Power Electronics and Distributed Generation
Prof. Vinod John
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 37
Examples in Power Electronic Design for DG Systems

Welcome to class 37 on topics in power electronics and distributed generation. In today's class, we will discuss a couple of example problems on power electronic component selection analysis of power electronic circuits.

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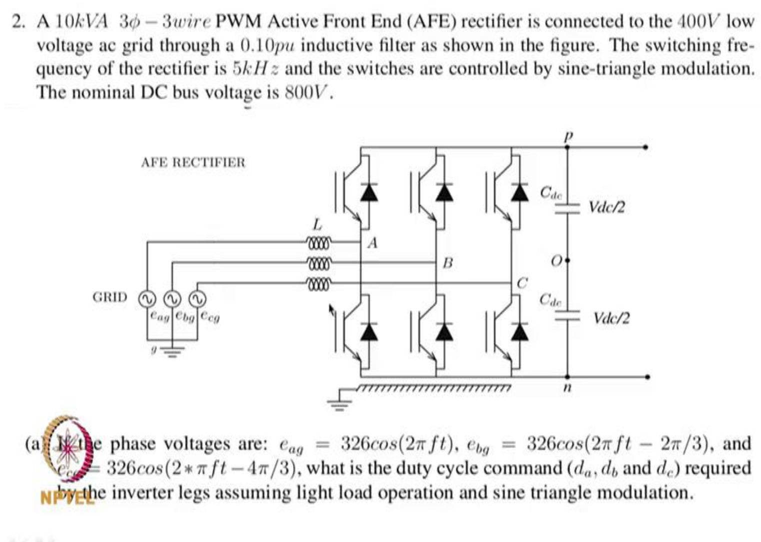

So, we will first look at the problem of three phase three wire power converter and it is operating as a active front end rectifier and it is connected to low voltage a c grid 400 volts with filter, inductive filter for interconnection. The filter is 0.1 per unit or 10 percent inductance and the switching frequency of the power converter is 5 kilo hertz and the DC bus voltage has nominal value of 800 volts.

So, we have given the grid voltages, v e a g a b and c, so this corresponds to the phase voltages of the grid and its balance in this particular case. So, the first question is what is the duty cycle command required by the legs of the inverter, assuming that it is light load and using sine triangle modulation. So, at light loads the drop across this inductor would be small, so the voltage at the grid would be closed to the voltage at the a, b and c points. So, we could use that to determine what is the voltage, the duty cycle required for leg a b and c and because this is sine triangle modulation. The fundamental voltage over here with respect to O would be similar to the fundamental voltage with respect to ground assuming small drop across the filter L.

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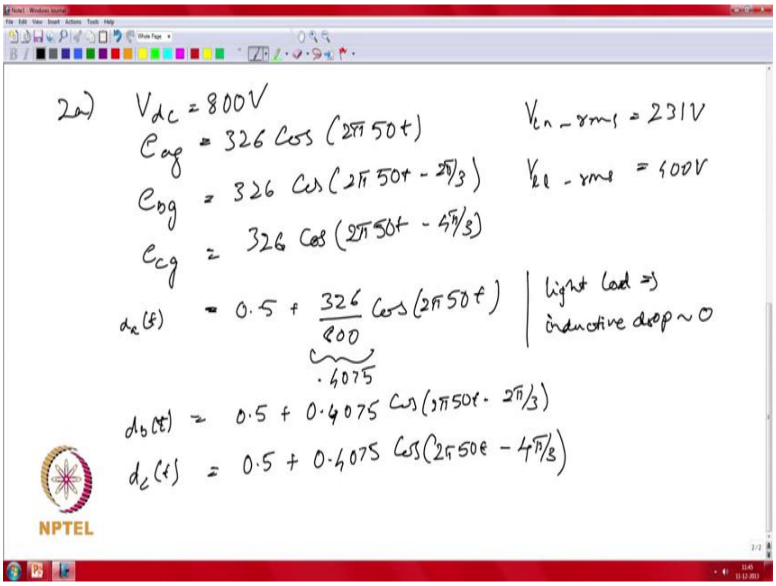

So, we have V DC is 800 volts and e a g is 326 cos 2 pi 50 t and e b g is a function of time is 326 cos 2 pi 50 t minus 2 pi by 3 and e c g and this corresponds to V line to line to RMS value of 231 volts and v line to line RMS value of 400 volts. So, if you look at your duty cycle d a of as a function of time is given by 0.5 plus 326 by 800 cos 2 pi 50 t. So, this is actually 0.4075, so this is because you have light load, so your d b of t is phase shifted by 120 degrees and DC free shifted by further 120 degrees.

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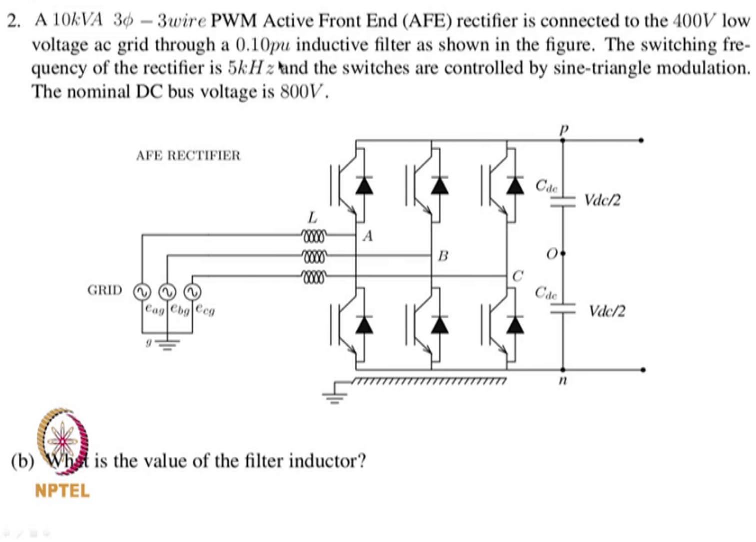

So, in the next problem you are asked to find what value of this particular filter inductor is, so it is 10 percent, so you can use that to calculate what the inductance is.

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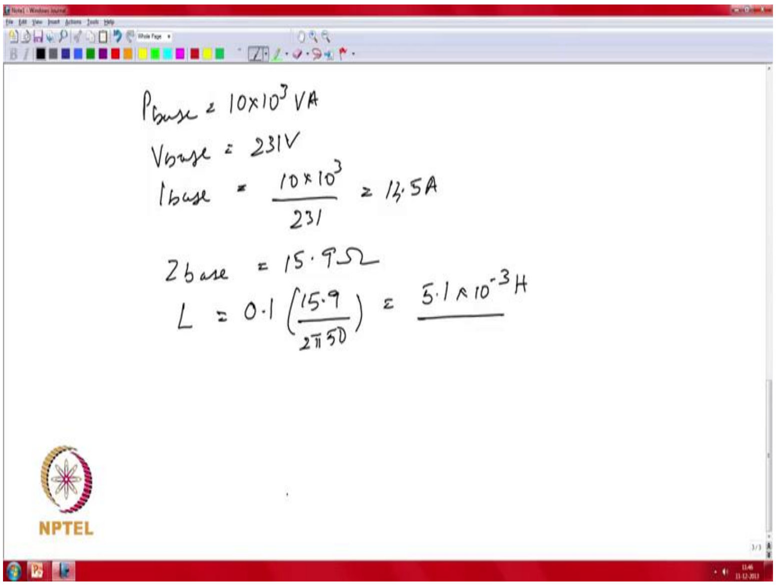

So, you have P base is 10 cube V A, 231 volts and I base is 14.5 amps, your z base is V base by I base. So, that is 15.9 ohms and your L filter inductance is 0.1 times 15.9 divided by 2 pi 50 is a fundamental frequency, so this corresponds to 5.1milli Henry.

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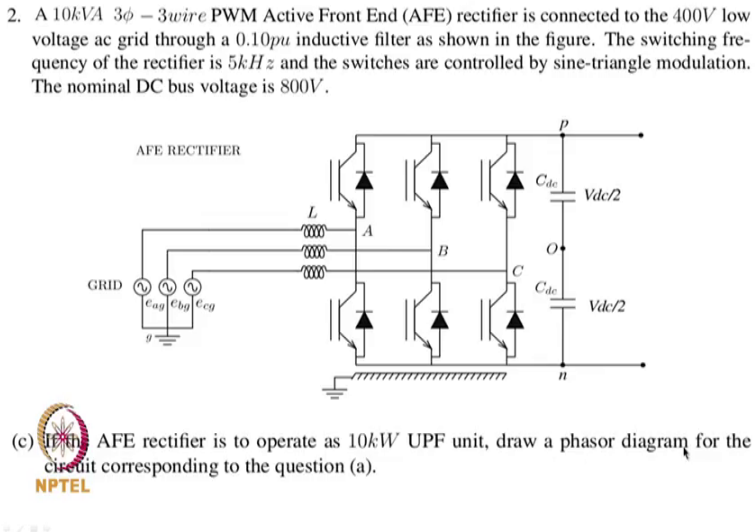

So, in the next problem you are asked to look at what would be the actual voltage at the a b and c terminals with respect to ground. The active front end rectifier is operating at 10 kilo watt unity power factor, by drawing a phasor diagram of this particular circuit.

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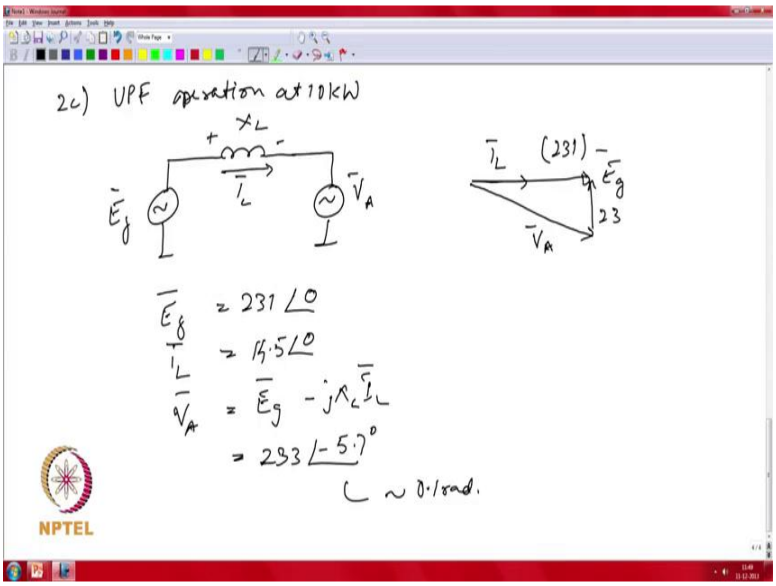

So, for UPF operation, unity power factor operation at 10 kilo watts, you have your grid voltage e g phasor, then you have your filter inductance with the current to the filter being ideal and you have phase a voltage phasor V A which you want to figure out. So, if we have the phasor diagram would be you are your grid voltage and you have the converter operating at unity power factors. So, I L is in phase V A, so your you know that this voltage is 231 volts and the filter inductor is 10 percent.

So, the voltage drop across the filter inductor is 23 volts and so you could use that to calculate what your v a phasor is. So, your e g is 231 at angle 0 I L is 14.5 at angle 0 and your V A is E g minus j x l I L and this could be 232 at angle minus 5.7 degrees, so this corresponds to about 0.1 radius. So, this gives you the information of what the voltages the terminals of the converter should be.

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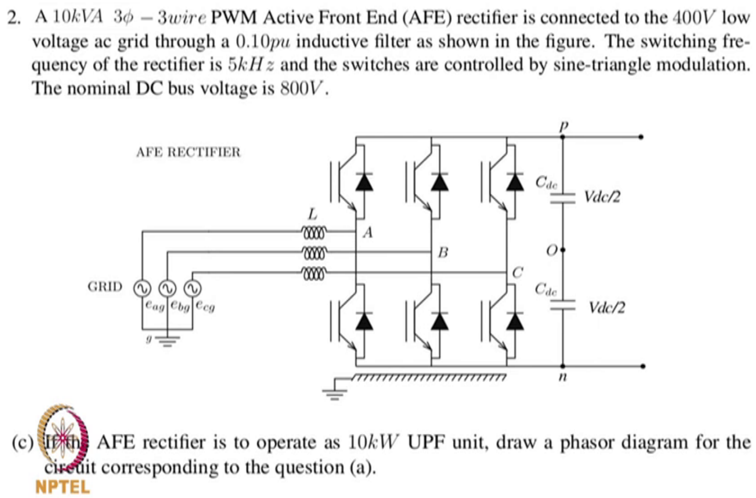

So, you have this particular voltage at when you are operating a 10 kVA, you can use that to find out what is a actual duty cycle that is commanded with a legs of a power converter.

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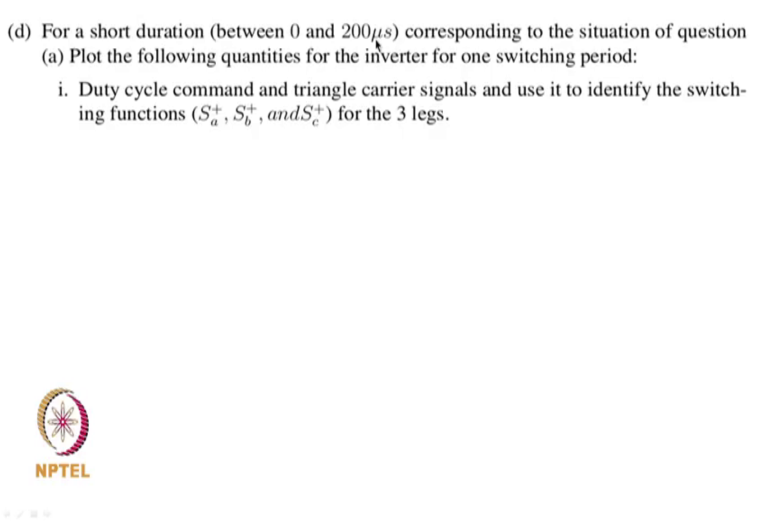

So, the next question is to actually determine the duty cycle and plot the switching functions for the first 200 micro seconds.

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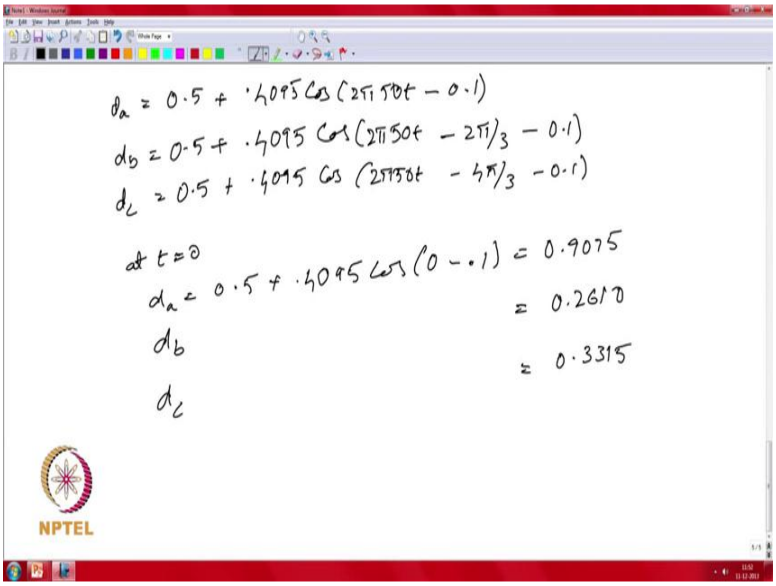

So, your duty cycle for leg A is now given by 0.5 plus 0.4095 cos 2 pi 50 t minus 0.1 and your d b is at this you can evaluate at time t equal to 0 and you get at t equal to 0. So, this would correspond to the value of duty cycle at time t equal to 0 and assuming that you have a digital controller, this would be the value that is used by the controller to compute what PWM commands to actually provide to control the power converter. So, you would have d a is 0.5 plus 0.4095 cos 0 minus 0.1.

So, this is 0.9095, now we can calculate d b to be 0.2610 and b c to be equal. So, now you have the d a, d b and d c for the first searching interval, so the first 200 micro seconds, you can then look at what is the switching function the corresponding switching function.

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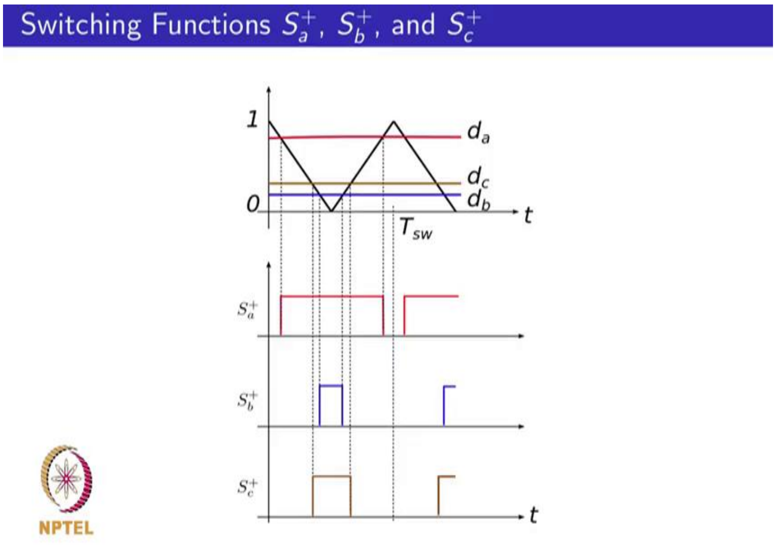

You can actually plot that, you have if you plot the carrier and the modulating wave forms d a, d b and d c.

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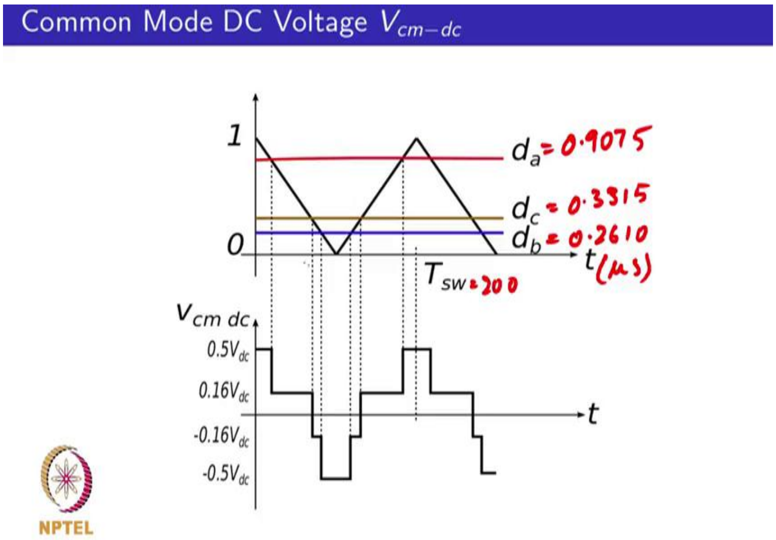

You have d a is equal to 0.9075 d b is0.3315 and your switching period is 200 micro seconds, you look at the time in micro seconds. This is 200 and you could then look at your different points of time, so your t.

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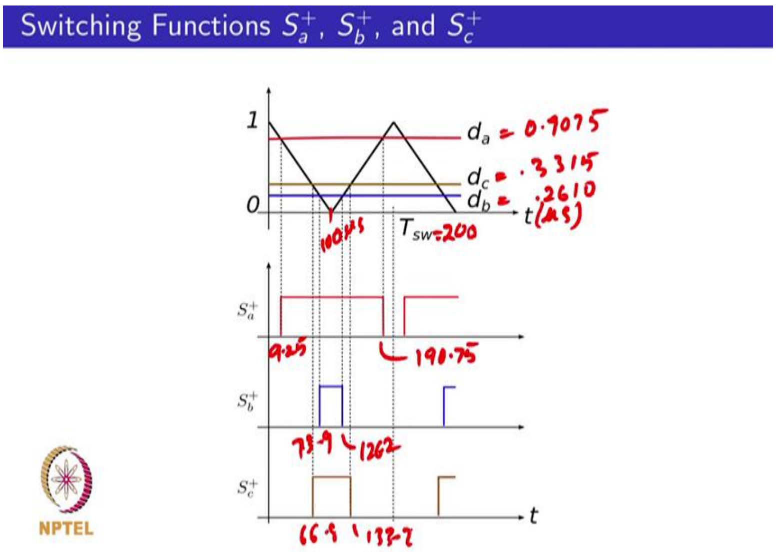

Your d a intersection would correspond to 9.25 going on till 190, your b t, b switching signal would correspond start from 73.9 up to 126.2 and your switching function of AC would be between 66.8 to 133.2. So, you could actually find a instance depending on the duty cycle and your triangle your carrier. So, this would be 200 micro seconds, this would be 100 micro seconds and you could actually plot your switching functions based on your value of the duty cycle and the carrier.

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(d) For a short duration (between 0 and $200\mu s$) corresponding to the situation of question (a) Plot the following quantities for the inverter for one switching period:

ii. Using the switching functions obtain the common mode AC side voltage, where $V_{cm-ac} = (Vag + Vbg + Vcg)/3$, showing the time instants and voltage levels.

So, in the next problem you are asked to evaluate what would be your common mode AC side voltage. The common mode AC side voltage is VA with respect to ground plus V B with respect to ground plus V C with respect to ground divided by 3 at the inverter terminals.

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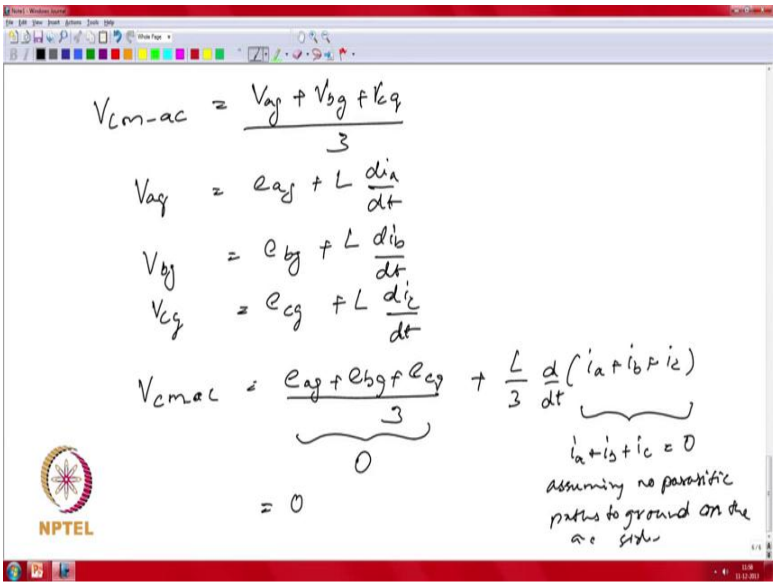

You can evaluate this on the ac side of a inverter is, so we have from the converter circuit it is a three phase inverter. So, from the circuit of the power converter, you have the voltage at v is equal to the voltage from the grid source plus LDA by d t the voltage drop across the inductor so you can use that to evaluate v a g. So, your common mode ac side voltage is the first term would be this, this term would be 0 if you are considering is balance grid operation.

A second term over here would be 0 if you are assuming a couple of things, one is that this is three phase, three wires. So, the sum of the currents should act 0, the second thing that you are assuming is that there are no parasitic parts to ground. So, your I a plus I b plus I c is equal to 0 on the ac side, so their common mode a c side voltage would be 0.

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(d) For a short duration (between 0 and $200\mu s$) corresponding to the situation of question (a) Plot the following quantities for the inverter for one switching period:

iii. Using the switching functions obtain common mode DC voltage, where $V_{cm-dc} = (Vpg + Vng)/2$, showing the time instants and voltage levels.

Next, you are asked to plot the common mode dc side voltage and your common mode dc voltage is V p, the positive bus with respect to ground plus v t bus with respect to ground by 2, we can use the definition of that to find the common mode dc voltage.

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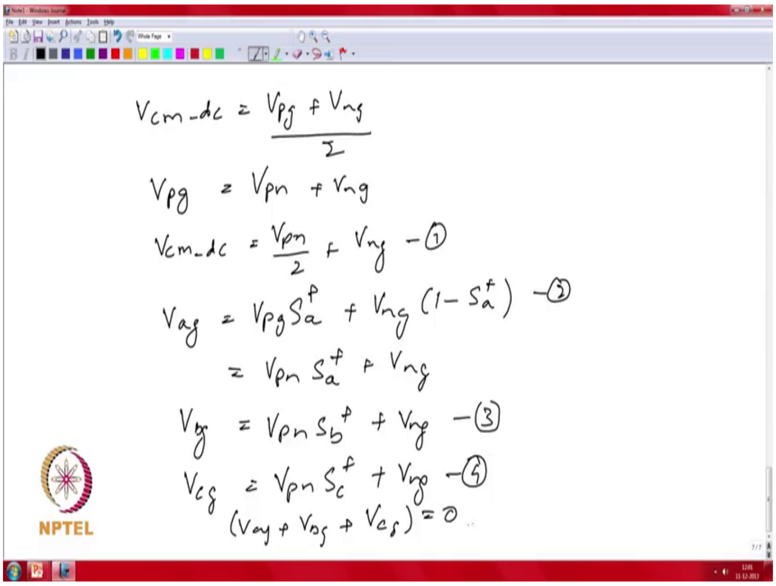

You know that v p with respect to ground can be drawn as v p with respect to m negative plus v n with respect to ground and so your common mode dc is V p n by 2 plus V n g. So, if you take that as 1 and you could then write you're a, b, c voltages as V a g is the voltage at leg a with respect to ground is V p g into s a plus V n g 1 plus s a 1 minus s a plus, so because it is a complimentary function. So, if you consider this as 2, so you could write this as V p with respect to n s a plus V n g, V p g into s a plus minus v n g into s a plus is V p n.

Similarly, you can write V b with respect to ground is and V c with respect to ground with respect to V n into V c plus V n g. So, if you have some 2, 3 and 4, you can get essentially V a g plus V b g plus V c g, which we know is 0 from the previous derivation from the common mode ac side voltage so we have this.

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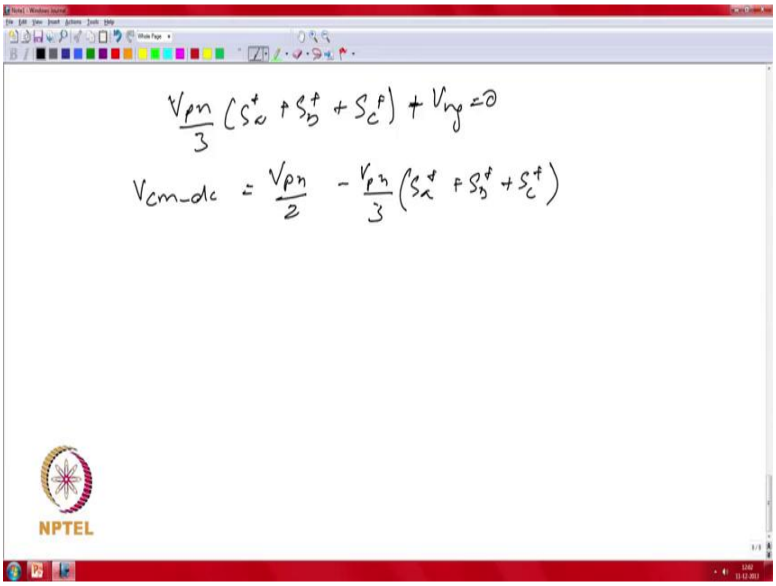

So, you could make use of this expression and substitute that in the expression one for the common mode dc bus voltage to get V dc common mode. So, you can express it in terms of your dc bus voltage and the switching functions of the individual legs, so if you plot it, you will get a function that looks roughly such a like this.

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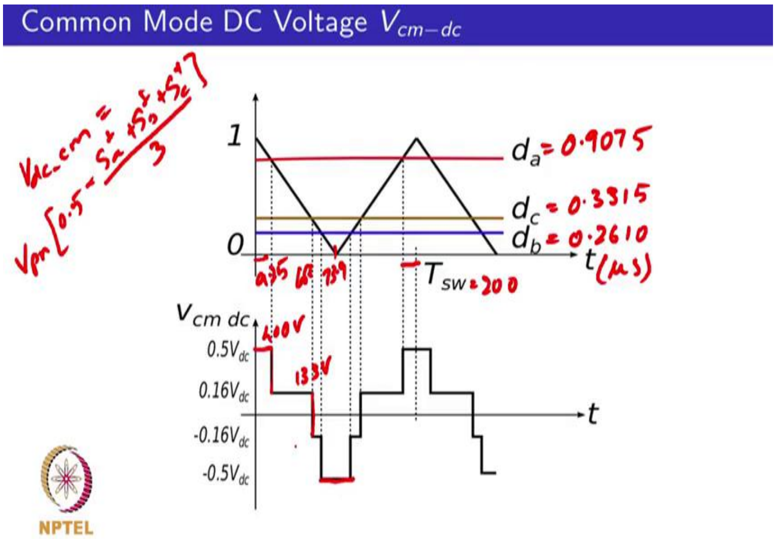

So, you have V dc common mode is equal to V p n into 0.5 plus minus, so if you plot that and all the switches s a, s b and s c are pi, then you have 0.5 minus a h minus 1. So, that would correspond to the duration over here, you will end up with minus 0.5 V d c when you have all the switches sitting at 0, which would correspond to say this particular duration, this two durations you would have V p n is equal to 0.5. So, this would correspond to plus V dc by 2 and then you have steps of one third V dc depending on whether you have just one switch being high or two switch being high.

So, you have a 0.166 V d c or minus 0.166 V d c and the timing instance, where this transitions occur. So, 0.5 V d c would correspond to 400 volts 0.166 V dc would correspond to 133 volts for a 800 volts dc bus. These points of time are the same intersection points, if this is in micro seconds, you have 9.25, 66.8, 73.9 and by symmetry it would continue on the other side.

So, you could actually plot the common mode dc bus voltage, which has a six steps structure in every a PWM cycle and one could then look at the edges when this sharp transitions occur. Depending on what it is, a parasitic with respect to ground at each of those points, those parasitic capacitors can get charged or discharged causing ground currents in the overall system.

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(d) For a short duration (between 0 and $200\mu s$) corresponding to the situation of question (a) Plot the following quantities for the inverter for one switching period:

iv. Identify the circuit parasitic components in the AFE rectifier through with resulting high frequency common mode currents can flow.

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So, the next question is to identify what are the parasitics to ground for this active front end rectifier, you have parasitic to ground, you have device heat sink to ground capacitance.

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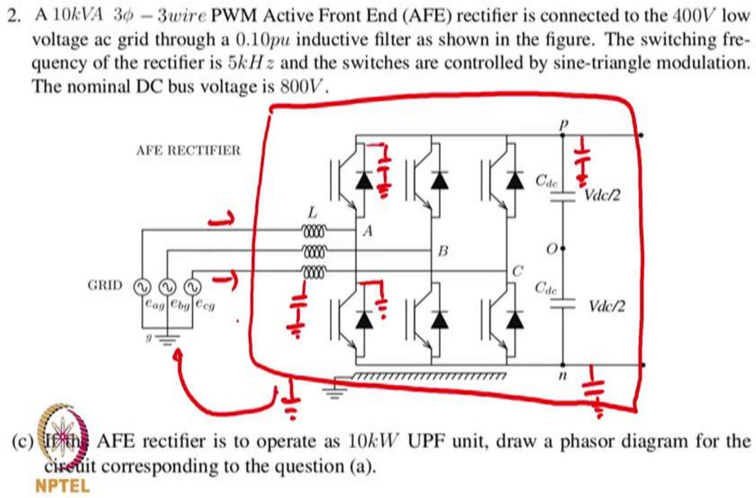

So, you have the device heat sink to ground capacitance, so you have capacitance between your collective of your IGBT chips or the cathodes, your diodes with respect to ground. So, for the top chip and for the bottom chip for all basic devices, you would have capacitors, you could have capacitances of the dc bus capacitor, the actual capacity faults with respect to the frame which connect to ground through parasitics. So, you have parasitics of the dc bus capacitance to ground, also the bus with respect to ground and the path could be your inductors are wound the windings are wound at core and the core might be connected to the cabinet.

So, you would have parasitic capacitance going to ground from the inductance to through the parasitics to ground. You could have then the converter sitting within a frame, so this ground currents would couple to the converter frame and the frame itself might be grounded. Then, there would be parasitic current powers going into the ground to ground point of the source and then going back to the power lines, so you can have a variety of parasitic parts.

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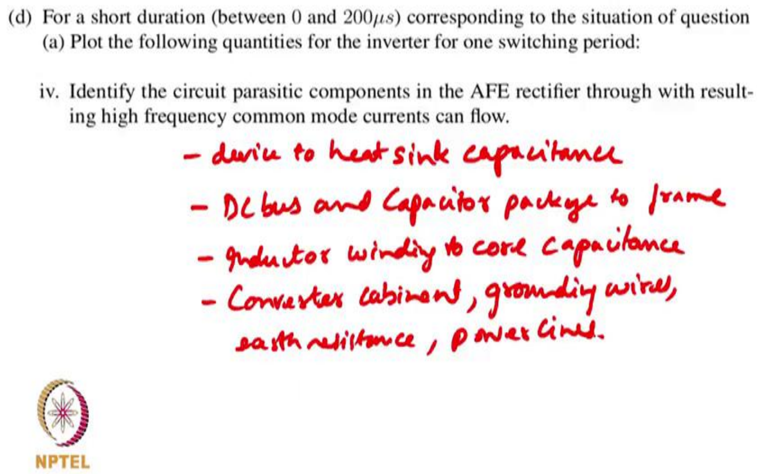

So, device to heat sink capacitance, then the split and capacitor package to frame capacitance, you have inductor winding to core capacitance and you have your actual converter frame cabinet, your grounding wires, your earth back through the power lines. So, this would form a loop through which you could have common mode currents flowing which would lead to interference phenomena.

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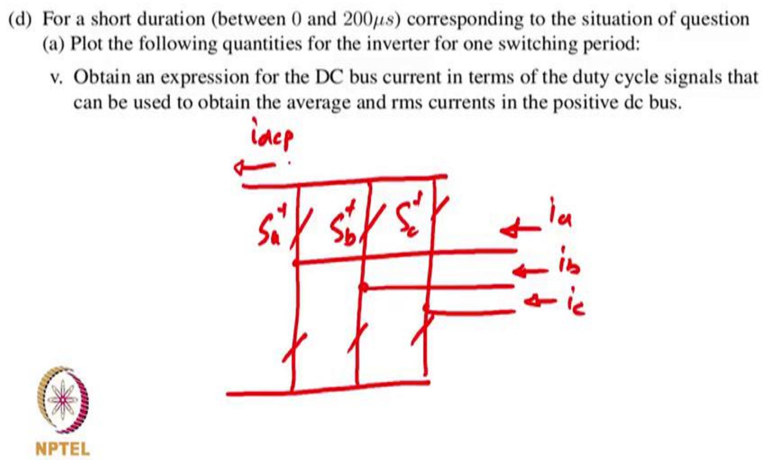

The next question is to look at what is the dc bus current obtained expression for dc bus current in terms of the duty cycle of the signal that can be used to obtain the average and

RMS currents in the positive dc bus. So, if you consider your power converter as three phase power converter, you have your three legs, so a quick schematic, so this is I dc of your positive dc bus. So, you have switches s a plus s b plus s c plus and you have currents I a, I b and I c and what you would like to evaluate is what is a average and RMS currents in the dc bus grid or in a per cycle basis.

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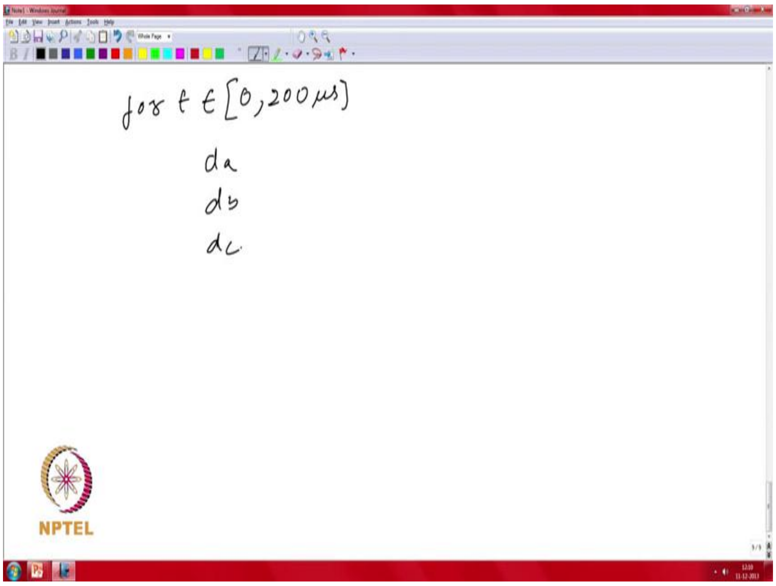

So, to evaluate this in a duration at 0 to 200 micro seconds, you can look at your duty cycle signals d a, d b and d c.

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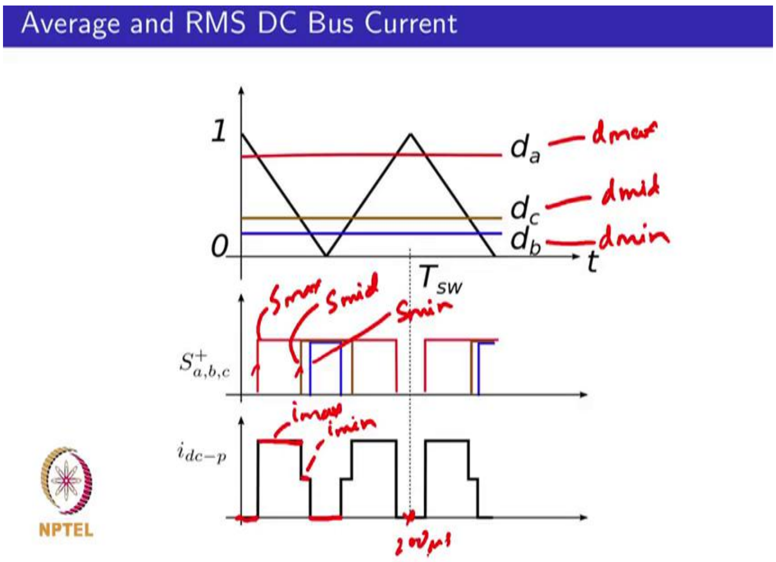

So, if you look at the duty cycle signals d a, d b and d c, so we had the values of d a, d b and d c, in a previous slide d a is the maximum, so this is your d max the d b signal is a minimum d min and d c is the midpoint in the middle between d a and d b. So, we will call it d mid, so if you look at the switching signals, similarly you could corresponding to the phase which is at the maximum and the minimum, you could call this as your s max and the one which is having the narrow pulse, we could call it the s minimum. The pulse which is in between would be s mid, so you could then identify what would be the currents that would flow through the dc bus, positive dc bus in each of these durations.

So, if you look at the first duration over here, when all the switches are low, then if all the switches are low, then essentially your dc bus current would be 0. Similarly, when all the switches are high, all the some of the input currents would be 0, so the currents over current over here would add up would add up to 0. So, you get 0 current in a, the duration corresponding to the first duration, when all the switches are high are low and when all the switches are high you will have 0 current.

If you look at the duration when corresponding to s max between s max and s min, then essentially you have one phase which is connected to the top and the other phase which is connected other two phases, which are connected to the bottom. So, if you consider the current in phase corresponding to d max to be I max, then the current that would flow in this particular duration between the point at which your s max rises. The point at which s s mid rises would correspond to the current in the phase which has d max, so we will call that as that current as I max.

If you look at the duration between the midpoint and between the mid the switching of the mid switching signal and the narrow switching signal, then you have two switches which are connected to the top. You have one switch which is connected to the bottom, so if you have two switches which are connected to the top and one switch which is connected to the bottom and the that particular switch would connect to the bottom dc bus. This would circulate and come back through the positive dc bus with a negative sign, so you would have this level corresponding to minus I of the phase, which corresponds to the minimum duty cycle.

So, you have identified the durations of a duty cycles and you have identified the magnitudes, you can use that to calculate your average and the RMS currents in 1 PWM duration, so this would correspond in our case to 200 micro seconds.

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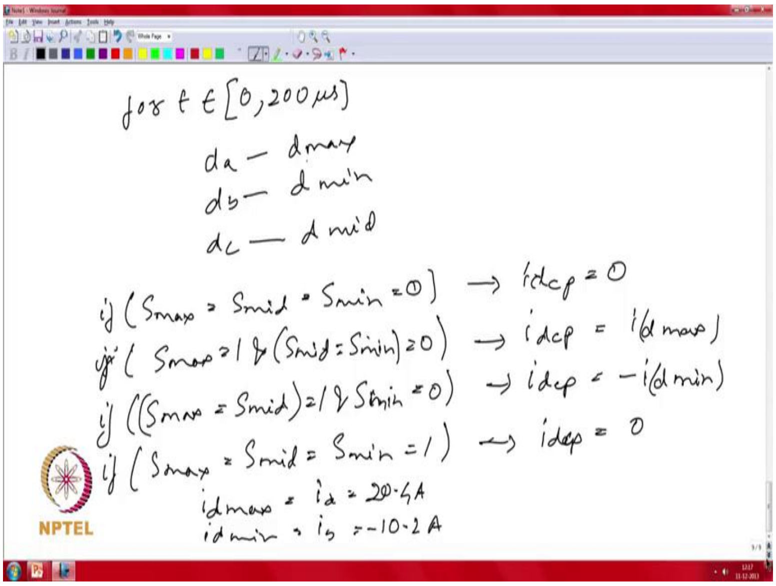

So, an expression for this in this particular case, we had would be their maximum and db was the minimum and d c was the middle value. So, if you look at the expression for the dc bus current, you have I f is max is equal to s mid is equal to s min and all of them would be 0. Then, you have I d, c p would be 0 if s max equal to 1 and s mid is equal to s min equal 0, then I d c p would correspond to I of the d which is at the maximum level. If s max is equal to s mid is equal to 1 and s min is equal to 0, then your I dc p would be minus of I d in the phase corresponding to the minimum duty cycle.

If s max is equal to s mid is equal to s min is equal to 1, then dc p is 0, so in our particular example, if you evaluate the time instance your I of d max is I a, which is 20.4 amps and I a t d min is your b phase current, which is minus 10.2 amps. So, you could use that to calculate the dc bus current and as you are moving along the sin wave, the value of what phase would have the d max and d min and d min, d mid would actually interchange as you proceed with time. So, you could actually evaluate your dc bus currents at each of the switching instance.

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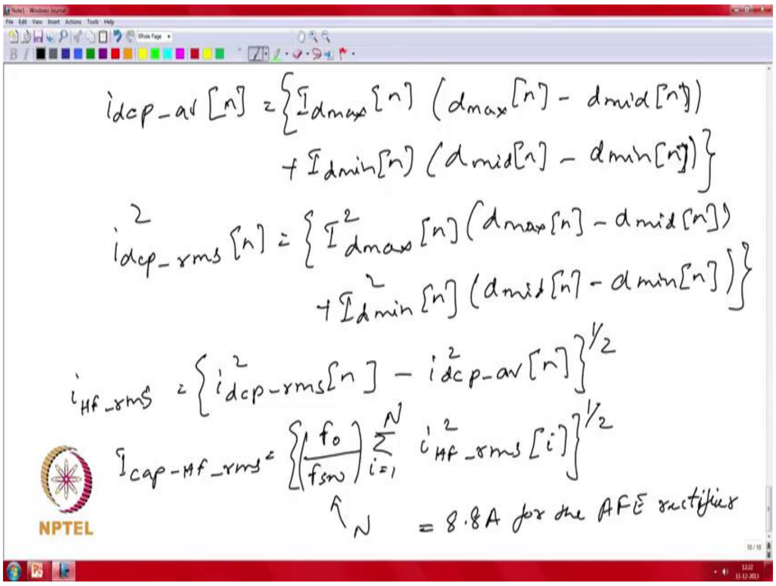

So, you could write an expression for your average current of I d c p average at the end instant would be I of d max at the instant into d max at the end switching cycle instant and the mid. So, you could write an expression for your average d c bus current and similarly, you could write an expression because these are square wave pulses. You are ignoring the rippling or phase currents and you are assuming the switching duration to be sufficiently long that your ac currents can be assumed to be approximately flat, so your I d c p, RMS square at instant n is I d max square at n.

So, once you have the average RMS dc bus current in the bus plate, you could then calculate what is the high frequency RMS currents, which would essentially flow into your dc bus capacitors. So, your high frequency RMS is you subtract the squares of these and take the square root, you would get the high frequency RMS currents that would essentially flow into your dc bus capacitor. So, this calculation is on a per cycle basis, so if you want to calculate over the entire fundamental cycle, you have I cap high frequency RMS to be given by which is given by your number of switching instance on a switching cycle.

So, this would be f naught divided by f s w summation I is equal to 1 to n, so we have considered this particular term to be equal to n of I high frequency RMS square at the instant I and taking the square root. So, if you evaluate it for the active rectifier at 10 kilo watt, 5 kilo hertz switching frequency, so you have 100 switching cycles for a fundamental. So, you get high frequency RMS current in a dc bus capacitor to be about 8.8 amps, so for the active front end rectifier operation, you have about 8.8 amps flowing through the dc bus as high frequency RMS currents.

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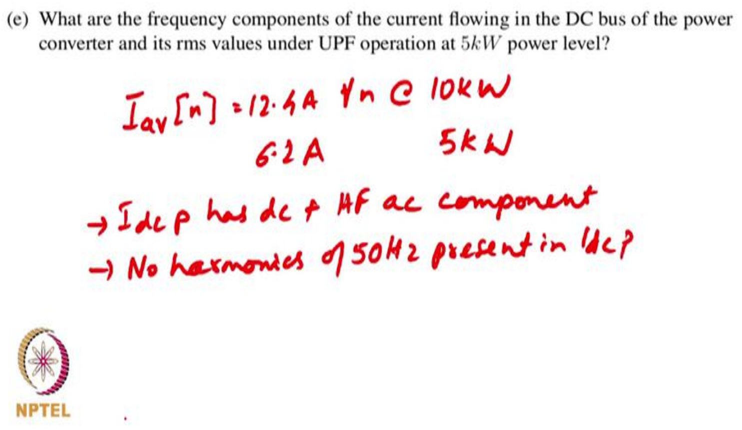

So, if you look at the frequency components of the currents that are flowing through the dc bus, what we calculated over here was the RMS high frequency RMS. So, if you look at it at different power levels, you can change the different power levels would correspond to change in current levels on the ac side current you can evaluate that this expressions. You will find that for occupation of a three phase power converter, the average balanced operation, I average of n stays constant at for a power level of 10 kilo watts.

It stays constant that 12.4 amps for all n at 10 kilo watt and if you look at the 55 kilo watt per level, this would be 6.2 amps. So, essentially the average current stays a flat as a function of time there is no low frequency riding on top of the average current.

So, if you look at then the frequency positive bus current it is essentially a d c plus high frequency components. So, high frequency if you if you look at the current way from you would find that the geometry of the wave forms if you do a time domain summation would have the geometry would repeat every 60 degrees. So, just looking at it you would think that there is a fix harmonic, but under ideal switching conditions taking ideal switches there would be no frequency components would essentially be a dc bus high frequency component.

There are no harmonics of 50 hertz considering a ideal power converter, of course if you have non ideality such as dead time on fixed drop etcetera, those could actually introduce harmonics in a system. In a ideal case, it would essentially be dc, when you are having a balanced three phase operation.

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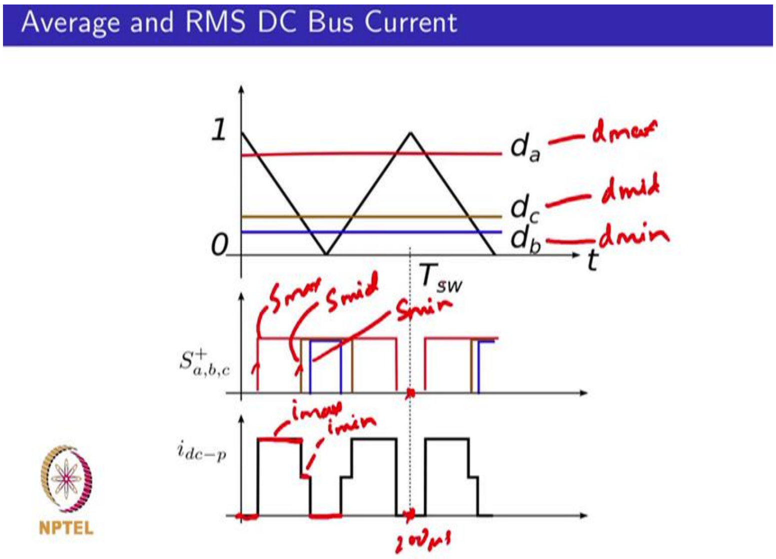

If you look at the speed of repetition, you would have essentially the switching period would be the period corresponding to when you have similar way for they are not exactly similar, because the duty cycles are changing over the sinusoid. You could think about the high frequency component repeating at 5 kilo hertz or t s w.

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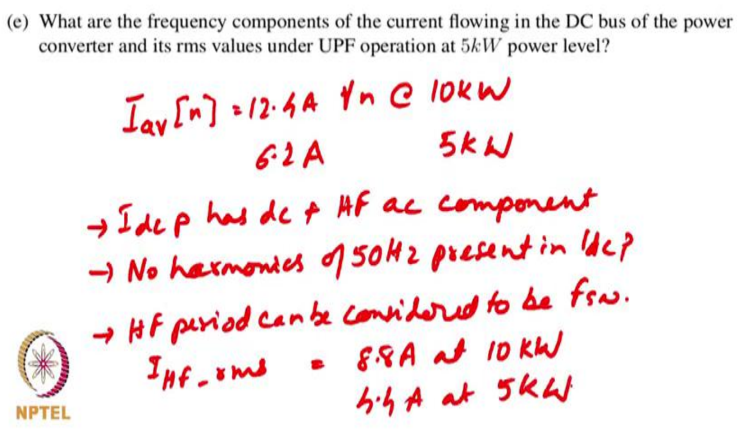

It would not exactly be fsw, it would have side lines, because your duty cycle is varying as the sine wave proceeds and your duty cycles are actually varying with time. So, if you look at your high frequency RMS currents, it is 8.8 amps at 10 kilo watts and 4.4 amps at 5 kilo watts.

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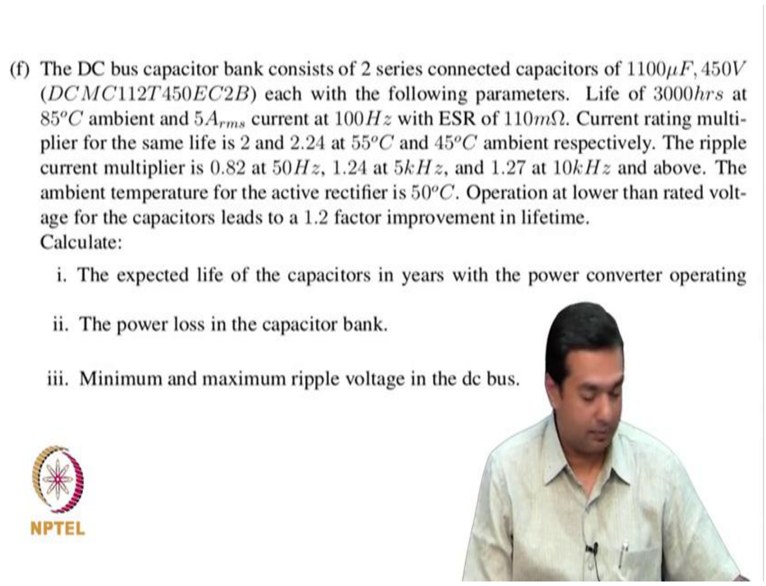

In the next problem you are given details about the dc bus capacitor, so we have in problem two capacitors that are connected in series.

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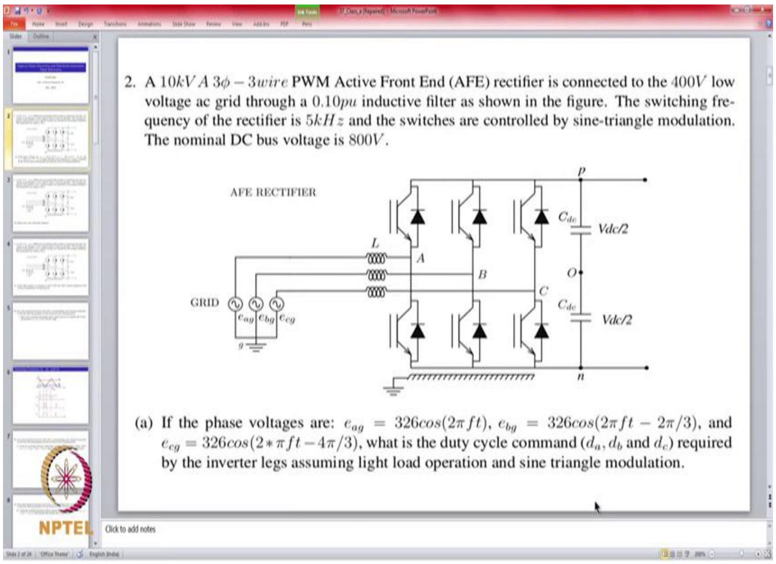

So, you have two capacitors in series.

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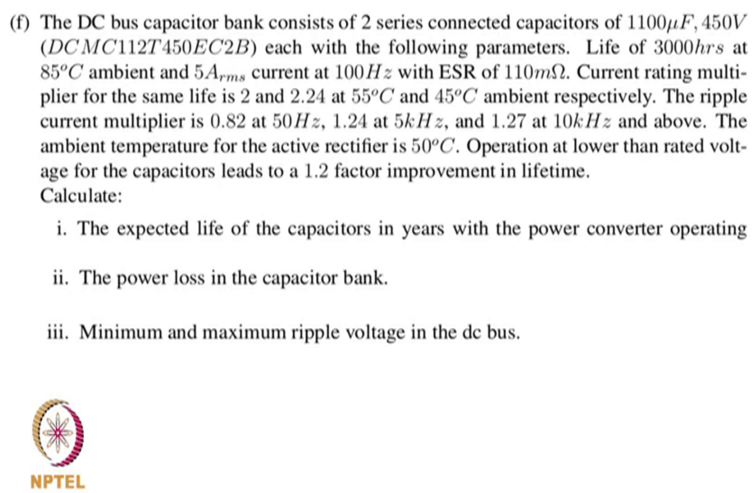

Their value is 1100 micro farads at 450 volts and your given a lifetime parameters, 3000 hours at 85 degree centigrade ambient an 5 amperes RMS current at 100 hertz and the ESR are at 100 hertz is a 100 and 10 milli ohms. You have current multipliers in the ambient is reduced, so at 55degree ambient, you have a current multiplier of 2 at 45, you have current multiply of 2.24 and we have also a ripple current multiplier. So, this you can have 5 amps at 100 hertz, you can have 0.82 times of that at 50 hertz, you can 1.24 times of that at 5 kilo hertz and 1.27 at the high power frequencies.

You are told that the ambient temperature for the active rectifier is 50 degrees, so this is the temperature within the converter cabinet and your actual rating of the capacitance 450 volts your dc bus voltage is 800 volts. So, the capacitor voltage is 400, so you have a improvement in the lifetime factor by 1.2 because your operating at a radius voltage. So, you are asked to calculate the expected capacitor life, the power loss in the capacitor bank and at the ripple on the d c bus voltage, so to do that we will start with looking at the thermal properties of this particular capacitor bank.

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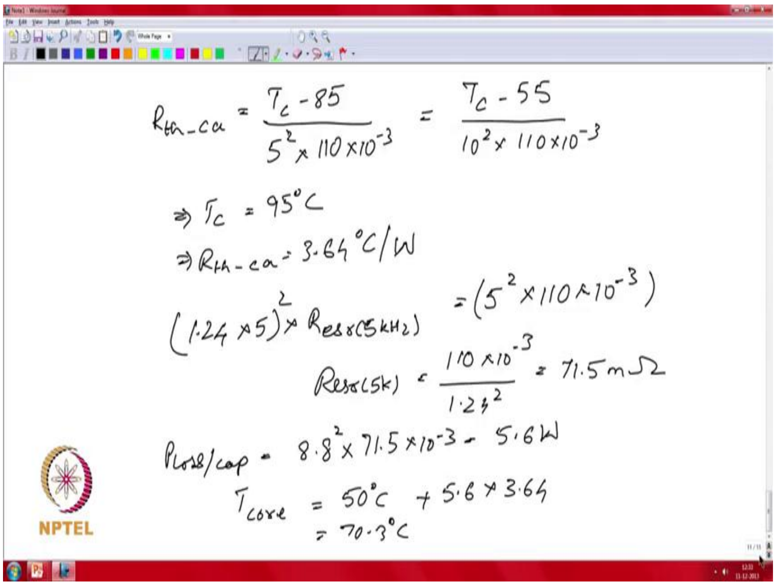

So, you have you have your terminal resistance R th from your core to ambient of the capacitor and you are told that at 85 degree centigrade, you have this would be the temperature rise between the ambient and the core and you can pass 5 amps. So, your power loss I square r, I square is 5 amp square times 100 and 10 milli ohms and you are told that you can pass twice that current if your ideal temperature is reduced to 55. So, t c minus 55 is 10 square into 110 inverse, so this a I square r, so you could then use this particular expression to calculate what the core temperature is and the terminal resistance from core to ambient.

So, the core temperature is 95 degree centigrade and your R th from core to ambient is 3.64 degree centigrade per watt. Your current multiplier at 5 kilo hertz is 1.24, so you can use that to calculate your E s r at 5 kilo hertz. So, you have 1.24 into 5 square into e s r at 5 kilo hertz is I square into r, the power dissipation at 100 hertz. So, you could use that to calculate E s r at 5 kilo hertz, so your E s r at 5 kilo hertz is 71.5 milli ohms and your power loss in the capacitor is I square r and calculated high frequency RMS currents to be 8.8 amps.

Your R is 71.5, so you have 5.6 watts power loss in each capacitor, so you can calculate your core temperature is 50 degree centigrade, which is a ambient. Your power dissipation which is 5.6 into your R th which is 3.64, so this is 70.3 degree centigrade, you are also asked to calculate the power dissipation in your capacitor bank, there are two capacitors.

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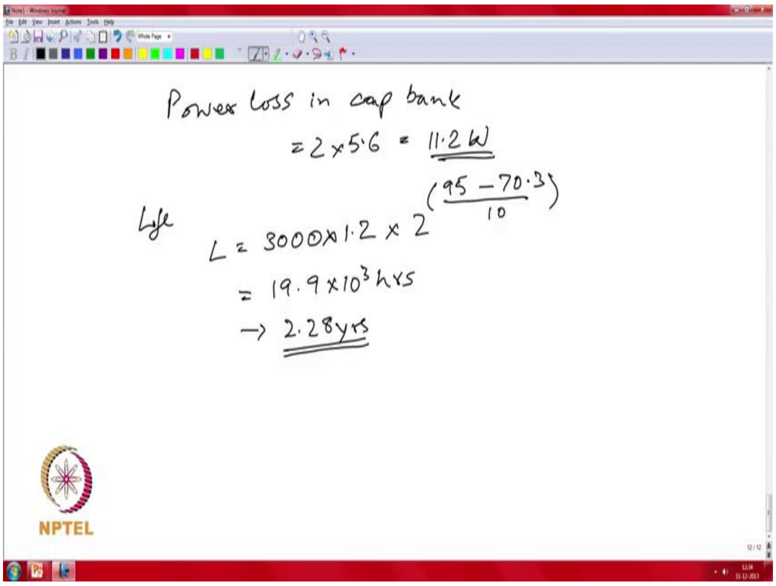

So, you have your power dissipation in total is 11.2 watts, so you know your core temperature, which can be used to calculate your life. So, you have 3000 hours at a nominal core temperature and you have a factor of 1.2 because your operating at reduced voltage provided from the data sheet. You have your nominal temperature at the core is 95, your actual operating a 70.3 and considering the simple lifetime order of doubling life for a 10 degree reduction in temperature.

This would correspond to 19.9 into 10 to the power 3 hours or 2.3 years. So, you have the power loss in capacitor bank your expected life, so this is running at rated temperature at twenty four hours a day around the clock. So, the next thing you could calculate a what is the ripple voltage in the d c bus capacitor bank.

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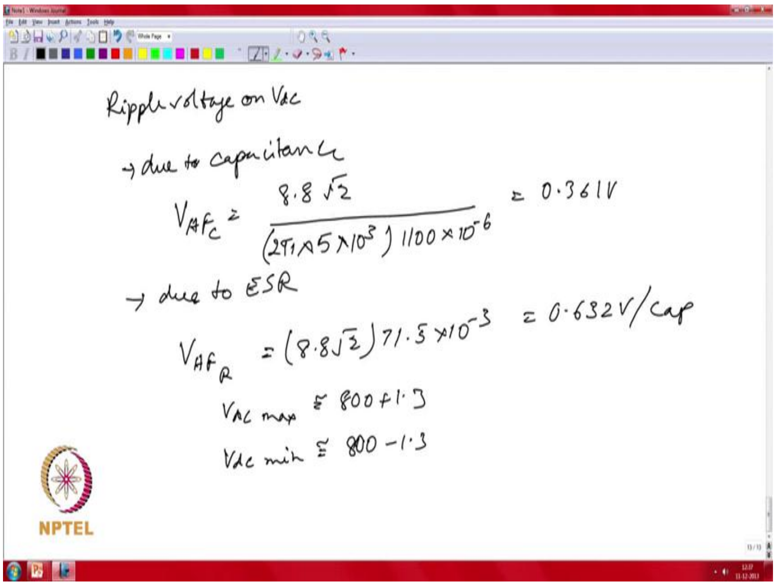

So, one thing we can do a sound simplifying assumptions, we would assume that your 8.8 amps. This is high frequency RMS current at the switching frequency would have underlying sinusoidal value of 8.8 amps into root 2 to be the envelope of this high frequency r m s current. So, due to the capacitor capacity effect, your v high frequency ripple would be 8.8 amps into your root 2 divided by 2 pi into 5 kilo hertz, which is in switching frequency into a value of capacitance. So, you have about 0.361 volt as the capacitive voltage ripple, it would also calculate the voltage ripple because of ESR.

So, that would be high frequency due to the resistor ESR effect would be 8.8 root 2 times the ESR at your high frequency, which is 71.5 milli ohms, so this is point six three two volts per cap. So, if you look at the cap bank you have two capacitors in series, so you have a total voltage drop of about 1.3 volts, so your v d c max is 800 plus 1.3 and V dc min is approximately 800 minus 1.3. So, it is good think of as noise which is around your nominal dc bus voltage assuming that your controllers are working and ensuring that your dc bus is related to 800 volts. In the next problem your asked to look at a case where you have a unbalance.

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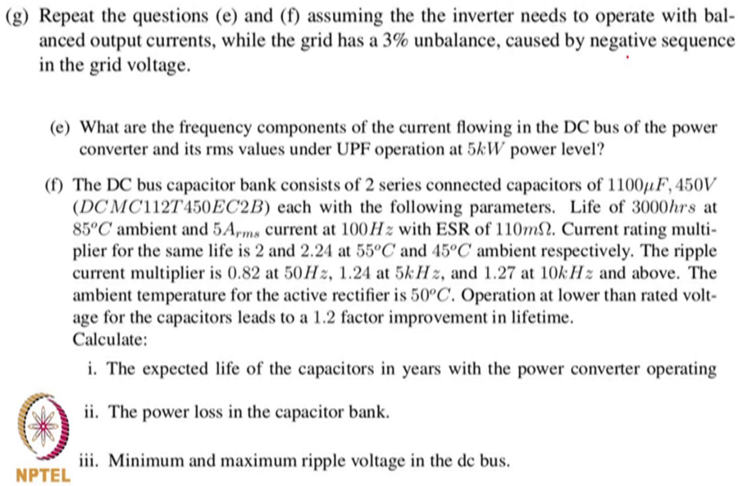

So, we are essentially repeating this problem for this analysis when the grid has a 3 percent unbalance caused by a negative sequence in the grid voltage. So, the first thing is to evaluate what this negative sequence voltage is and then make use of that to find what your a b c voltages are and use that to evaluate your duty cycles.

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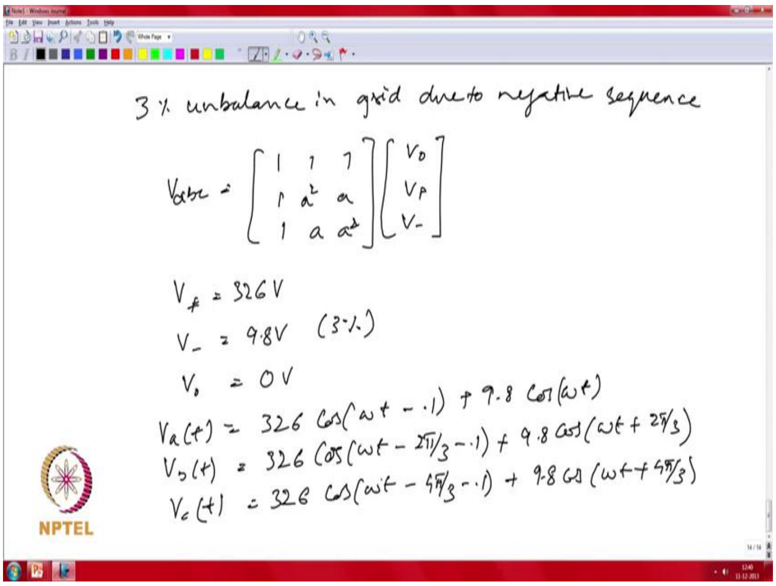

So, we have v a b c is and we have already to be 326 volts, it is continuing to operate under the nominal positive sequence voltage, your negative sequence voltage is 3 percent. If that corresponds to 9.8 volts and your zero sequence, you are assuming that to be not present which is 0 volts. So, you could actually now calculate what is your a b and c voltage, we did that previously for the balance condition. So, we could now add the unbalance term which would correspond to the 9.8 volts, the a b c voltages can actually got be obtained through the phased the sequence to phase transformation. You have V a of t to be 326 cos omega t minus 0.1 plus 9.8 cos omega t.

So, your negative sequence is rotating in the opposite direction compared to the negative rotating opposite direction compared to the positive sequence, so you have the sine to be handled appropriately using this, then you can calculate your duty cycles.

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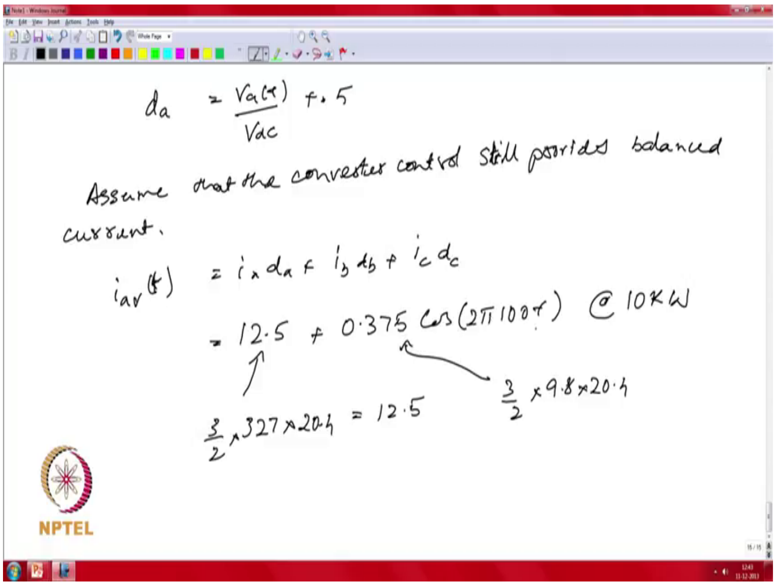

Your duty cycle for example, if you say da would be V a of t divided by V dc, which is 800 volts plus 0.5 and you could then calculate you db and dc, you know your I a and I b and I c, we will assume that your converter control still provides balance currents. So, by appropriate compensation, it should balance current even when the grid voltage is unbalanced. So, you can you know I a, I b and I c which the same as what you had for the balance condition, so you could then calculate your I a average of as a function of time would be I a times d a plus I b times d b plus I c times d c. You could evaluate that to be, it happens to be 12.5 plus 0.375 cos 2 pi 110 kilo watt.

So, if you look at the value of 12.5, this correspond to your 3 by 2 into 326 equals to 327 times 20.4, this is your 10 kilo watt, the peak current corresponding to your 10 kilo watt power level. So, that would be your 12.5, so by working out this particular simplification you could actually see that this is indeed the case and your 3.75 would correspond to 3 by 2 into 9.8, which is your unbalanced voltage times. Again, 20.4, so it is your interaction of your unbalanced voltage times your balanced current, which gives rise to your 100 hertz ripple on your dc bus.

Thank you.