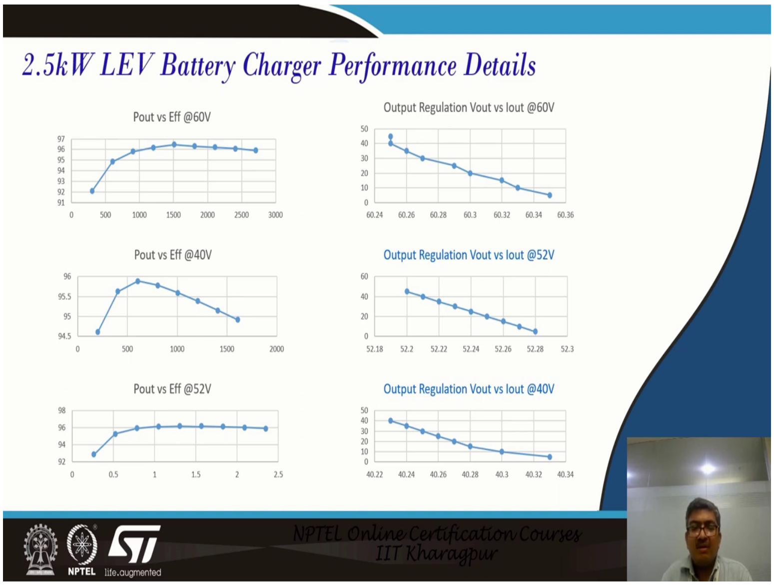

So, here you can see using this same scheme, we have the results of the LLC converter part of the battery charger.

So, at 2.5 kilowatts you can see it is running at very high efficiencies, at light loads the efficiency is more than 93 percent, at very high load, the efficiency touches almost 97 percent and it is always more than 96 percent under all load conditions.

So, for different regions of operation, we have shown 60-volt operation for the 40-volt operation which is the other extreme, and a nominal operation at 42 volts, which is a natural voltage for a 48-volt system.

You can see the output regulation is very tight, output regulation. So, nominal is the nominal and the two other extremes vary within less than 0.1 percent. So, extremely tight load regulation and extremely high efficiency both are possible by using this hybrid control without sacrificing anything.

We have the flexibility of changing on the fly, the battery charging parameters yet we have a very easy implementation, easy less time-consuming implementation of the power plant by using the analog control blocks. So, it is a happy marriage of partially analog and partially digital control to achieve a high-performance charging solution.

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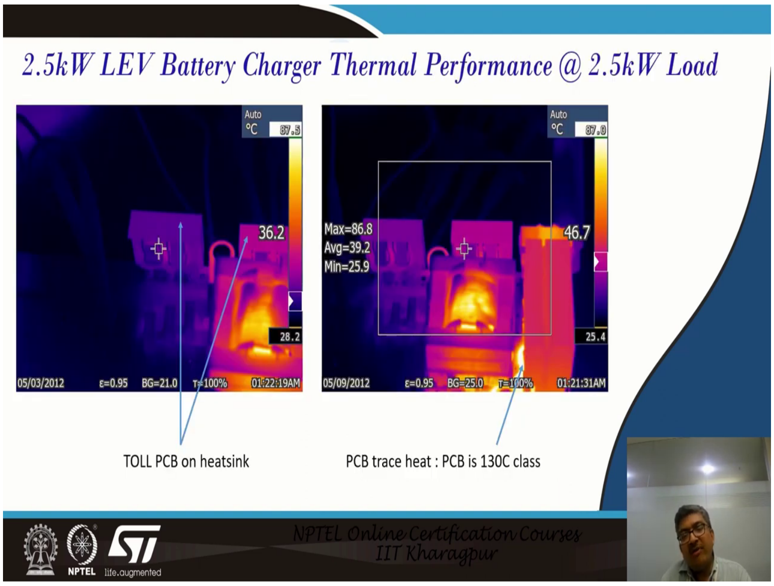

You can see the 2.5-kilowatt converter thermal map. So, this is the heatsink of the LLC MOSFETs, you can see we have we call this package the toll package, it is not the standard TO-247 or TO-220 through all packages that you are aware of. You can see that if you look at this monograph, the maximum temperature is reached somewhere in the transformer and the PCB traces, while the main MOSFETs are cold.

So, the temperature is in the 30s. So, this proves that it how highly efficient the LLC converter can be. Most of the heating is happening in the magnetics and the PCB copper trace. So, we have used a PCB which is of 130-degree centigrade class and here also you can see that the heatsink of the diode output rectifier also is not very odd. So, that is in the range of around 60-65 degrees, which is very much within the operating margin.

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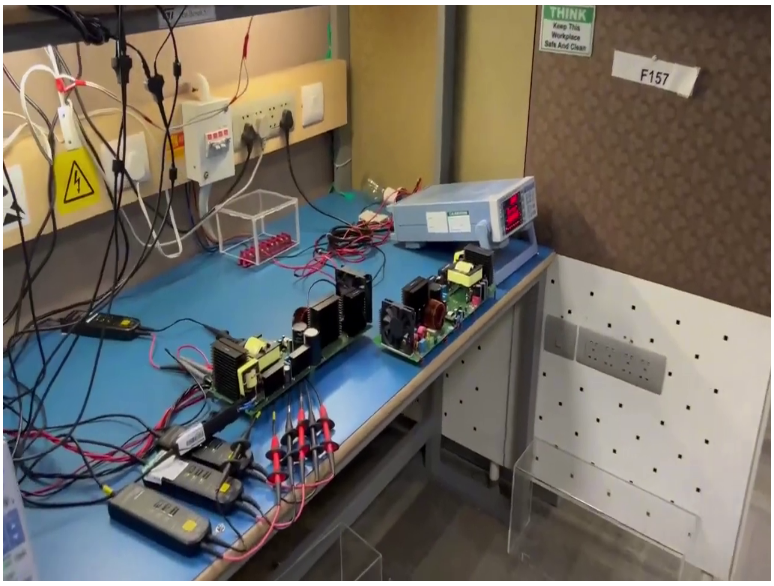

So, now that we have gone through the slides, it is time for the practical demo session. So, I will walk you through the lab, where we have set up the 2500-watt light electric vehicle charger based on the hybrid control that I mentioned. So, these are the two boards that we have kept here, one board has been wired to the measurement setup, and one board is here to show you a close-up, but before that let me walk you through the instruments that we are using.

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Here we have the Chroma 15 kilowatt power source, it is a regulated AC power source, is a 3-phase power source. But it is now wired for a 230-volt single phase as you can see here, this is the calibrated instrument. So, all readings coming from here the voltage, the current, the power factor, the phase angle everything is accurate.

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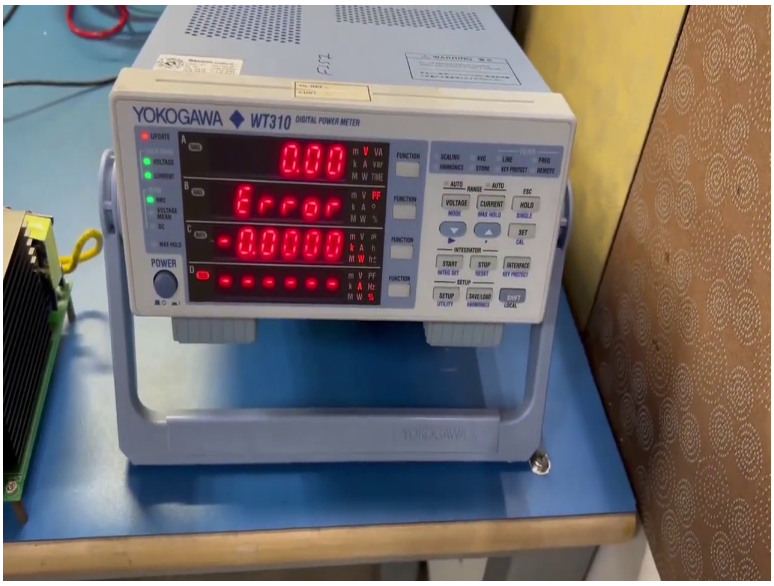

Here we have the input side power analyzer, again this is the calibrated instrument. This measures the input voltage, the input current, the input THD, the current THD, and the input power factor, this is one of the boards that I would like to show you in close-up.

So, on the left-hand side, you can see the fan which is used to cool the board, it is a 65 CFM fan and the air draft is sufficient to cool the hard-switched PFC stage and the very soft-switched highly efficient LLC stage. So, here we have the close-up of the LLC stage, these two are the bulk capacitors, which are the output capacitors of the PFC.

These two heat sinks mount the toll package SMD package power MOSFETs, which is of the full bridge. This is the main transformer, this is the LLC transformer, this is the LLC inductor, the resonant inductor. This heatsink houses the output rectifiers, the output Schottky rectifiers.

Here you can see these are the output bulk capacitors and here you can see the surface mount devices, those are the power MOSFETs, 4 power MOSFETs are used in the bridge configuration and it delivers a total power of 2500 watts. I would request my colleague to kindly put away this board from here.

So, this is the actual board that we have connected. So, these are differential probes, very high-performance differential probes with very high and common mode rejection ratios. And here we have the current probe, the current probe is used to measure the resonant current.

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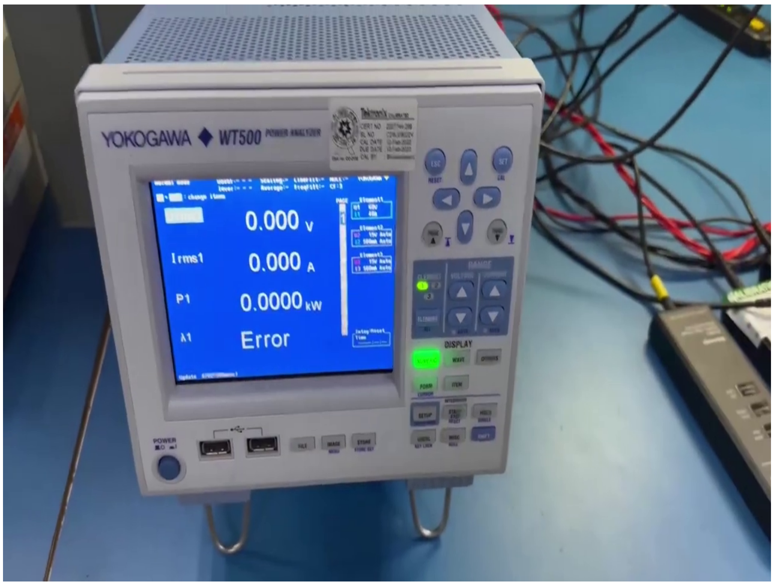

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You can see the same board, at the output of the board we have connected the Yokogawa power analyzer, again this is used to measure the output DC voltage and current. And this is the 6-kilowatt active load, this has been configured now for 5 amperes and this we will also use to stop the load from 5 amperes to 25 amperes and back again to 5 amperes to demonstrate to you the transient response of the converter.

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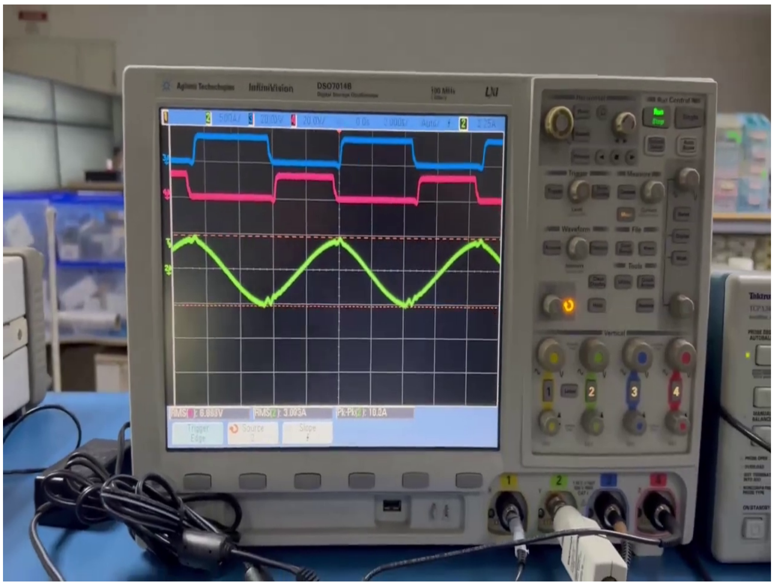

So, if you now watch closely on the oscilloscope, I am asking my colleague to turn on the system. It will take a bit of time because there is a short start routine involved and an inrush current routine involved. So, kindly observe.

So, you can see that the system has started in soft start, it has not abruptly started. So, here you can observe the two gate drives, you see this is absolutely no miller plateau on the gate drives, which means its running in ZVS, and also this kink, the slight downward kink on both sides implies that it is in full ZVS.

So, it is working slightly above the resonant zone, at resonance its voltage is around 54 volts, but at the moment we have tuned the voltage to 48 volts, as you can see here and the current is around 5 amperes.

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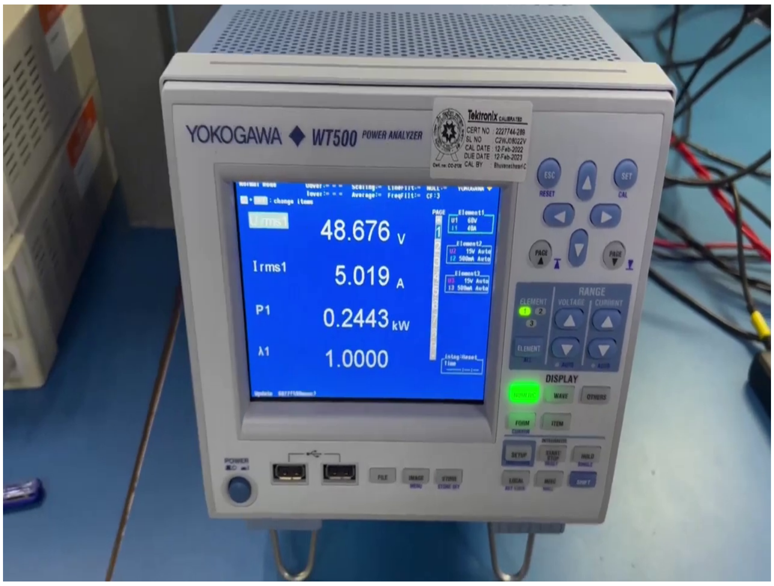

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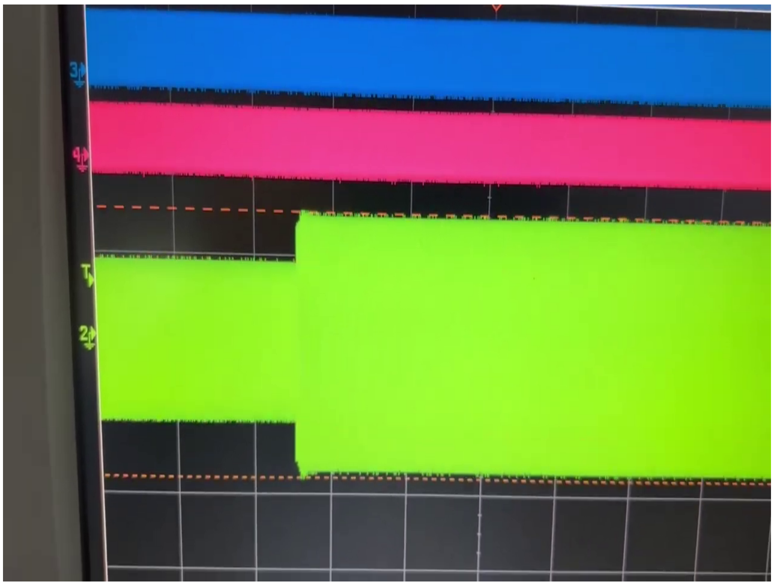

So, now I will ask my colleague to increase the current of this system to 25 amperes. So, we are doing a slow roll so that you can see the actual transient response happening. You can see it has shot up we have shot the load from 5 amperes to 25 amperes, and there was absolutely no overshoot and now he will again cycle the load from 25 amperes down to 5 amperes.

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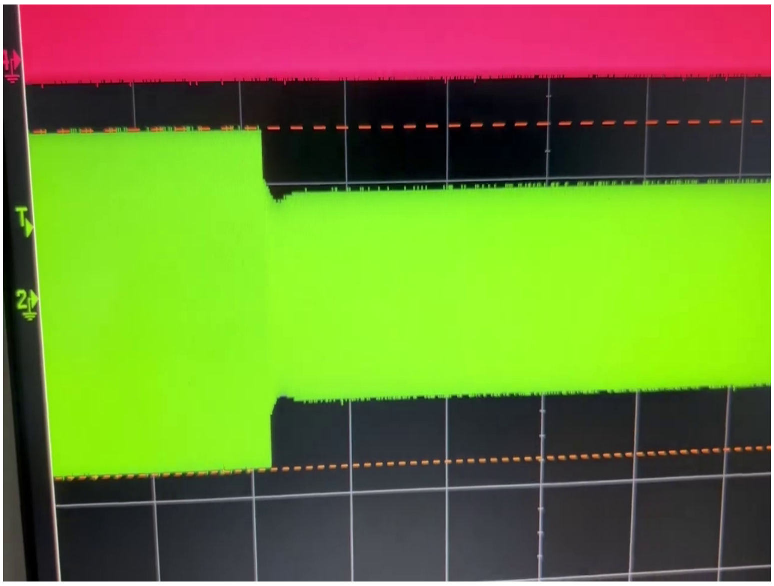

Again, you can see it is recovered very quickly, because this is the battery charger application we do not need a very fast transient response. We have a moderately fast loop, but you can see there is no absolute overshoot or undershoot in the resonant current waveform.

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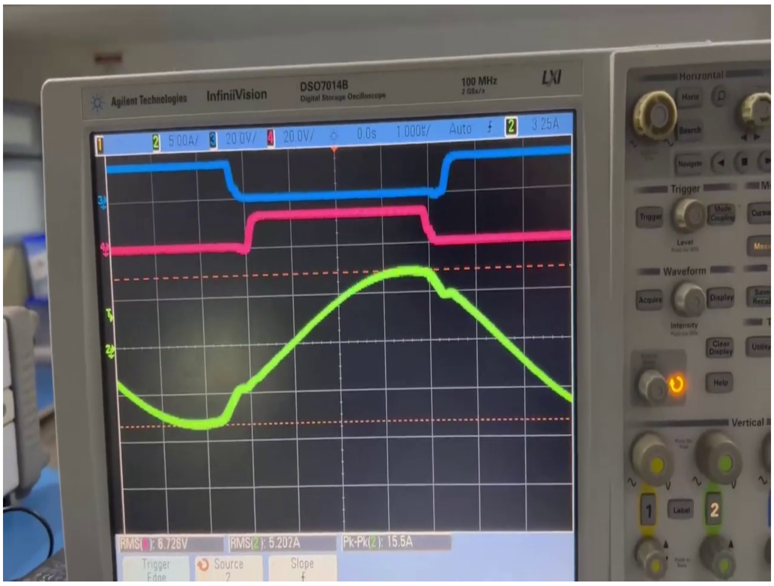

So, now it is running at 5 amps, I would ask my colleague to once again step the current to 25 amperes. So, you can see this is the resonant current; it is slightly above resonance as you can see.

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And now you can observe the input parameters, the input power factor is 0.998 and the input THD is 4.3 percent, while the output is at 48.6 volts and 25 amperes. At 1.2205 kilowatts. So, if you note the output and if you note the input, and if you calculate the input power by output power, you will find that the efficiency is close to 94 percent.

We will now show you the most important part of the control, which is the hybrid control. So, the hybrid control I mentioned uses a tertiary PWM from the MCU to modulate the reference of the analog controller.

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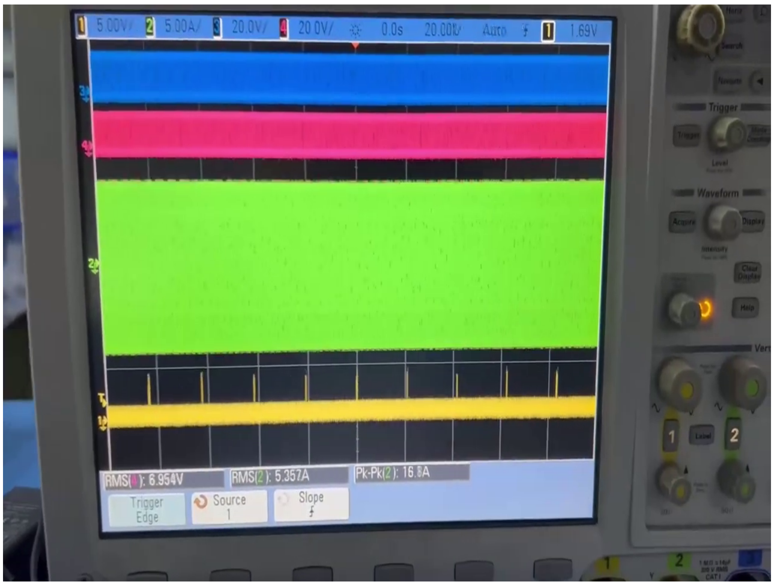

So, basically what we will do is at 48 volts we need a very small duty cycle, we need a very small duty cycle of around 1 percent as you can see here, very narrow spikes to arrive at 48 volts.

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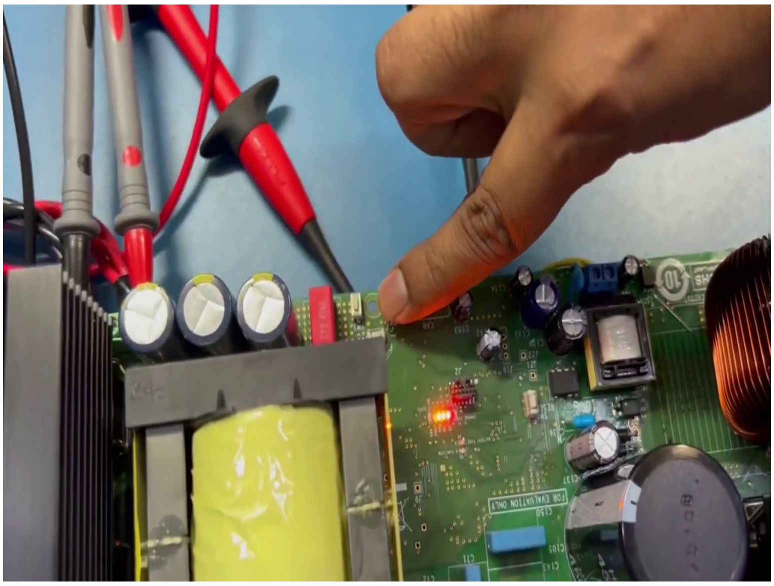

Now, my colleague will increase the value of this tertiary PWM so that, the output voltage increases. So, before that let us quickly make a note of what the output voltage now is under this condition. So, the output voltage is now 48.6. So, my colleague will now change or emulate the change in the tertiary frequency.

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You can see now that the tertiary PWM duty cycle has increased. So, we have stopped it for your convenience.

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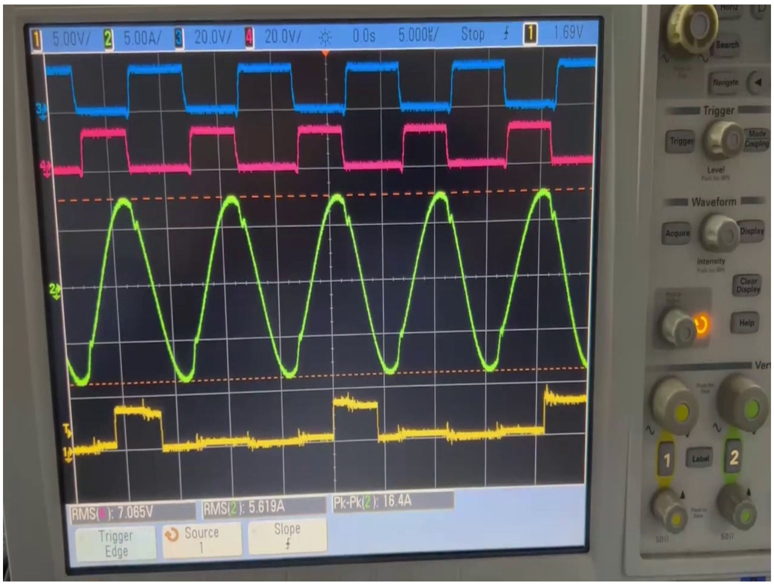

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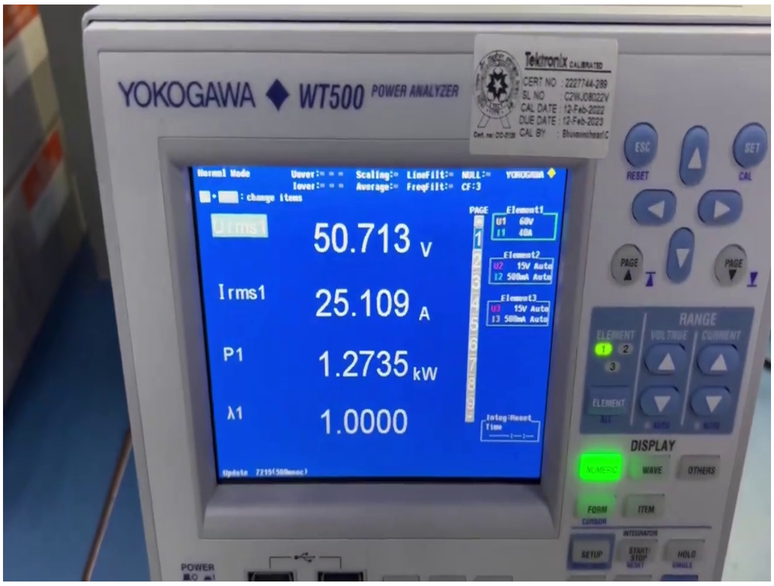

We can now see that the voltage has increased to around 51 volts. We will do a one-more-step jump.

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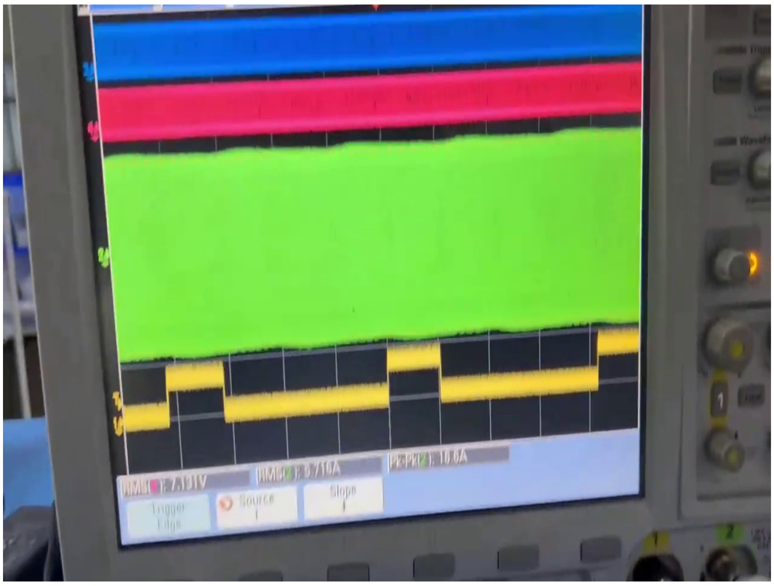

You can see that the voltage will jump to 54 volts, you see this tertiary PWM frequency has increased even further. So, now, it is at around 54.5 volts. So, let us do it the reverse way. Now, we will decrease the tertiary PWM, you can see the tertiary PWM has decreased.

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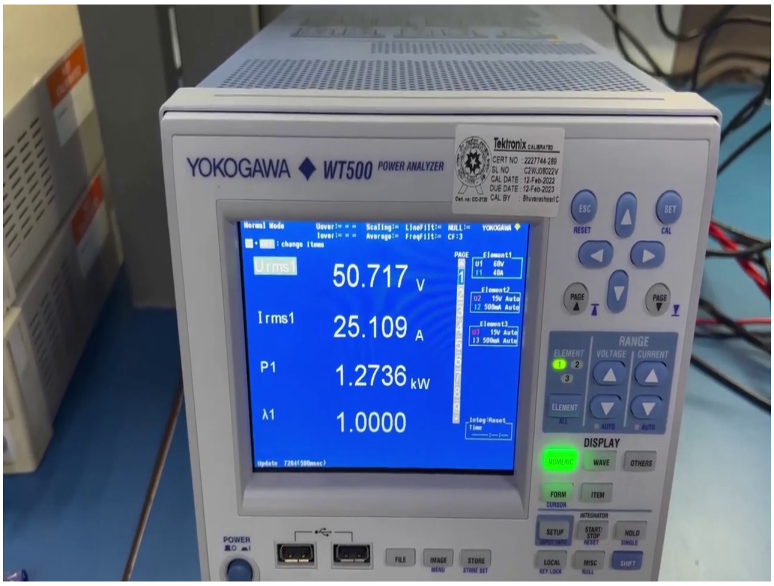

So, the output voltage again has come down to 50.7 which is around 51 volts.

We will further decrease the tertiary PWM to very narrow and you can see that the output voltages again come back to 48.5 volts.

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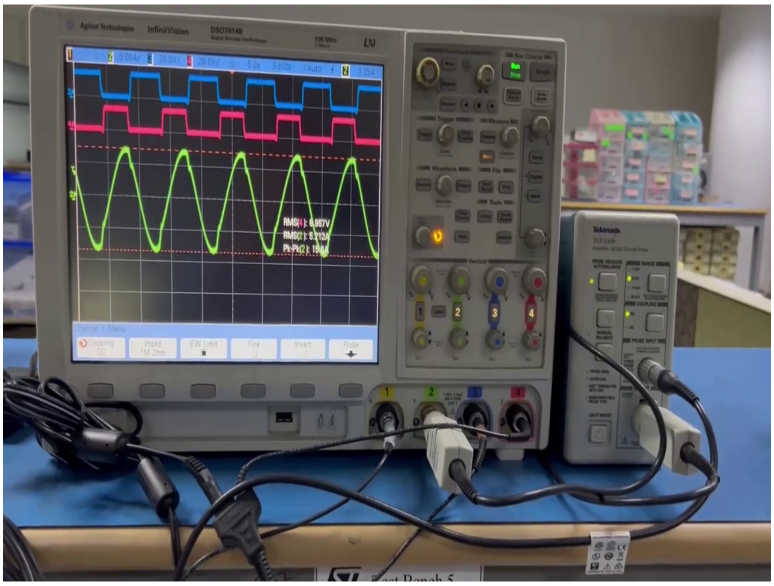

So, essentially by changing the tertiary PWM, we can change the output current or the output voltage depending on what sort of information the master controller receives from the battery BMS. So, this completes the live demo session of the hybrid control 2.5 kilowatts light electric vehicle charger. I hope you can pay attention and observe the function and the important waveforms of this board in question.

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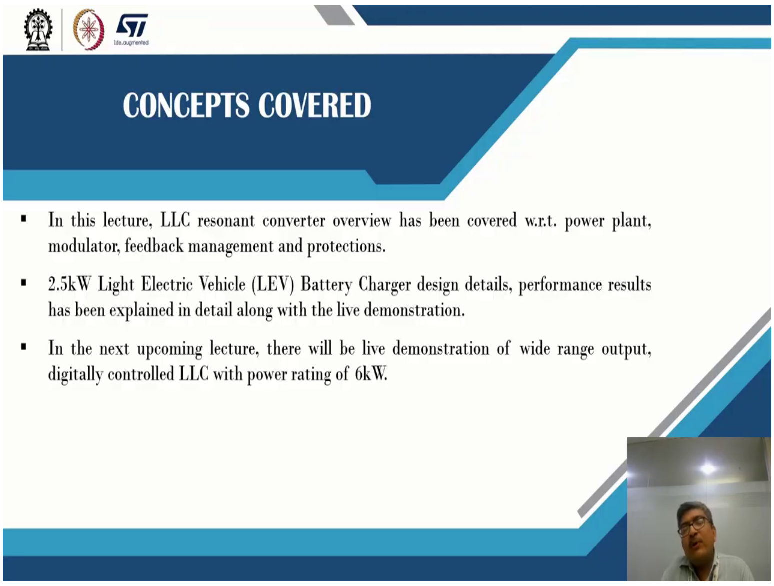

So, hope you can carefully observe the practical sessions and all the waveforms, and all the operating modes that we have shown you in the live lab session.

So, in a nutshell, in this lecture, we have tried to show the LLC converter overview we have we have covered concerning the power plant, and the modulator, with respect to the protection schemes and feedback management. We have also demonstrated to you the 2.5 kilowatt light electric vehicle charging system.

The performance results we have shown you and we have explained in detail with the live demonstration. In the next upcoming lecture, we will show you the wide output range 6 kilowatt converter, which is a fully digital implementation. Again we will show you we will walk you through the actual live session on the actual board that has been developed here in Noida. And we hope you will find that also enjoyable.

Thank you for being patient and for observing and watching the episode. I hope it helps you in designing your LLC converters.