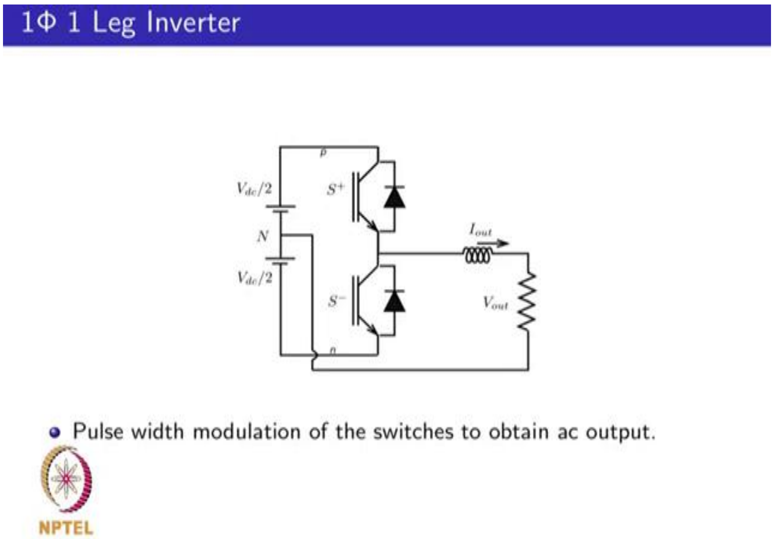
Power Electronics and Distributed Generation
Prof. Vinod John
Department of Electrical Engineering
Indian Institute of Science, Bangalore

Lecture - 24
DC bus design in voltage source inverter

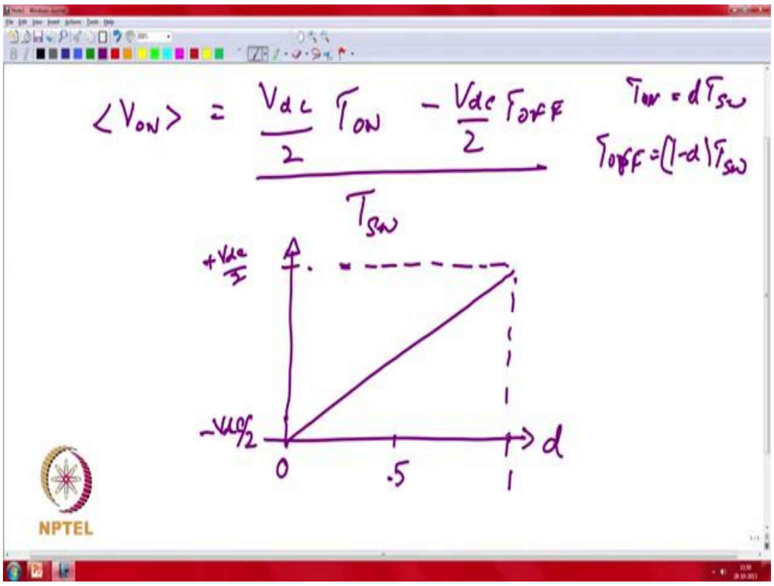
(Refer Slide Time: 00:41)



Welcome to class twenty-four and topics in power electronics and distributed generation. In the last class we talked about a transfer of power between two sources. We looked at a efficient way of transferring power from one source to the other. With one side being a voltage source and other side being a current source, a efficient switch arrangement to transfer power in such a condition can be modeled as a single pull double throw switch. We saw how it can then be extended to a d c to a c inverter, which is commonly required for a distributed generation or a power quality or the inverter application.

We looked at a simple case of it were we are looking at it on a single phase basis one leg at a time. It can also then be generalized to include the actual diodes and transistors to form a role realization of such a power converter circuit. You are saying transistors and diodes to implement the single pull double throw configuration. Also one can then look at what is the output voltage that can be generated in such a system. We looked at the average output voltage that can be obtained.

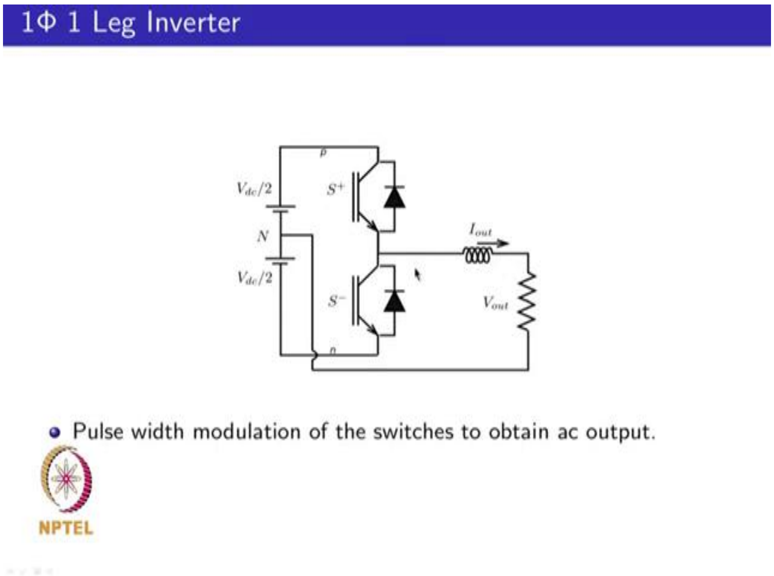
(Refer Slide Time: 02:01)



So, we looked at the average voltage from the output to the neutral midpoint of the receivers. This was V d c by 2 T on minus V d c by 2 T off and this is average over duration of T S W, which is a switching duration. We know that T on can be related to the duty cycle as T on is equal to d times T S W and T off, yes? So, it gives the time T on as a time duration of the top switch being on. We saw that we could actually get a relationship between the duty cycle and the output voltage on a average switching cycle basis.

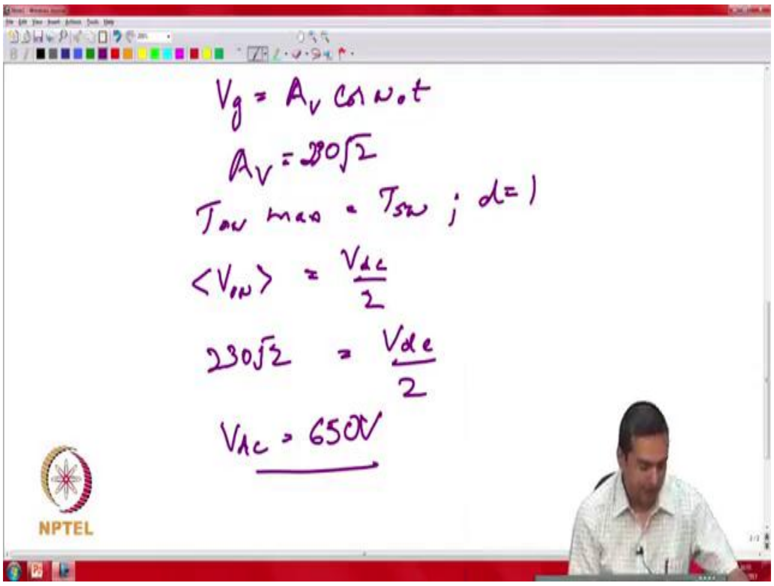
So, if your duty cycle is varying between 0 and 1 your output voltage can have a value of minus V d c by 2 at a value of 0 and plus V d c by 2, when duty cycle has a value of 1. So, if you look at grid voltage that or the voltage that gets connected to a power converter at the output.

(Refer Slide Time: 03:48)



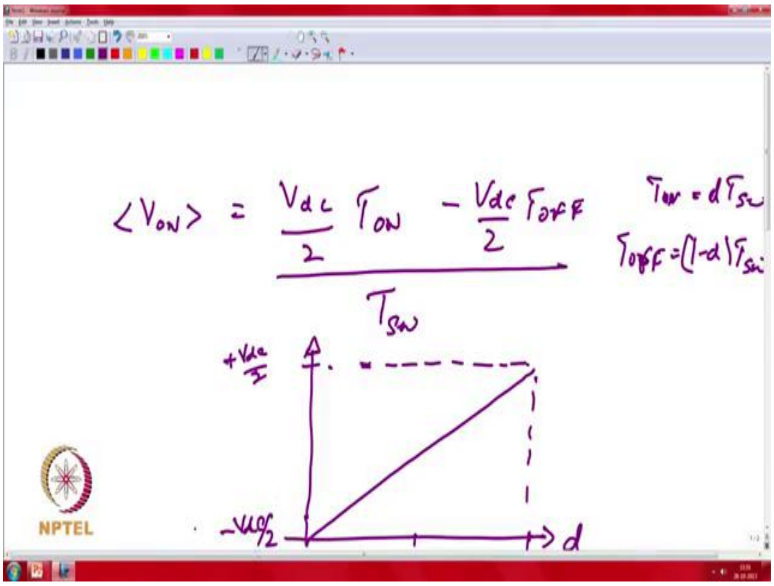
You would like to get a relationship between what is actual output voltage at your load or at the terminal of the inverter. The d c bus voltage that is available to you and that you can get a relationship based on if your grid voltage V g s.

(Refer Slide Time: 04:16)



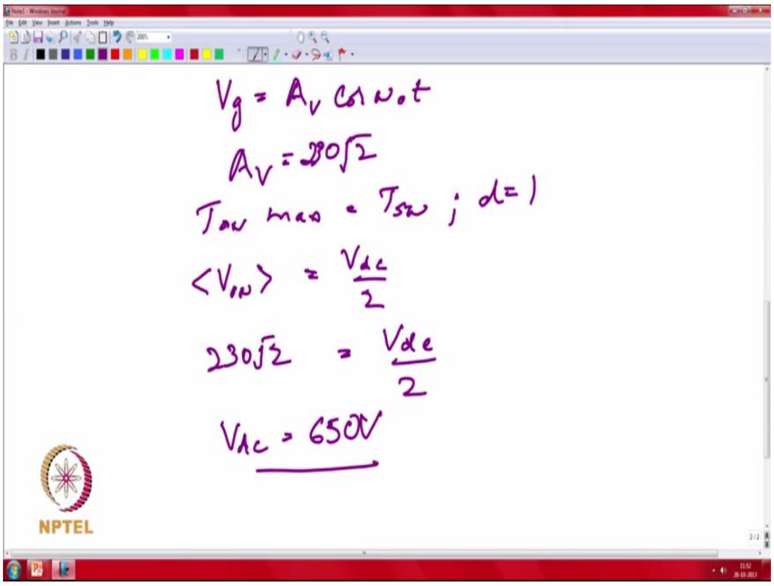
A times V amplitude of voltage A V cos omega naught t common voltage that we have in single phase system in India is 230 Volts. So, A V is 230 square root of 2 would be or the amplitude of a voltage, that you are being that is being applied. For the positive half cycle your T on max can be as much as your…

(Refer Slide Time: 04:57)



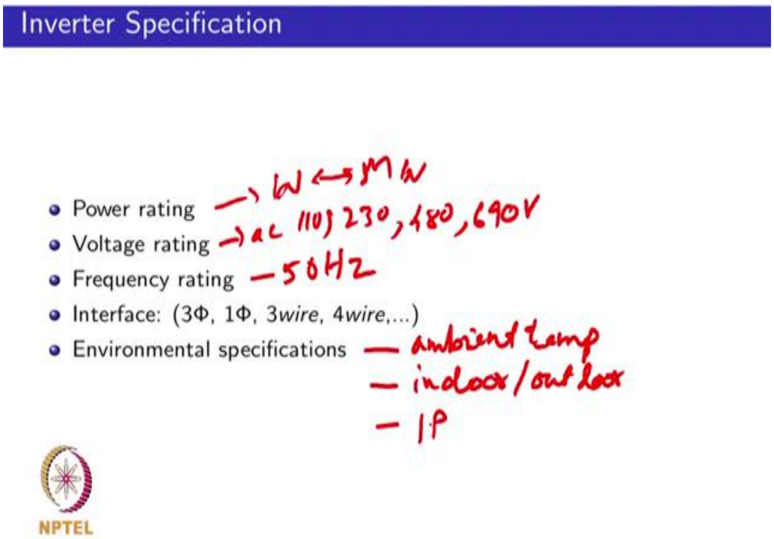
So, the positive half cycle your T on max can be as much as T S W. So, you can apply as much a voltage as V d c by 2 in the negative half cycle T off can be as large as T S W. So, you can apply as much as minus V d c by 2.

(Refer Slide Time: 05:18)



So, you can get a relationship between what is the output voltage that you are applying and what is your d c bus, your T on maxis T S W when duty cycle is equal to 1. So, you get your average V o n that is being applied can have maximum value of d V d c by 2. If we take V on average to be equal to the peak of the voltage that you are applying. You are talking about 230 root 2 is equal to V d c by 2. So, this is about 230 root 2 is about 325 volts. So, we are talking ideally of about 650 volts as your d c bus voltage, when you are input voltage is about 230 volts. We will see that you have to add additional factors over and above this particular d c voltage in a actual application. So, before we do that we will actually look at what it means to say you are building a inverter of a given specification.

(Refer Slide Time: 06:37)



So, typical or converter that we will be built, you first need to know what power rating it is going to handle. So, whether it is 100 Watts a kilo Watt 10 kilo Watt, mega Watt, so a basic quantity of a that is that is specified when you design a power converter is the power rating. So, once you know the power rating the next important quantity is what is the voltage rating, especially the a c voltage rating, which is what gets connected out of the terminals of your power converter.

A common a c voltages are can be 110 Volts 220, 230 volts, 480 volts 560, 690. There can be a range of voltages depending on different geographical locations etcetera. A common voltage for a single phase system is 230 volts for us. So, it is not just a the voltage rating, we also want to know what is a range around the nominal voltage. Because, ideally you get the exact voltage, but we know that there is going to be a range around nominal voltage.

You might have positive value above the range a negative value below the range. You might have plus 5 percent voltage over the nominal minus 10 percent. So, depending on the range around a nominal, we also have to know to actually design the specification of the power converter. So, you are talking about in terms of power rating you are talking about of range of wards could be even as large as mega watts, depending on the application. So, voltage rating you are talking about you are a c voltage rating. So, you are talking about 110, 230, 480 volts 690 etcetera. All these voltages are below 1000 volts.

So, what is typically considered a low voltage systems the frequency rating is also important factor. Though it may not directly affect your power semi conductors, it might affect your speed of cooling fans etcetera nominal frequency, in our case will be 50 hertz. Again the electrical interference required is also a important consideration by electrical interface. It is the most basic aspect of it, as whether it is a three phase system single phase system, where you have three wires four wires. So, the number of a c connections coming into your power converter is a important aspect of the design. So, what we have been considering in our start basic design?

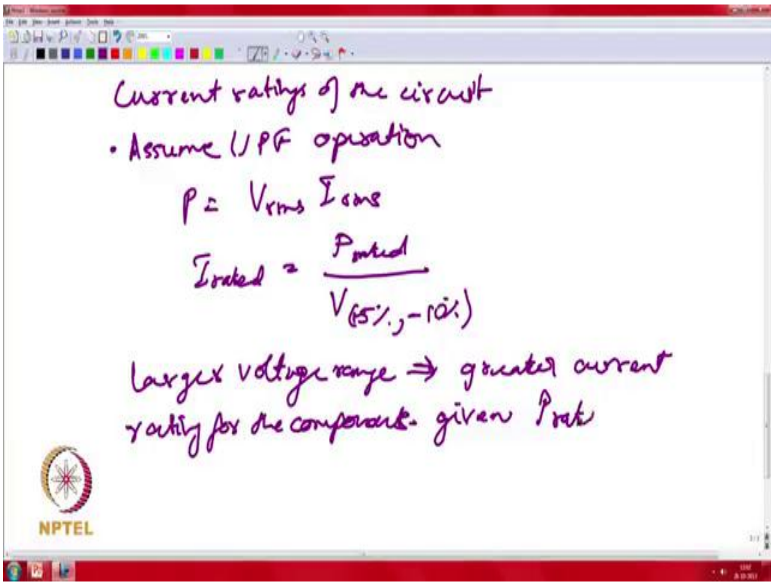
As a single phase power converter other important factors, which are important are environmental specifications. So, when we talk about environmental specification number of factors one is what is a ambient temperature. So, you have a higher ambient temperature would be more challenging design for a power converter also, whether your power converter is designed for indoor or a outdoor application. The environmental the degradation experience by a converter meant for outdoor can be more severe compared to a indoor. So, you have to pay attention to where exactly is the location of your power converter.

You also have what people refer to as the ingress protection of your power converter. So, people talk about i p rating of your converter cabinets i p ratings like i p 0, means that there is no protection. You can put your hand in any vents potentially get a shock. There is no water proofing there where as a large number like i p 66 means that, it is fully sealed. Your dust will not enter the cabinet, also you can have water jug space, which some of these cabinets can be immersed. You would not have damage to the electronics the electronics would function, even when the ingress protection number is at the higher side.

Again the cost of equipment goes up with a highest higher i p numbers ingress protection numbers. So, if have a enclosure, which is very tightly sealed. It means terminally cooling it is more challenging where as something, which is open frame is easier to cool, but that is more risk that some dirt might fall on it, it might get damage. So, there is always a risk between a how you handle your i p ratings typically, when we develop something in a academic lab. We might develop things in a open frame basis, but finally when you have to send it to a customer aspects such as i p protection is important.

Also there are other important factors such as vibration or whether you are equipment will survive in a earthquake. Depending on what level of a impact or shock is being experienced in the cabinets, whether there are capacitors in the cabinet, which might fall off from your mountain. These are important aspects of specifying power converter. We will start with a the basic a single phase power converter. If we take a single phase power converter and assume that it is going to be operating is going to be operating as a distributed generation unit, we will assume that it is going to be at unity power factor.

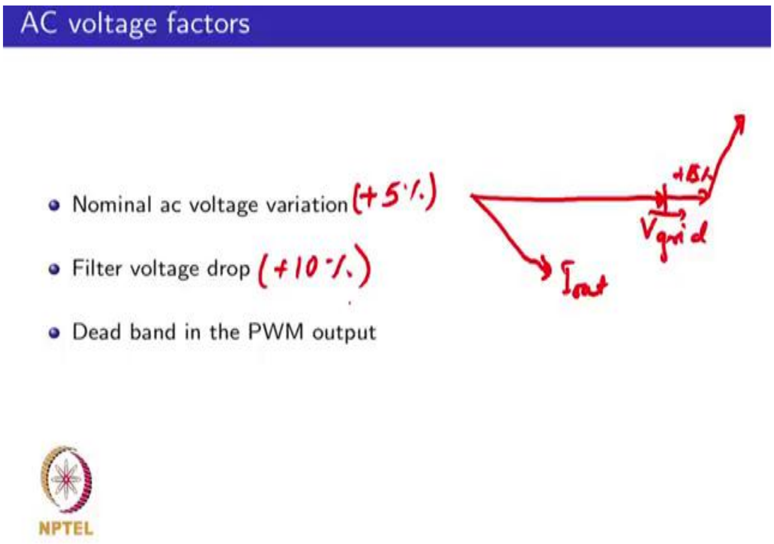
(Refer Slide Time: 13:23)



So, we will assume that there is unity power factor operation sinusoidal a c voltages and currents. So, your power is V r m s I r m s, so your I rated is P rated divided by your V. One thing that we just mentioned is the V depends on what range around nominal you want to actually operate. So, for example if you have a range a nominal as plus 5 percent minus 10 percent, it means that for a given power rated if your voltage is 10 percent lower. It means that you current has to be rated higher, which means that your component cost are going to be higher. If you have a a system which is now going to be used in an application were the power quality is going to be poorer. It means that your voltage range may be wider.

It has impact on the cost, because that it means that you have to have higher current ratings. So, you need to make sure that there is a tradeoff between how much power quality situation, you are willing to encounter. To what specifications you want to maintain your power requirement so a larger voltage range would imply that rater current rating or the components given P rated. So, we will again look at what is the voltage, which that we would we need to have on your d c bus given a given a a c Voltage.

(Refer Slide Time: 16:13)

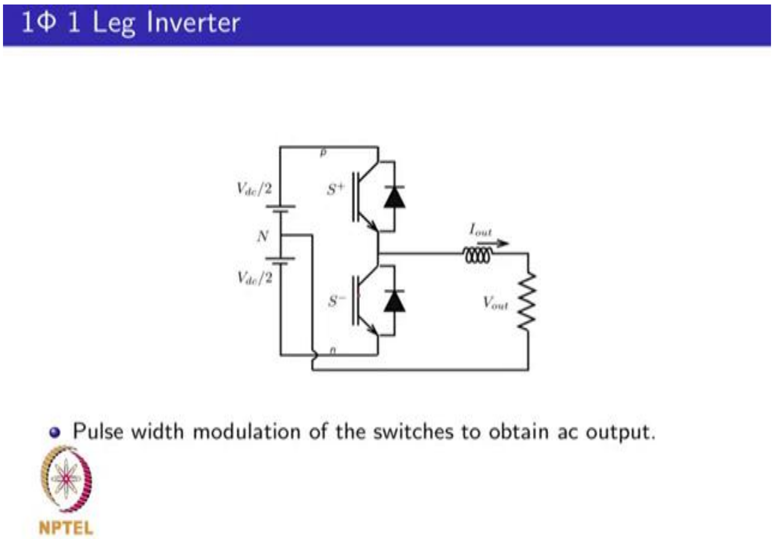


These voltages are related to your nominal a c voltage variation. So, if you think about the grid voltages are as V grid you can have a and number of factors. One thing that we mentioned is the grid voltage might have some tolerance, which might increase the value of the actual V g the other factors. That can actually affect as between the power converter. Your output voltage and your inverter, you have a filter inductor. So, we might end up with a drop under filter inductor. So, you need to also incorporate how much drop you might expect under particular filter inductor drop.

So, depending on the power factor of you are I out is going to be lagging for some reason. You want to actually provide capacity wards, you might end up with further increase in value in your terminally voltage, that is required by a power converter. If you take a typical filter starting assumption might be your filter inductance, may be 10 percent.

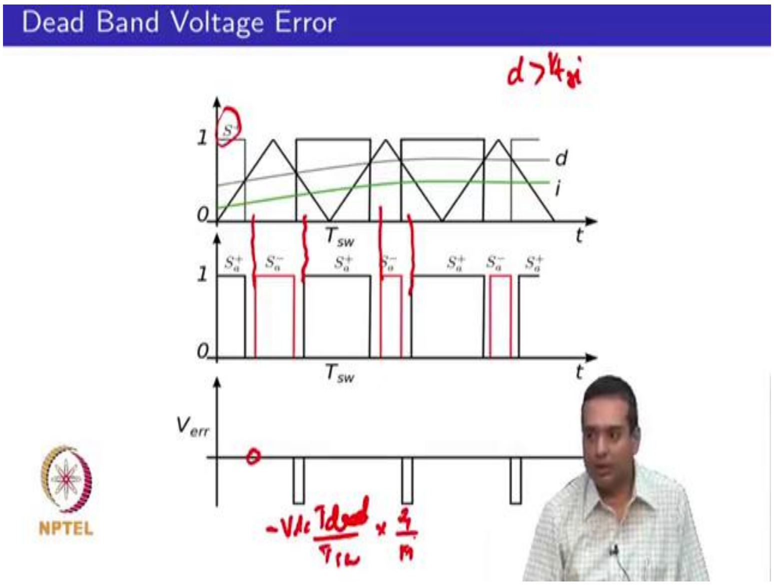
So, you are talking about here a a c voltage variation of say 5 percent addition over. You might be talking about a 10 percent addition over here. You also have factor such as dead band, which is we will explain what the dead band is typically when you have a leg of a power converter.

(Refer Slide Time: 17:53)



We saw that to one of the condition is that we cannot short both the tops and the bottom together or you will cause a shoot through across a voltage source. The other is that your current always has a path. So, to prevent the positive and negative being shorted you always have a duration, where both S plus and S minus is simultaneously kept off for a short duration called a dead time. Now, if you look at a the affect of this particular dead time, the affect of the dead time depends on the polarity of the current.

(Refer Slide Time: 18:29)

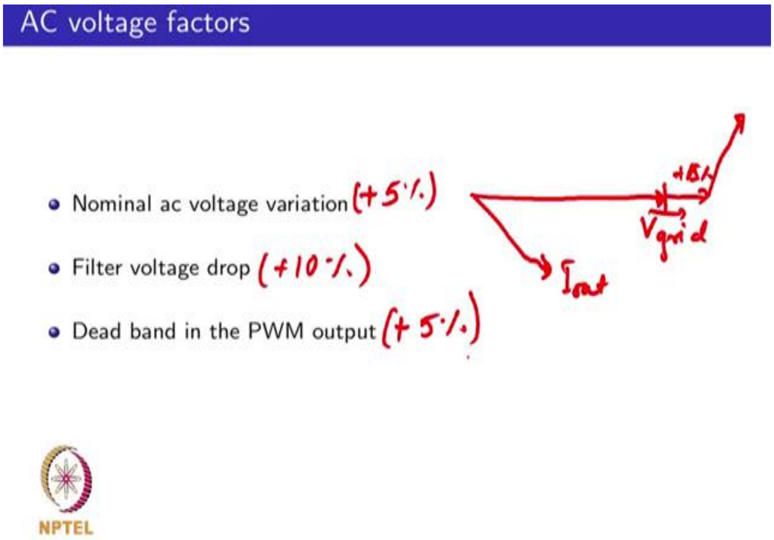


So, if you look at an ideal sine triangle modulation when ever your duty cycle is greater than your triangle V t r i. Your S plus is on and S minus is on whenever S plus goes slow, but in the actual signal that is provided to the gate of the devices where S plus and S minus. You are starting edge of your signal always divided a little bit. So, as to prevent both top and bottom switches from shooting through and delayed duration is that called a dead time.

Now, if your current polarity is positive or turning off as long will automatically cost the complimentary diode to turn on. So, there is no error being caused during the positive polarity current. When your current is in positive polarity, but when you are trying to actually turn on the top switch any delay in the turn on of the top switch will increase. The amount of time for which the bottom diode is still conducting, which leads to a error in voltage. This error in voltage depends on the ratio of you are the average value of this particular error in voltage depends on your v c bus voltage. In this particular case the error is negative it depends on a dead time; it depends on your switching duration T S W.

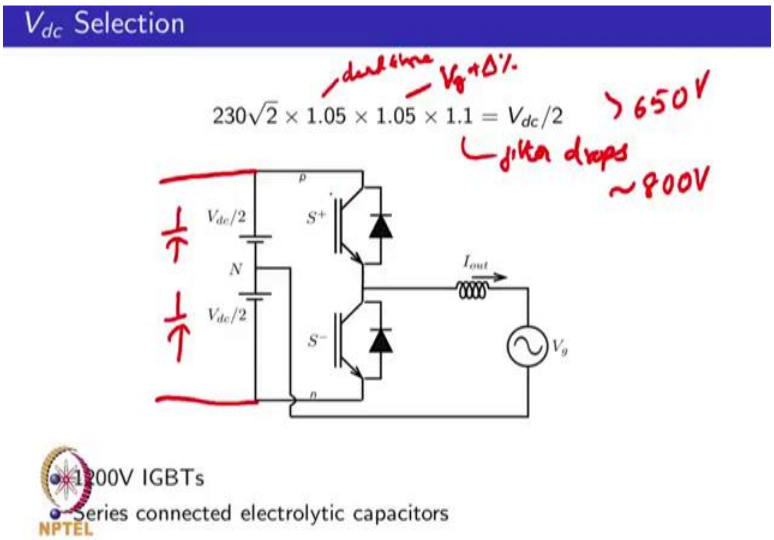
You can think of it as voltage, which is like a square root. If you want to convert it to back to a sine wave or of a some particular fundamental, you can add a factor of 4 by pi to get the fundamental effect of the dead time. This gives you an additional factor, which we need to have in your a c voltage output to generate, you are required P W M output.

(Refer Slide Time: 20:49)



So, we will assume that this is also having a factor of plus 0.5 percent, so if you look then look at relationship between your d c bus voltage and you are a c output.

(Refer Slide Time: 21:08)



You will end up with now your 230 times root 2 plus a factor for your dead time plus a factor for your delta V g your V g variation. You might have a factor for filter drops some of these factors might be not exactly in phase. For example, the filter drop might be ninety degrees lagging where as your dead time might be in phase, but we also need to consider that you have a margin between what is the actual dynamic voltage available to control your output. Hence, the actual voltage is that is there at the terminals of the inverter. So, we are all keeping in mind factors such as thus we will see that the actual d c bus voltage required as not just 325. It might have it would have a 650 volts. It has to be greater than 650 volts a common voltage you might end up requiring, may be you multiply this factors.

You might be getting a voltage close to 800 volt. So, you can see that these factors do add up and you have to actually get adequate margin between your actual d c bus voltage. Your operating voltage for your a c side of your system also keep minding that we are assuming, basic single phase sine triangle modulation for your pulse modulation switches. This voltage now has an implication on your selection of components within your power converter two parts are there. Throughout, we know that in actual power converter. Your d c bus which is over here shown as two voltage sources of V d c by 2 is actually built with capacitors.

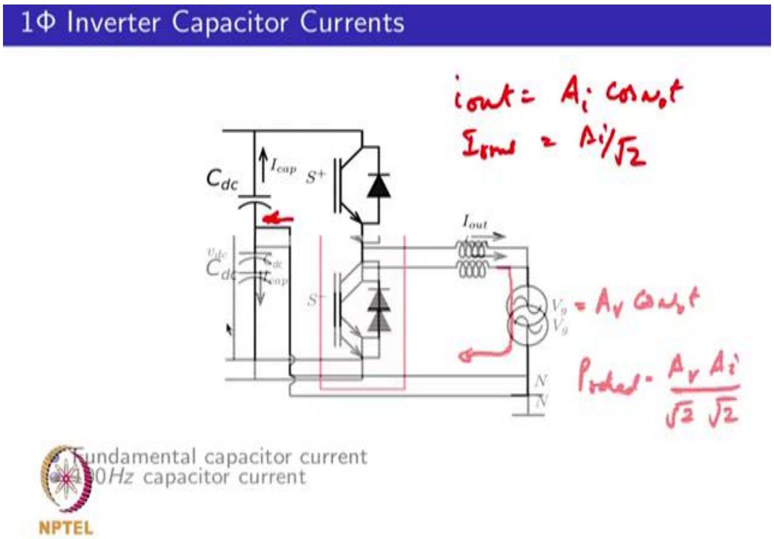
So, the first implication is on the rating of capacitors that are used in your d c bus. So, if you have to have a d c bus voltage of 800 volts. It means that your electrolytic capacitors have to been be 859 volts etcetera, because it is not very common to have a high voltage capacitors of greater than 500 volt. You might have to end up now having series connected capacitors in a power electronic application, where your having to have a say 230 volts a c. So, in this particular case may be, because you are d c bus voltage is 800 volts, you might use two capacitors each capacitor having 450 volts.

Other important implication of this particular relationship of a c voltage the d c voltage is the rating of the switches and the diodes. So, the switches that you typically use should might be transistor to some extent we could even find a set, which can operate at that voltage commonly people might use I G B Ts, which are insulated gate bi polar transistors. Again the voltage rate is of these components, this transistor is not continuously varying. You might have a first set hundred volts to 200 volts, 400 volts, 600 volts.

Then it might jump to 1200 volts there may be a few components, which are available at 1000 volts. So, quite often you might end up selecting the voltage rating of your switches to be 1200 volts a commonly. When you deal with a 230 volt system, because it now directly release your side voltage to what is required on your d c. We will see that you also need adequate margin in your transistors. Because, there is large d I d t is during switching of the transistors. You need adequate margin between your actual voltage rating of your d c bus and your voltage rating of your transistor devices.

Now, that we have a feel for what could be a the preliminary voltage rating, required by some of the components. We can then take a look at what could be some of the currents that are flowing through this particular circuit, especially on the d c bus.

(Refer Slide Time: 26:05)



We look at the capacitor current closely and they are actually a circuits such as this different frequency components of that actually flow through the circuit. The first component that we will look at is a fundamental component of the capacitor current. Because, this is a single phase system, where I out is actually a 50 hertz a c quantity. We saw how I out is related to your P rating and your a c voltage rating.

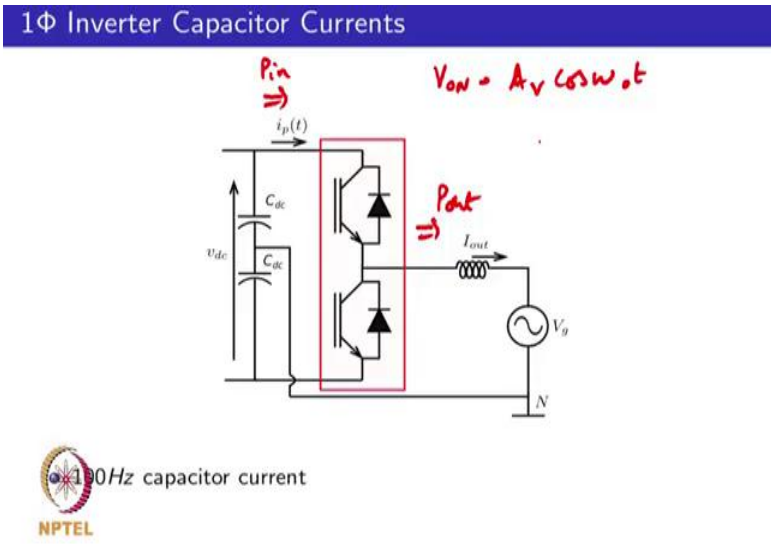
So, your I out in this particular case can flow through your source, which is your a c grid, but then it has to flow back through your neutral and come back to your d c bus. If you take your current I out to be A I cosine omega naught. There your I r m s is a I by root 2 taking the output current to be a sinusoidal quantity, which is well filtered. We also know that you can relate your grid. We have taken it as a V cosine omega naught T, where the instantaneous the grid voltage is related to the amplitude and is a sinusoidal function.

So, you can relate your power rating your p rated is A v A I by root 2 root 2. So, you know what your A I has to be in terms of your power rating and your terminal voltage rating. So, you may know what your current is that is actually flowing into your neutral point. So, this neutral point is actually a 50 hertz current and you are assuming that the switches S plus and S minus are being modulated in a symmetric manner. So, during the positive half cycle what is happening to S plus. There is identical to what is happening in the negative half cycle to S minus. So, there is symmetry between the operation of the top and the bottom leg of the switches and this particular converter.

So, whatever current is flowing in splits between the capacitor C d c as I cap going in one direction into the top bank. I cap going to the bottom direction in the bottom bank and one thing that you could immediately know about this current. So, if there is a current flowing into the bottom bank. This is actually charging this bottom capacitor whereas, th0e same current, which is flowing out into a top bank is actually discharging the top capacitor.

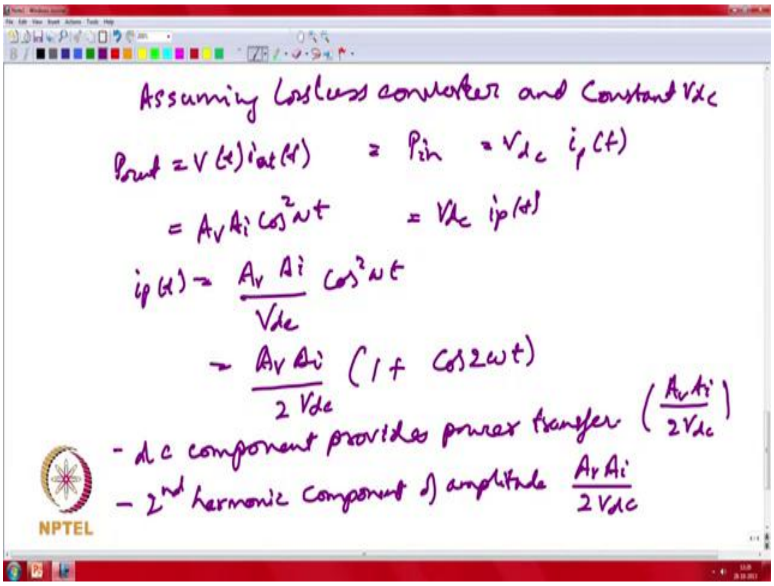
So, the current is actually common mode current it does not affect the differential voltage between your positive and negative d c bus. Even though it affects the individual capacitor voltage that total voltage between a positive and negative is not affected by this common mode current, because one is charging when the other is charging. The other way around depending on the instant at which the current is flowing.

(Refer Slide Time: 29:58)



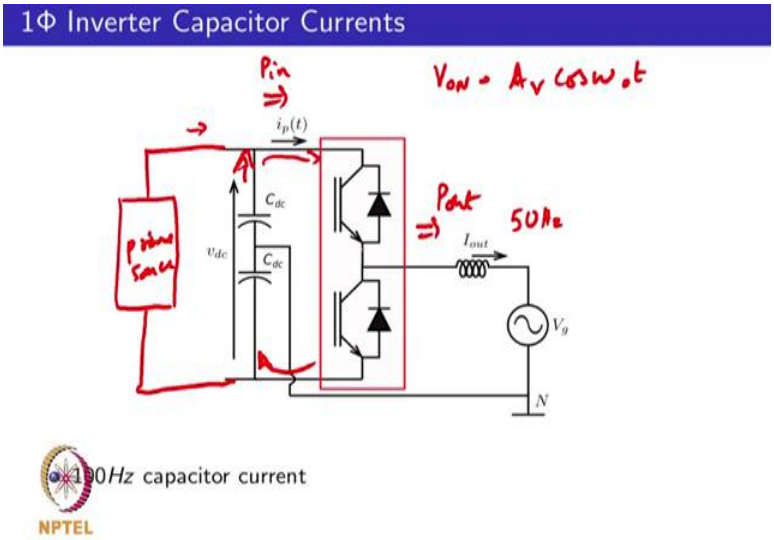
So, then next component of the current that can flow through this capacitor bank is… We will see that, it has A d c and 100 Hertz component. For this again we are assuming our voltage to be A V cos omega t. So, V o n is A v and we can look at what is the power going out of your per of the a c leg and the power coming in. We make assumptions, we will assume that the inverter is very efficient, which means it is a loss less and a the filter is purely inductive, so this again no losses in the inductor. So, we will also assume that the voltage at the input V d c is quite stiff a typically by design we will try to maintain that voltage to be a constant.

(Refer Slide Time: 31:10)



So, assuming we have P out i p is the current going through your positive d c bus. So, this I S P out is a v a I cosine square omega t. So, you can write what your i p of t is A v A I by V d c cosine square omega t. So, you can see that by looking at the power balance between your input and your output. We can see that there is d c quantity that is flowing through your d c bus, which you would naturally expect. Because, you are exchanging power from one source to the other, but in addition to that, now you see that you have a 100 hertz component, which is coming in the d c bus and has a value of A v A I by 2 V d c. Then there is second harmonic component and it is amplitude is also A v A I by 2 V d c. So, if you then look at a whereas the this particular second harmonic.

(Refer Slide Time: 34:07)



This particular current flowing this component is actually flowing through this particular circuit back through this particular loop. This is actually component which is circulating in the d c bus. So, it shows up as a a differential voltage across your d c bus. So, this component, which will. So, if you actually measure the voltage across the d c bus the 50 hertz would not show up across the d c bus across the total voltage, where as the 100 hertz component will actually be measured across the d c bus. To some part of it, because if you are thinking about say an application like an photo voltage converter. You might have a prime source, which might be your P v panels, it might be your batteries. If it is a storage system, it might be a fuel cell stack depending on whether what application it is.

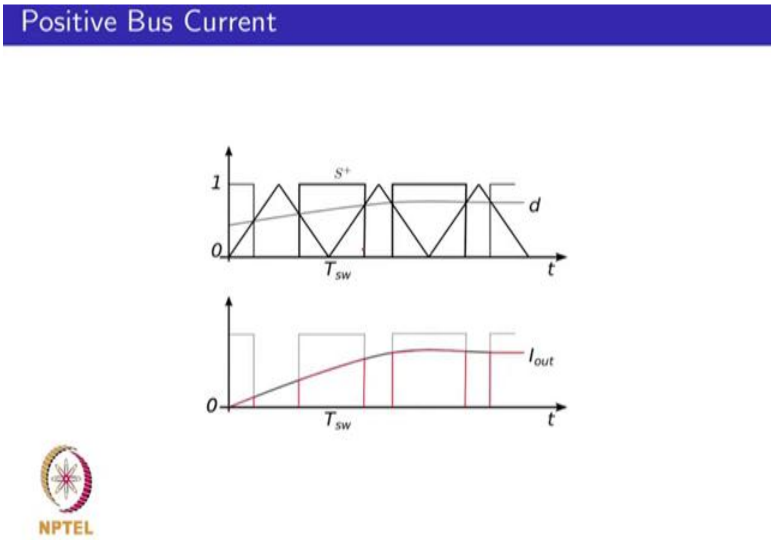
So, one thing that a 100 Hertz component can actually do is it will split between a your capacitor C d c. Your prime source, because depending on the impudence of these two sources at that particular 100 Hertz. So, if you have a higher impudence for C d c means that most of your 100 Hertz might flow through the prime source. Many times the affects of this a 100 Hertz ripple in the prime source is actually negative. In the sense that in a photo voltage system the 100 Hertz component would just cause heating of the elements not any real generation of power also the 100 Hertz voltage, which would mean that your actual operating point is deviating from your m p p t point.

So, multiple these you are actually losing out on per hour, if you are taking an battery you are your effective capacitance of the battery can be quite large, which means that a fair amount of 100 hertz can actually flow into it. This will cause losses in the electrolyte the electrodes etcetera again in a things like a fuel cell, it is will cost a cause heating of the stack etcetera. So, this are and desirable components to some extent that people might even think about adding a power converter over here, to prevent that 100 Hertz ripple from actually flowing into the prime source and affecting the performance of the prime source. The other item of interest when we are looking at the 100 Hertz component is that, if you look at the path for the 100 hertz component the output current I out consists of largely the fundamental.

So, this is 50 Hertz it might have some switching frequency ripple, but we are assuming that your filtering is being designed in a efficient manner. That its largely 50 Hertz and your not having much of switching ripple. Also, your controls are insuring that you are not having low frequency harmonic distortions in your output voltage. So, if you look at where is the path for the 100 Hertz component, which is flowing through the d c bus, which is flowing through the switches.

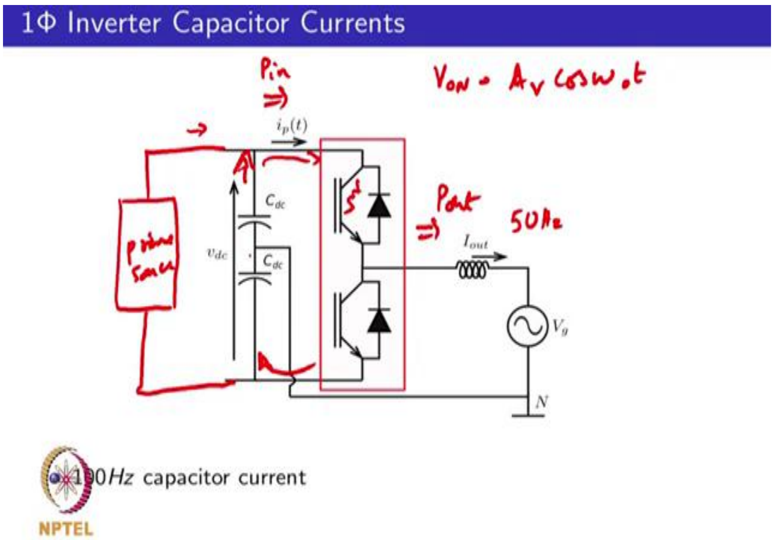
So, it is a interesting path that even though we know that the both the switches do not conduct simultaneously, because of the modulation effect of a power converter. The non-linearity involved in modulation you end up with a 100 hertz current through the switches through your d c bus. You could actually exquisite look at these v forms in a time domain simulation to convince yourself that the path for this 100 hertz component is actually through the inverter.

(Refer Slide Time: 38:16)



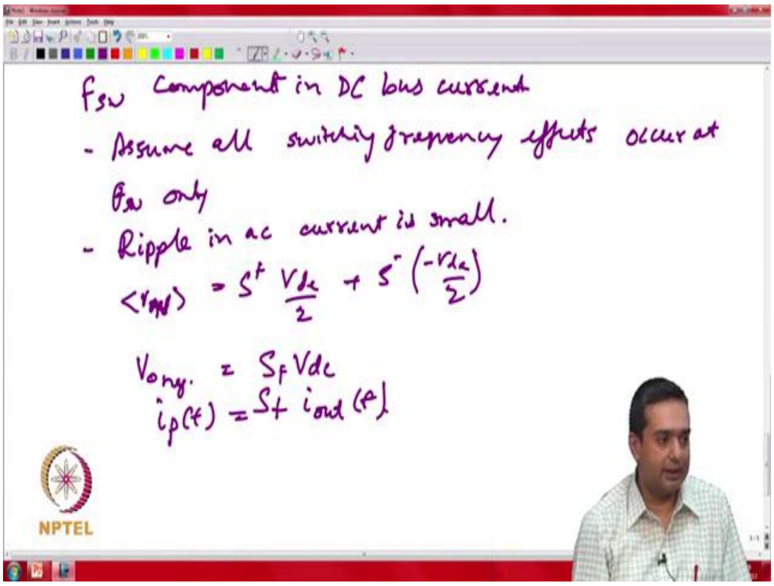
The third component of the current through a power converter, such as what we have just discussed if now the high frequency component. So, we looked at that d c 50 Hertz 100 Hertz. So, you also have because of the P W M switching action a high frequency component of the current flowing through the switches. To determine what this high frequency currents are in the switch a, we can look at this switching function that are being generated a by the power converter.

(Refer Slide Time: 38:56)



So, if you look at the power converter we have essentially, we had the switching function of this top switch being S plus. We have essentially, we had the switching function of this top switch being S plus. So, whenever S plus is on your current in i p is connected to I out. So, there is a you can make use of the switching function to relate i p to I out you also can make use of switching function to relate your output voltage to your d c bus voltage, which was what we did to look at what the average output voltages.

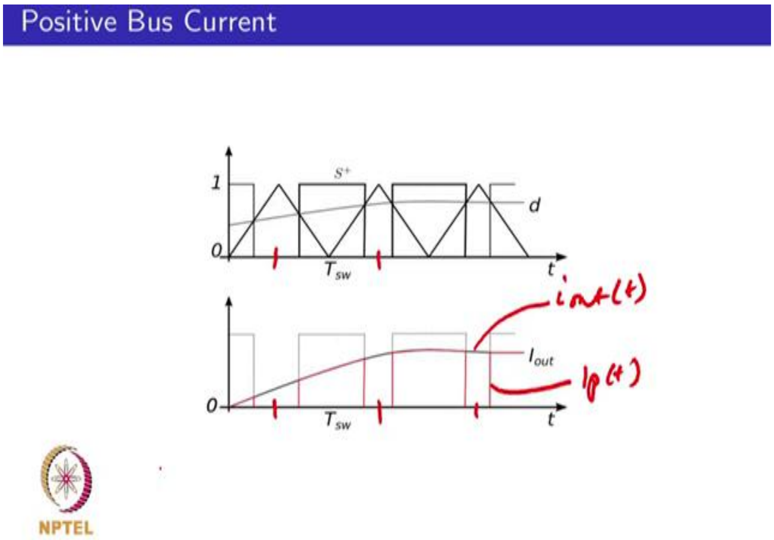
(Refer Slide Time: 39:38)



We will assume that how the switching f x occur at this switching frequency, rather than spread around a range of band, around the nominal switching frequency. We will also assume that the ripple in a c current is small. We can make use of the switching functions to obtain your voltage relationship. We saw that V o is S plus V d c by 2 plus S minus V d c by 2. So, this is o, with respect to the neutral, if you look at voltage o with respect to the negative plus, you would have S plus v d cat v directly giving your v o with respect to your negative d c bus.

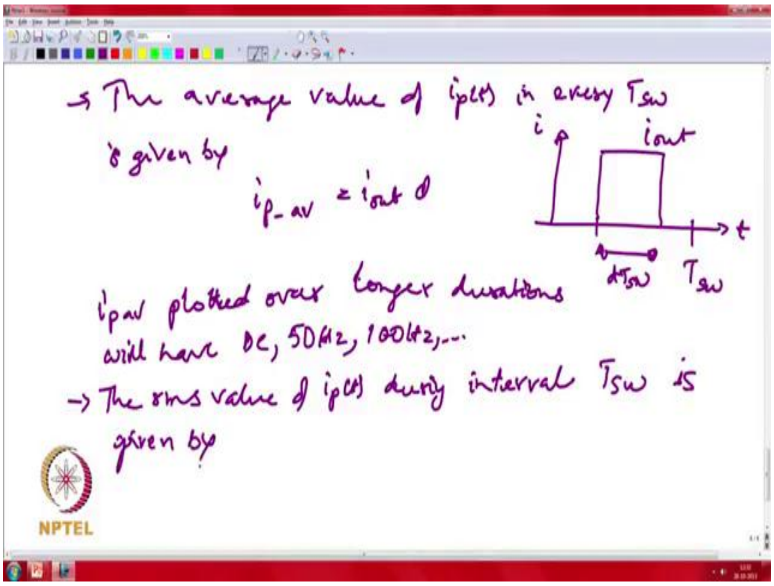
Similarly, you can write an expression for what is your positive d c bus current is S plus your I out of t. So, this gives a relationship between your actual current that is flowing in your positive d c bus to our a c output current. The a c output current you know what it is based on the specification of the inverter. We saw how the specification of the inverter is length to the power rating voltage rating, etcetera.

(Refer Slide Time: 41:59)



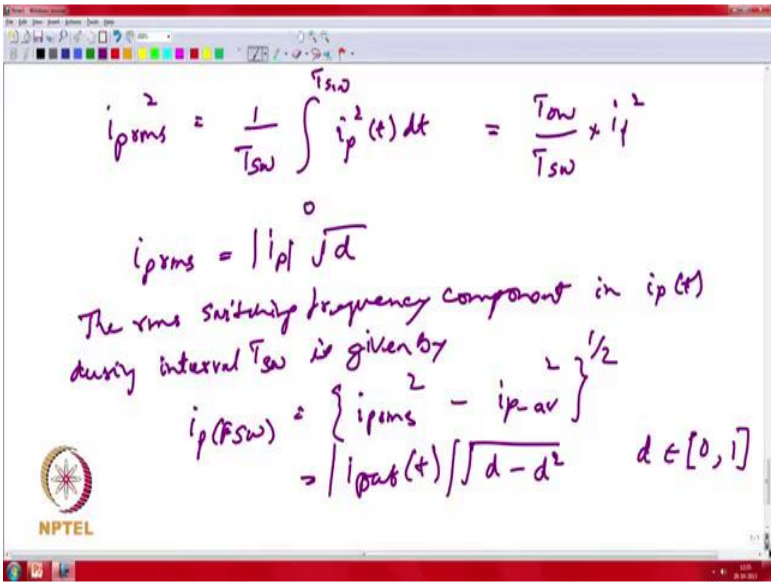
So, you what spotted over here is this black v form over here is I out what is shown over here in red is your i p of t this is I out of t. We can actually then calculate what the average value of i p is in the different duration. So, if you look at your one switching period interval say from one peak to the next peak you we will take that your current is not changing by much. Because, you have about 200 switching cycles. When you are talking about 20 Hertz I mean 50 Hertz fundamental and 10 kilo Hertz switching frequency.

(Refer Slide Time: 43:02)



So, I out times d because d is a duration were d times T S W is here on duration. So, if you look at your I out your on duration over here is d times T S W. Now, if you look at the i p average over and what we have averaged it is over the duration of T S W. The actual if you look at it over multiple such cycles you at you will see an average, which has a 50 hertz buried in it. It has 100 hertz buried in it, it has d c. So, it is not just a flat quantity it is something, which is changing slowly on a cycle by cycle basis. You could also then look at what is r m s value of this i p current, which is flowing on a flowing in a positive d c bus. So, the r m s, so you can calculate what your i p r m s is.

(Refer Slide Time: 45:38)

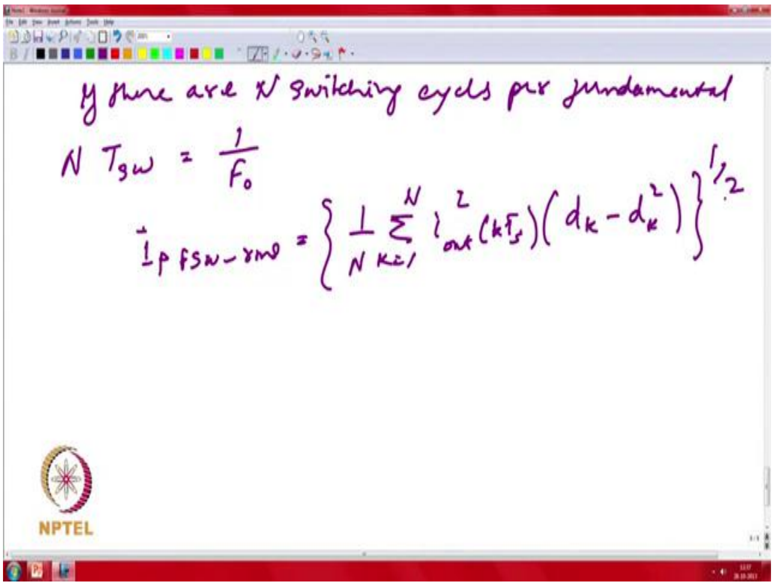


We know that i p square of t can be written a sit is on when during the T on duration. So, it is T on divided by T S W into i p square on by T S W is your duty cycle. So, you can write your i p r m s to be equal to magnitude of i p times square root of d. So, if you look at the r m s component of the switching frequency in i p during this particular T S W duration, the r m s switching frequency component because, the i p average contained over. So, the low frequency 50 hertz 100 hertz effect, you want to then calculate what is the switching frequency of a component.

We will get we can get it as so we can take the i p r m s square minus the i p average square. Take the square root of that to we will get here the i p switching frequency component during that particular duration T S W. So, this is equal to I p i out of t times square root of d minus d square where the d term is because of the r m s. The d square is because of the average effect. We know that your d belongs to the interval 0 to 1. So, d minus d square will always have the appropriate sign.

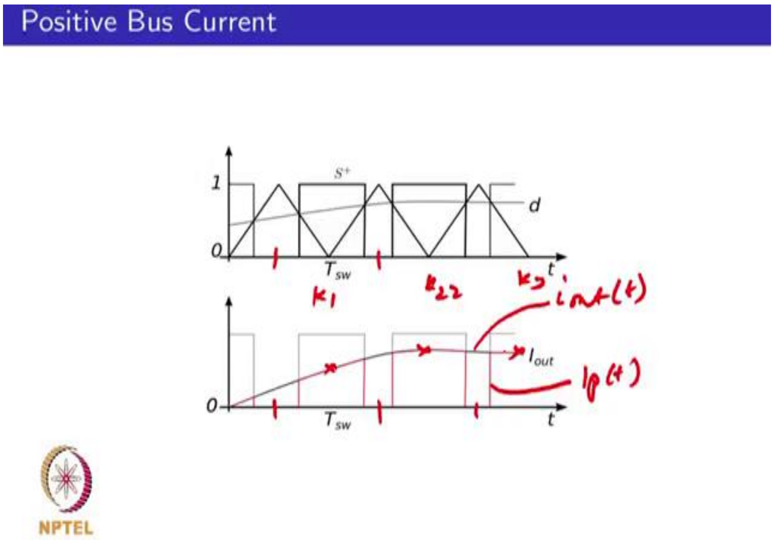
Now, we know that this is on a per switching cycle basis. So, if you want to look at the switching frequency affect over the whole fundamental cycle. Then we need to take this individual high frequency harmonics and sum it up appropriately, on a sum of square basis over the longer time frame.

(Refer Slide Time: 48:59)



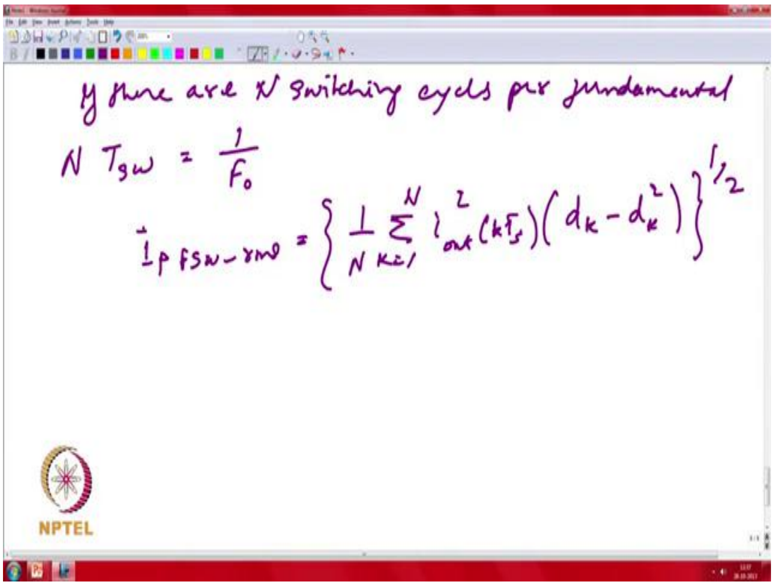
You have N times T S W is 1 by F naught F naught is your fundamental frequency. So, using that we can get a relationship for your output for your r m s current as i p f S W r m s is 1 by N summation k is equal to 1 To N over the n points I out of k T s. So, it depends depending on what your a c output is at the particular instant square. So, you do the r m s calculation over the number of cycles.

(Refer Slide Time: 50:23)



So, if you look at… So, if this is duration say k is equal to 1 K is equal to 2, K is equal to 3. You know what your i p values are at these different instance you can go through a fairly simple calculation just sum over sway 200 points for a fundamental frequency of 50 Hertz and a switching frequency of 10 kilo Hertz.

(Refer Slide Time: 50:50)



So, you be able to calculate what your high frequency current is going to be through your capacitor bank. Now, once you have the value of the currents calculated at the different components frequency components. Then we have to make an decision about what type of capacitor. We would actually be using in the d c bus. The type of capacitor depends on many factors one important factor is the type of the electric that is being used. Depending on the type of the electric you can have ceramic capacitors, mica capacitors, paper capacitors. These are high frequency type of capacitors you could have tantalum type capacitors or electrolytic.

You can have polypropylene or polyester if it is easy application. In the d c bus of a the voltage source converter a common capacitor, that is being that would be used that is a electrolytic capacitor. And we see that now once you have this effects how next can we actually go in and see what would be the appropriate electrolytic capacitor, that can be used in the d c bus of a power converter.

Thank you.