Power Electronics and Distributed Generation

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Lecture - 23
Single Phase Inverters

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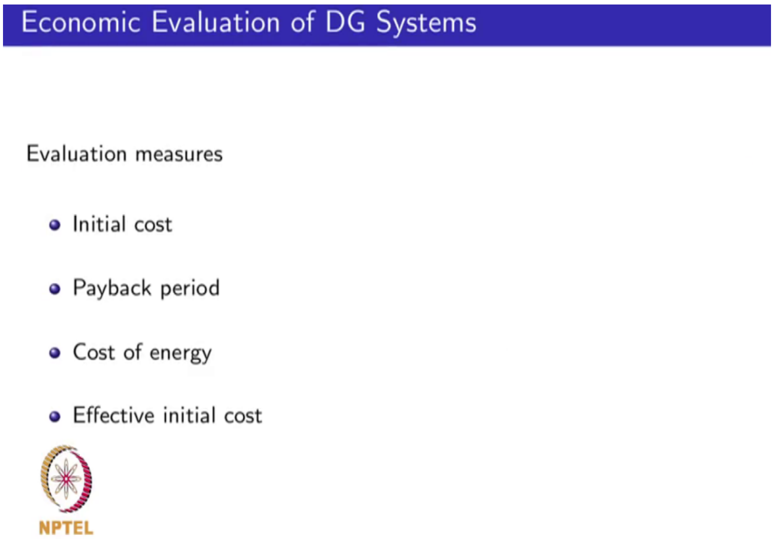

Welcome to class 23 on topics in Power Electronics and Distributed Generation. We have been talking about economic evaluation of DG systems and we looked at few measures for doing that the simplest is initial cost, which is a short term immediate decision. Payback period is something which is more on a commercial time flame maybe order of the year and to make a decision on whether a meaningful investment is being made in terms of investing in DG technology. The cost of energy we saw is much longer term time frame, which is a useful for policy considerations.

And we looked at a examples in this methods, and we will start looking at effective initial cost and one of the advantage will see effective initial cost is that as a power electronic designer, we may not know the entire system which is been assembled together, we might know only the poly electronic part of the subsystem. And we would like to actually make a decision on whether to how to go about doing the design based on a portion of the system, which may not be 100 percent clear at the point at overall DG system is being built.

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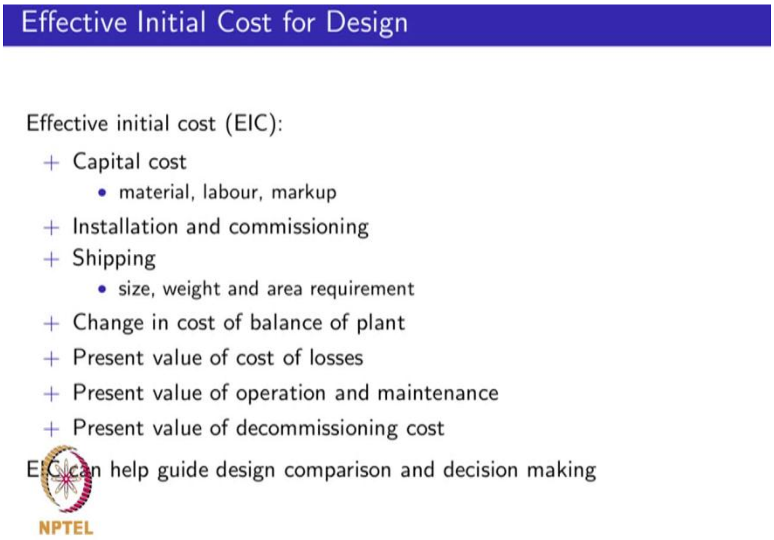

So, if you look at the effective initial cost it is a way of summing together, different cost which some of which might be upfront and some of it might occur later in time. Some of the upfront cost would be things, like material, labor, markup, etcetera. For example, if you need to build a power converter you need a IGBT is you might need a capacitors. So, these are upfront material cost, you might need controllers, you might need human input in terms of actual manufacturing process, you might also need people to do controller development etcetera.

And you also have any company would need some percentages of profit or markup on whatever system their building. Once you have manufactures say for example, a power converter, you may want to ship it to the end location where the power converter is going to be located. For example, you might be building power converter, may be in Goa, may be the winter burn in which the power converter is going to be sitting might be in Tamil Nadu.

And you need to actually ship the this thing across the country and depending on whether it is a bulky device. Whether it is a compact device you have shipping cost, you have in terms of systems which are used in a transportation system, like aircraft, space, size and weight where it is very important requirement. Also once the equipment reaches the end location you need to commission, you need to make sure that the civil work, mechanical structures are in place, if you are sending it to a location, where it is a urban area, the cost of area might be different from a rural situation.

So, depending on many of these things now reflectors, initial cost upfront which is very well known understood. That can also be other cost, which can occur when you run this particular power electronic system on a ongoing bases for example, you might have operational maintenance, you might have circuit breakers, which might need periodic maintenance, the springs, the contacts might need cleaning. You might have capacitors whose ears might change as function of time, you might think about replacing the capacitors after a, so many years of operation.

So, those are futures cost which actually have to be encountered when you operate your system. You might also have cost on a running bases for example, ideally we might think of a power converter as being lossless, whereas a in a real power converter we know that there are finite lose. And in a DG system one might consider as something that has been lost in the power converter as something that is not available for you at the load or not available for you as a unit of power, which can be sold.

So, you can think about losses in your converter or, so as a ongoing expense over a life of the systems. At the end of the life of such as system we are talking about power related equipment, so you are talking about longer time frames of we are talking about might be 20 years, 30 years, etcetera for large par system. So, you might also have cost associated with decommissioning, if you have electronic things, you might have to look at how to dispose of electronic waste, if you are having machines, windings, etcetera.

You might value in the copper or the iron source depending on what the decommissioning costs are you have to make a decision. And if you have all this costs can be effectively rolled up to often number to see whether it makes affective design which particular difference might be more appropriate depending on your application.

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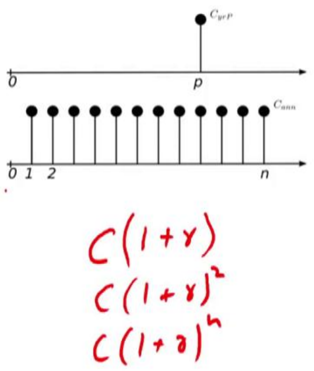
Present Value of Annual and Future Costs

$$PV_{cp} = \frac{C_{yrP}}{(1+r)^p}$$

where, C_{yrP} is the cost incurred in year p and r is the interest rate.

$$PV_{cann} = \sum_{p=1}^{n} \frac{C_{ann}}{(1+r)^p} = C_{ann}\frac{(1+r)^n - 1}{r(1+r)^n}$$

where, C_{ann} is the annual cost incurred incurred over n years.



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So, one way of looking at a cost which is going to happen in the future is that, if you have a if you have some amount of C at the end of the year. And if your interest rate is r we have one plus r into c at the end of 2 years you would have C into one plus r square at the end of p or c you might have 1 plus r to the power of n. So, if you have a cost that is incurred at your p here you want to see what is the cost today your facing because of that you will have the present value of the cost that your through incurred in the future to be c in the year p divided by 1 plus r to the power of p.

So, if you have some expense that is going to happen over here, you can actually reflect back to the present value. Similarly, you might have a annualized cost C a n n occurring over n years, so depending on what this annualized equal cost r, you can actually then take this particular number. And take over the entire duration over which your doing your particular calculation and some it up to get the present value of say for example, and annualized cost.

So, in this example annualized cost might be the losses that you incurred in a power converter. You might know how much kilowatt of hours of losses that and you know what is the cost per kilowatt are of ((Refer Time: 07:49)). So, in a way you can then reflect back the losses to a upfront number to the initial point to look at what is a effective cost. So, a many times what can be encountered in the future can be reflected back to the present, to see over all what would be the benefit of making one decision or the other way.

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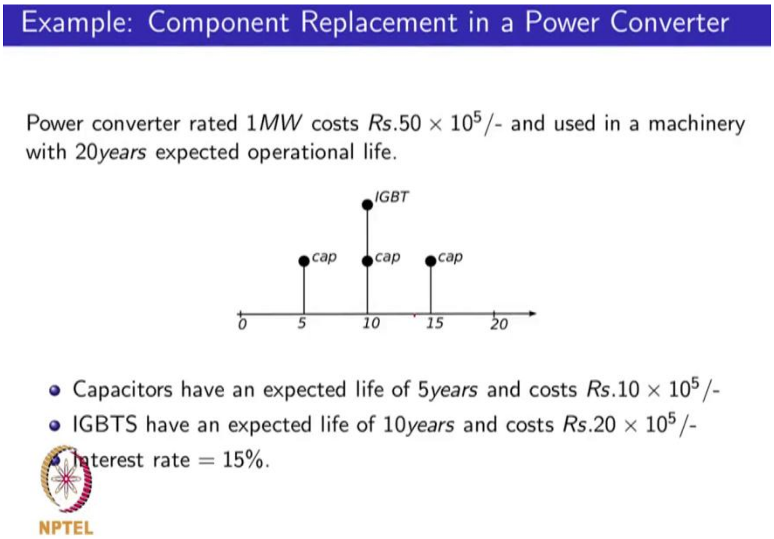

So, we look at an example where say for example, you have a 1 megawatt power converter and say the cost of the converter is 15 to the 10 to the power of rupees and it is using a machinery with 20 years of expected operational of life. And we will assume that in this particular power converter, you might have capacitors that might need replacement every 5 years and the cost of the capacitors are given, you might have IGBT which may need replacement every 10 years and you have cost of the IGBT known.

So, for example, 5, 10 and 15 you might replace capacitors 10 th year you might replace your IGBT. You are given some interest rate which you find reasonable for your particular application. So, the question is when you decide on purchasing this one megawatt power converter, it is not just the initial upfront cost, you will have to also look at what is the cost associated with the operational maintenances associated with an equipment.

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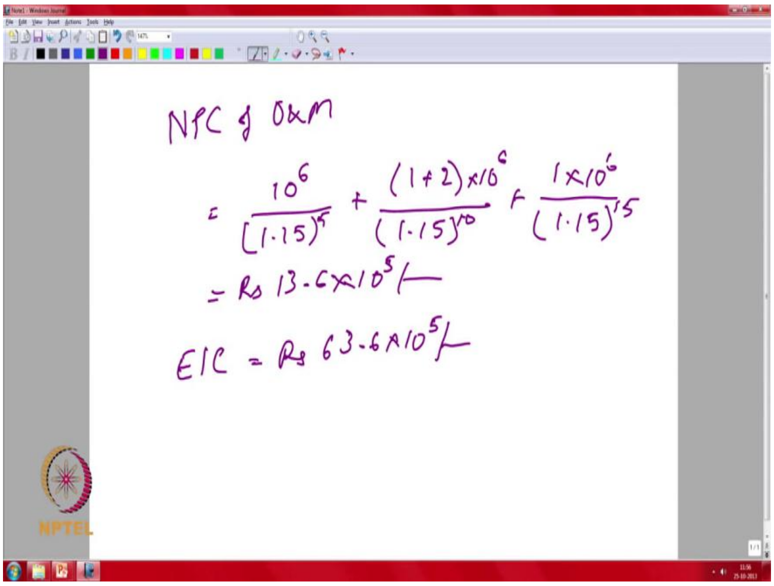

So, you could then look at what the cost could be, so if you look at your net percent value of 1 m operational maintenance. So, you might have capacitors 10 to the power of 6 divided by 1.15 to the power of 5 years plus 1 plus 2 10 to the power of 6 divided by 1.15 to the power of 10. So, this is IGBT and capacitors that your 10 plus capacitors your 15, so if you look at the net percent cost of your operational maintenance in this case, it works out to rupees 13.6 into 10 to the power of 5.

And then if you look at now your overall cost including your upfront cost, which was 15 to the 10 to the power of 5 you will need to add this to actually reflect. That you need your making a commitment to operate this particular equipment for 20 years, which reflects in the additional operational maintenance cost. So, your effective initial cost including o and m in this particular cases rupees 63.6 into 10 to the power of 5.

So, we can next ask say is suppose you have this 1 megawatt power converter, you have say three options in technology. Whether you might have something which is the latest technology your having very high efficiency, you might have something which is older or something which is now commercially available.

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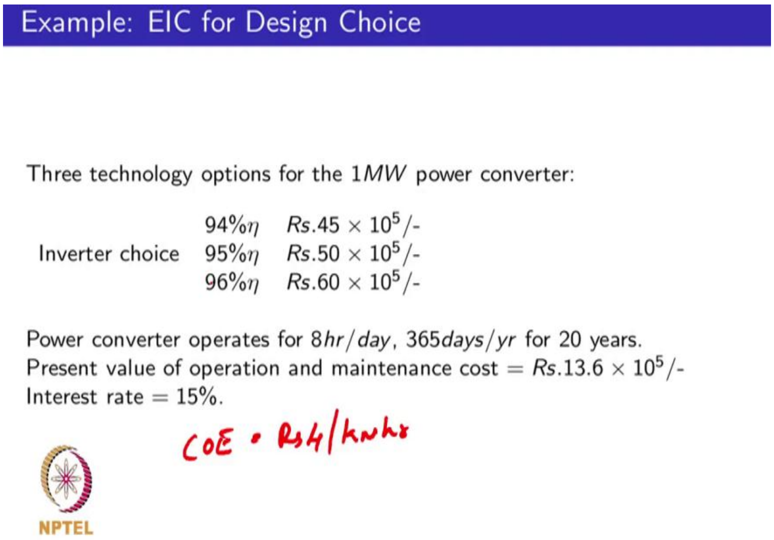

So, depending on the type of inverter which is being used you might have a say 1 inverter which is 94 percent. And it is cost might be 45 into the 10 to the power of 5 or you might have another inverter which 95 percent, 1 percent more efficient which is 50 into 10 to the power of 5, so cost lightly more. And then you may have another inverter which is very efficient 96 it is cost is slightly more, so then the question is if we know the way.

In which your particular part converter is going to operate, will assume it is 8 hours per day 365 days year and for 20 years your expecting to operate this particular unit. And will assume that the operational unit maintenance cost is same as what we calculated in a previous example, will assume 15 percent interest rate we also assume the cost of energy is rupees 4 per kilo watt hour.

So, we could then look at what is now the cost of the losses that your incurring in this particular equipment. And clearly the choice over here is you trade of between paying more for more efficient a converter or paying less for a efficient and the question is what would be reasonable appropriate decision.

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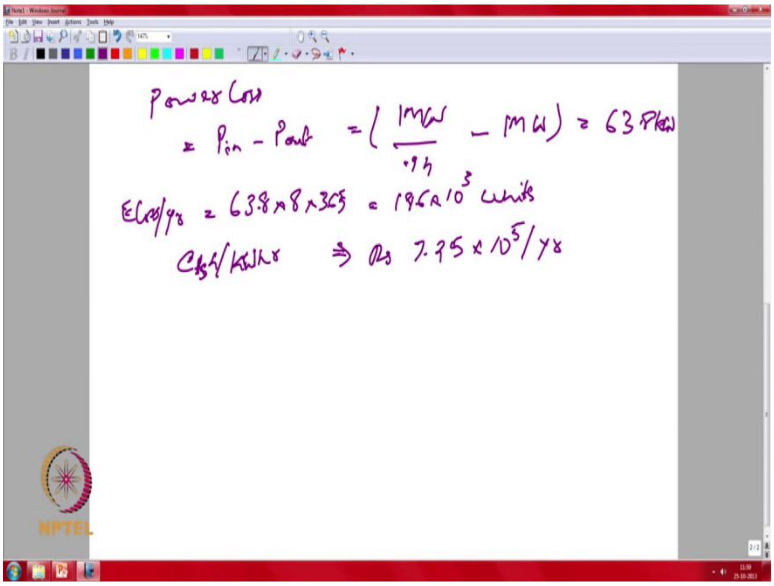

So, if you look at the example of the 94 percent efficient power converter, you can calculate the power of loss. So, this is p in minus p out, so there's 1 megawatt divided by 0.94 p out is 1 megawatt, so this about 63.8 kilo watts of power is getting dissipated, so if you look at your energy loss per year. So, this should be 63.8 into 8 hours per day 365 days a year, so this turns out to be 186 into 10 to the power 3 units per kilo watts hours per year.

And assuming at 4 rupees 4 per kilo watt hour, this turns out to be rupees 7.45 into 10 to the power of 5 rupees per year. So, then you could then calculate what the net percent value of your cost is based on the expression that we just had, ((Refer Time: 15:11)) so using the expression for the annualized cost, you know what is the cost per year you know the rate, you now it is operating over 20 years of life, you can then calculate what the net percent value of losses.

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Example: EIC for Design Choice

Inverter η %	CC Rs.	PV of O&M Rs.	PV of loss Rs.	EIC Rs.
94	45×10^5	13.6×10^5	46.7×10^5	105.3×10^5
95	50×10^5	13.6×10^5	38.5×10^5	102.1×10^5
96	60×10^5	13.6×10^5	30.5×10^5	104.1×10^5

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So, you have the capital cost being 45, 50 or 60 into 10 power of 5 we assume the operational maintenance cost to be 13.6 for all the 3 units. If you calculate the present value of losses for the 94 percent it is 46.7 into 10 to the power of 5 for the most efficient it is 30 into 10 power of 5 because the losses are not lower. So, if you then look at what is the overall effective initial cost, you find that the what leads to the lowest cost of ownership or the initial cost is actually something, which is intermediate not the cheapest or the most efficient.

You will have to look at, what is appropriate depending on whether it is operating eta say day or 12 hours a day. So, you can actually go back and calculate according to a particular design and see what would be an appropriate design, in this particular case all the component in this particular systems is related to the power electronic converter. So, you could actually have make such design decision without knowing much about the balance of plant.

So, you can see that in some of these numbers are good as comparison, physically the present value of losses is not something that you actually spend out of your pocket, it is something that happens. So, these numbers are more for comparison rather than absolute numbers which reflect expense that will be in current, but it can give you a guidance in direction of what is appropriate or what may not be the most appropriate in terms of making a technology decisions.

So, if you look at the different application depending on whether your designing a solar inverter or a winter bind or may be auto motor power converter using electric vehicle, depending on the time frame. You can adjust your interest what is suitable for your particular application or what might be available as a interest rate for small business may not be same as what is available as interest rate for larger business, more established business.

You can actually again keep in mind that these numbers are not absolute your making comparison and when you are making comparison, you can make comparisons at equal level. Rather than use one rate for one particular comparison, another rate for another comparison, so you can actually make a decision on whether the technology that your selecting is the appropriate technology. Suppose you have we discussed in the last class that many times because of that addition of the power converter, you can have benefits to the balance of the plant.

So, balance of plant were you get benefit can be reflected as negative cost in depending on your particular part of converter technology. Also people can refine it further, here we are just consider as just simple interest rate, you could also include factors like depreciation, inflation, tax numbers, things like that to refine it. But, those are essentially details, the basic frame work is essentially taking cost that can occur in the future of ongoing bases ((Refer Time: 19:09)).

And people look at the this type of design and as people call it cradle to cradle design, end to end point design, were all aspects of not just your initial cost. But, also your operational cost or included in making a designed decision and often as a engineer you may not just make one particular design, your costumer your payback period may not be important for you are actual design engineer may be effectively initial cost might be important.

As a company management who might be trying to see whether the technology is going to be broadly useful to the society, you may actually want to calculate cost of energy. So, you often it is important to calculate all the methods and actually see, which particular methods gives you justification in making a particular designed decisions. And help you guide through whether the power converter or power electronic technologies are appropriate for the particular application.

So, with this background in essentially making designed metric or making a decision on how to actually go about with making a decision on your power conversion equipment. We also saw that the role of power electronic is actually increasing, quite rapidly in distributed generation applications and your electronic converter is actually intermediary ideally it is 100 percent efficient at no cost it is compact, light weight, reliable, etcetera. So, will look at what it takes to transfer power, so this is the intermediately transferring power from one particular source and another source and what it takes to actually transfer power.

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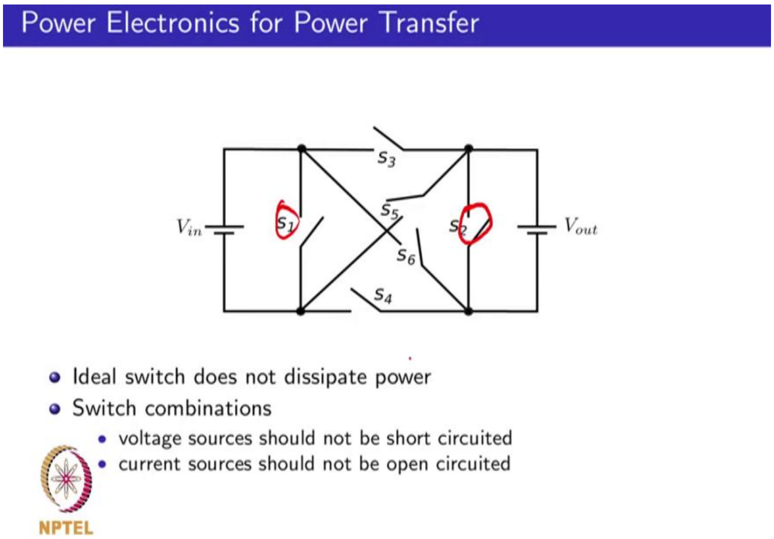

So, if you look at typical power transfer system, which is based on power electronics, what you would what to do is transfer power between sources. So, here what is shown is 2 voltage source, one is V in and the voltage source is V out and you want to transfer power say between the two sources and if you use components such as resisters you always send up with disputation. So, if you use switches in active or in a linear range again you will end up with participation.

So, to get the best possible efficiency in power transfer, the method that people use in power electronics is to operate the switch, the component as a switch which is either on or either off. A switch which is on ideal, switch does not have any voltage drop a cross set, so there is no power dissipation a switch which is fully off does not carry current, so again there is no participation. So, ideal switch does not cost dissipation and the question is what possible combination or feasible for network of switches between say input and output, what is shown over here is that is shown is 2 voltage sources.

And one thing that we can immediately say is that, say in this particular system your switch S 1 and S 2 cannot be turned on because immediately they would short the voltage sources. Similarly, you could actually look at what are the other possible combination of the switches S 3 and S 4 cannot be on because the two voltage sources would get shorted through the switches S 3 and S 4. Similarly, you can see whether S 3, S 5 if you turn it on it is again equivalent to shorting V in. So, you will find that in switch network between 2 ports input port and output port, you cannot really operate any of the switch, without cosign, short circuit or you will not be able to transfer power between your input and output in a efficient manner.

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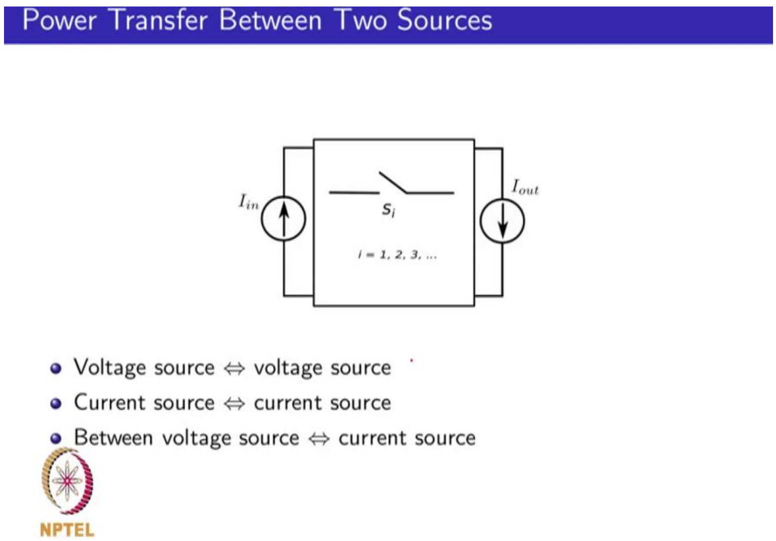

Similarly, we can think about what are the possible ways of exchanging power between different types of sources, we just saw that a voltage sources and voltage source, you can have problems. Will see that even in current source on both sides, you can have problems, if you have 2 current sources, such as this you cannot open a switch a current source because it would cause a large interruption in the current and that would cause a large voltage spike.

So, current sources cannot be opened, voltage sources cannot be shorted and even if say the current source are connected in series, one source will dominate the other and will cause the large stress to be applied from one source to other. So, both to voltage source to voltage source and current source to current source, would not work well in a efficient manner and it would be quite, it would cause a lot of stress on the component in the circuit. How, will see that once you have voltage source on one side and current source the other side, then it is actually possible to have fairly efficient good efficient power conversion.

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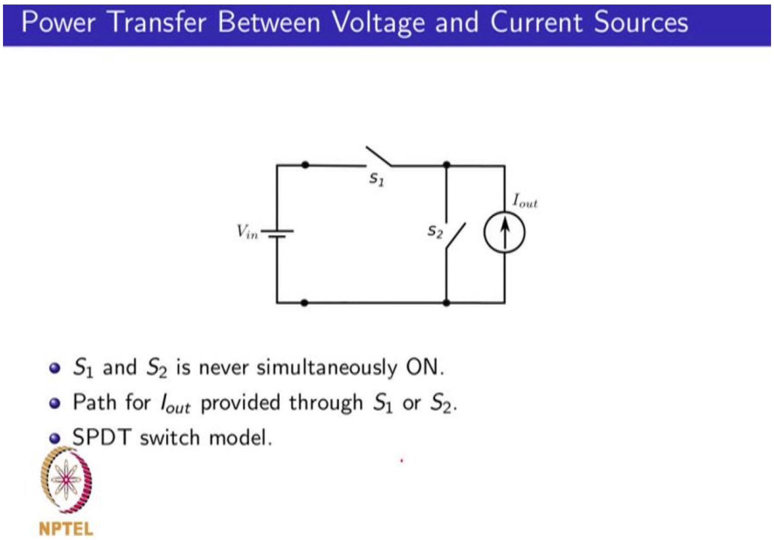

And in this particular case, the voltage source might be battery, it might be rectified AC voltage. A current source is typically obtained in a power electronic application as a inductor, a inductor does not like to change the value of it is current rapidly. So, depending on the design of the inductor you can end up treating as a equivalent current source. So, if you have a combination such as this, then the number of switches that you need can be reduced to just two S 1 and S 2 and to prevent the voltage source V in from getting shorted it means that S 1 and S 2 cannot be simultaneously on.

So, either S 1 is on or S 2 is on, but cannot be simultaneously on, similarly you need to provide a path current I out to flow, it means that S 1 or S 2 has to be on you cannot actually prevent the current from the flowing through the I out, which means that S 1 or S 2 has to be on. So, if you look at this particular model of two switches S 1 and S 2, this corresponds to a single port double through switch.

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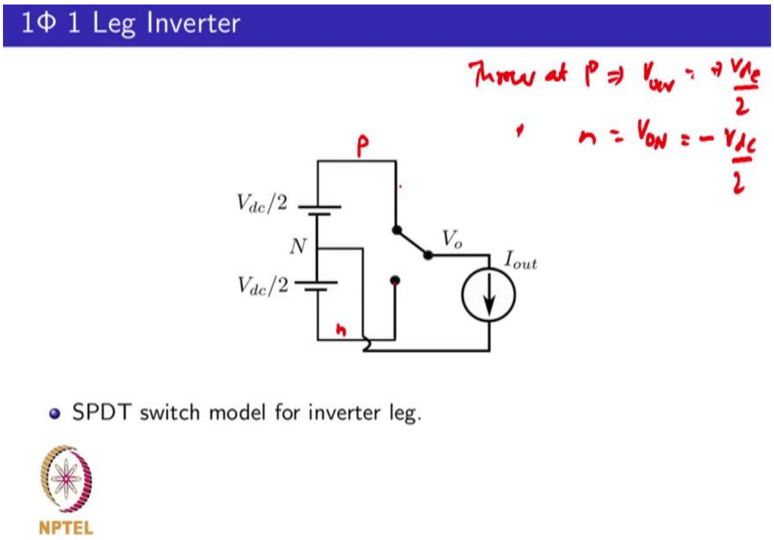

You can think of it as S will look at the next slide, you can think of it as switch, were you either connect to the bottom or the top. So, you through is either connected to the you are one end of your source or to the other end depending on, how you want to transfer power. And this can be used in a variety of configurations ((Refer Time: 26:55)) you can actually see that the basic buck converter, boost converter, etcetera are actually variance of this particular configuration of having voltage source on one side and current source on other.

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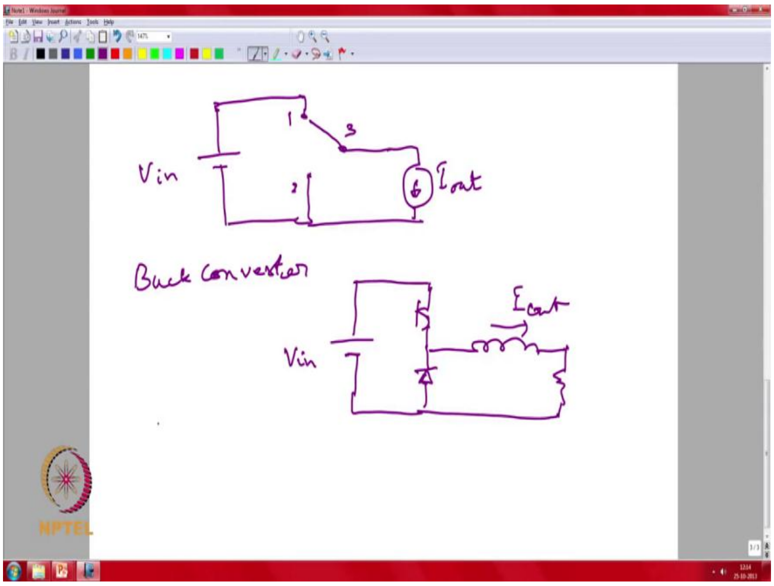

So, if you look at an example realization of this particular circuit, you in a DC to DC converter form you have V in. So, your pole is connected to 3 and because you are in location 1 or location 2 you always have a path for current I out and because 1 and 2 are not simultaneously connected any time, you will never create a short circuit in V in. So, it satisfy both the conditions for the voltage source and the current source, if you then look at what could we a realization of this particular circuit.

If you think about it in terms of practical switch along with diodes or to form a power converter, one realization would be a buck converter. So, buck converter is a simple realization this particular circuit, were you have a voltage source on one side and your filter inductor along with what were load is connected acts like a single port double through switch, a boost converter is equivalent to this particular configuration.

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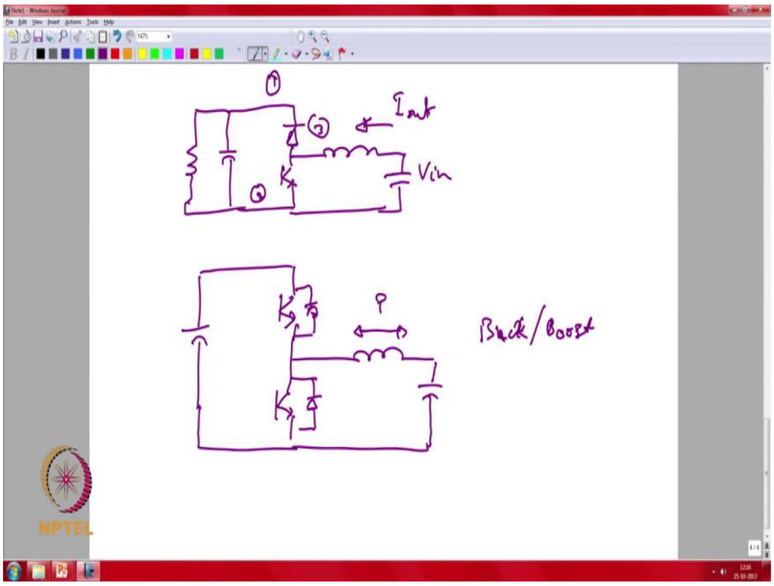

So, if you have a boost converter, so the boost converter also can be thought of as said a realization of this single pole double through configuration. And it is possible to have efficient transfer of power between your input and your output, whether it is a buck or a boost as we have familiar from our power electronic courses. You could also have directional power flow with a buck boost types of configuration, so depending on your control, you can actually send power in either direction.

And depending on how you send your power, you can have a buck or a boost effect, so the next thing that we would be interested in as what how to actually make use of it rather than on DC to DC bases how to actually generate a AC voltage, how to put together a elementary single phase power converter using in the same configuration. So, building a simple DC to AC converter a straight forward again assuming the SPDT configuration for your power converter ((Refer Time: 31:58)).

So, what is shown over here is essentially your DC input to be consisting of two voltages V d c by 2 and V d c by 2. And midpoint N, which one might consider to be the neutral and you have again the SPDT, which can either be into positions, if the SPDT is on the top position. So, if throw is at p, so your V on is now plus V d c by 2, where as if your throw is at N the negative DC bus your V on is minus V d c by 2, so depending on whether it is connected to the top or at bottom, it is possible to get an AC voltage and value V d c by 2 of minus V d c by 2 depending on the position of your throw. So, the next question is how can we then generate a sign wave from a configuration such as this. Because, many times you are interested in interconnecting to the AC grade and the AC grade voltage is sinusoidal order quantity.

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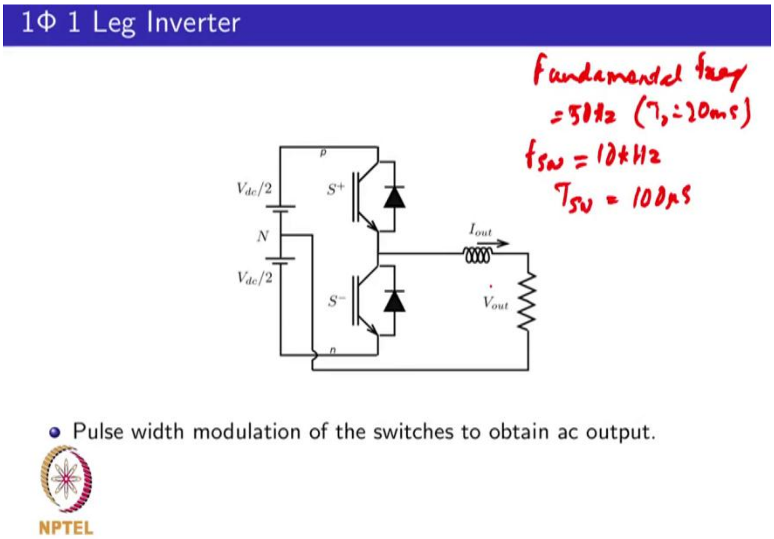

So, again similar to what we saw in the buck converter, boost converter example, converting this single leg, single phase, single leg inverter using transistors and diodes is possible. And we could make use of pulse width modulation switch by appropriately controlling your switching action of your switches, in the positive half cycle and for short durations. So, when you are talking about generating a fundamental output, your fundamental voltage is of the order of time duration you are talking about 50 herds or 20 minutes seconds.

The switching time that your typically talking about is of the order of 10's of kilo herds, so you are talking about 10 kilo herds, so you are talking about 100 micro seconds. So, if you look at in this particular case your fundamental frequencies is 50 herds, so your T naught your fundamental period is 20 milli seconds. Whereas your switching frequencies depending on your particular application, you might have switching frequencies which might be few kilo herds to may be 100 of kilo herds.

So, if you take a example of 10 kilo herds switching frequencies, so you are talking about T s w switching period of 100 micro seconds. So, you are talking about may be 200 durations of switching period per fundamental in a 20 milli seconds of fundamental time frame. So, when you operate such a power converter as a simple inverter on one side you have voltage source, which is shown over here as V d c by 2 and V d c by 2 with midpoint being considered the neutral.

The output is essentially again filtering action provided by inductor, we are considered over here as simple r l type of load and the inductor provides the filtering. So, the question is how quick, how fast you need to switch when you are looking at P w m action and essentially what you are looking at in terms of the switching period is in terms of your switching frequency has to be much higher than the frequency of the poles of your system.

So, from your filter perspective or from your equivalent physical system perspective, what you seen by the filter is essentially an average value rather than the instantaneous value. So, larger the value of the filter you have more integrating effect, so the ripple will be reduced, so the natural averaging effect of physical systems comes into picture and you get an averaging effect by the P w m operation of the power converter.

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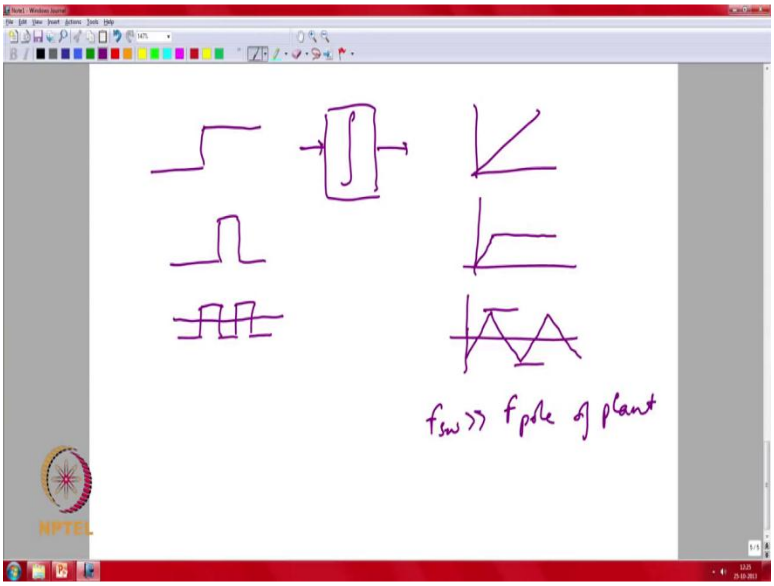

So, if you look essentially a filtering effect because of a inductor, if you look at the input to be a step way from going through integrator, which might represent a inductor or a capacitor or some electromechanical time constants in a motor type of systems. The output is essentially going to be a RAM when you are having a step input, if you are having say a pulse input. Essentially, we have something which steps up and stays flat as you proceed to the filtering circuit.

If you have something which is having a pulse input with an average of 0, essentially what you would have is in this particular case. The output of such a way form would be integral of that, the ripple would be riding on top of whatever is the fundamental that your trying to apply to the load. And the magnitude of the ripple is you can be reduced by selecting a larger inductor or a larger capacitor for improved filtering.

So, many physical processes naturally have integrators unit and they lend itself to P w m action and constrained is that your switching frequency is assumed to be a lot larger, than your maximum pore frequency of your plant. So, in such a situation what you get the output of power converter is essentially the average effect, rather than the instantaneous, so the average can be considered ((Refer Time: 40:34)).

So, if you look at the average voltage, your average voltage in the leg of your particular power converter essentially when the switch is on, your connecting out your put o to p S minus assume to be complementary to S plus. So, S plus is the value of 0 of 1 and S minus is actually a complementary of that, so you can then calculate what is the average voltage V o to the respect to N.

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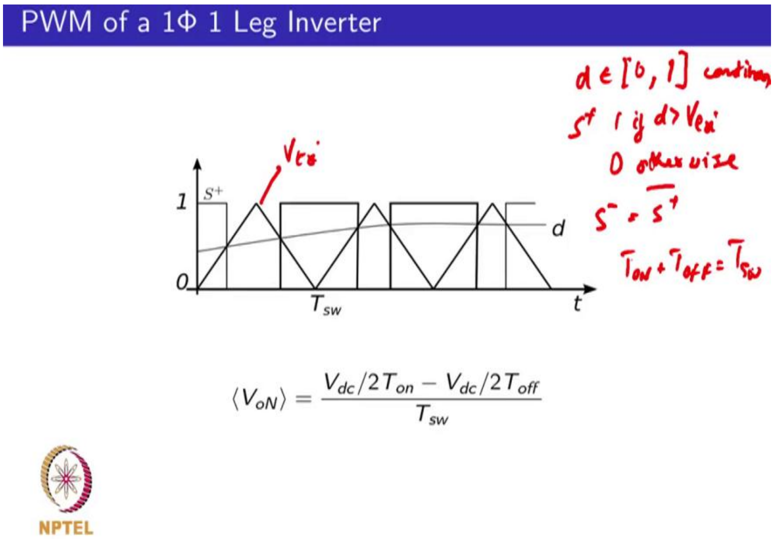

$$\langle V_{oN} \rangle = \frac{V_{dc}/2T_{on} - V_{dc}/2T_{off}}{T_{sw}}$$

So, when ever doing a say a sign triangle path comparison, will assume that say you are having a triangular wave form on V tri and you are comparing that with say due to cycle d and whenever the due to cycle is larger than the triangle, then you switch S plus considered to be turned on. And when the d is below the triangle, then will assume the switch to be off, in this particular case will assume the triangle is between 0 and 1, the due to cycle d is a continues signal which belongs to the range say 0 to 1.

And it is a continues signal whereas S plus is 1 if d is greater than the triangle and 0 otherwise, will assume that the bottom switch S minus is essentially the complementary of S plus. So, what where is a when S plus has a value of 1 then S minus is 0, so depending on weather S plus is on or S minus is on, you can actually calculate the average value of the voltage between o and N a average over a duration of T s w, were T s w is a situation period. So, when a switch S plus is on you have plus V d c by 2 of duration of T on when your duty cycle is below your triangle, you have minus V d c by 2 for a duration of T off. Also T on plus T off is you are switching period.

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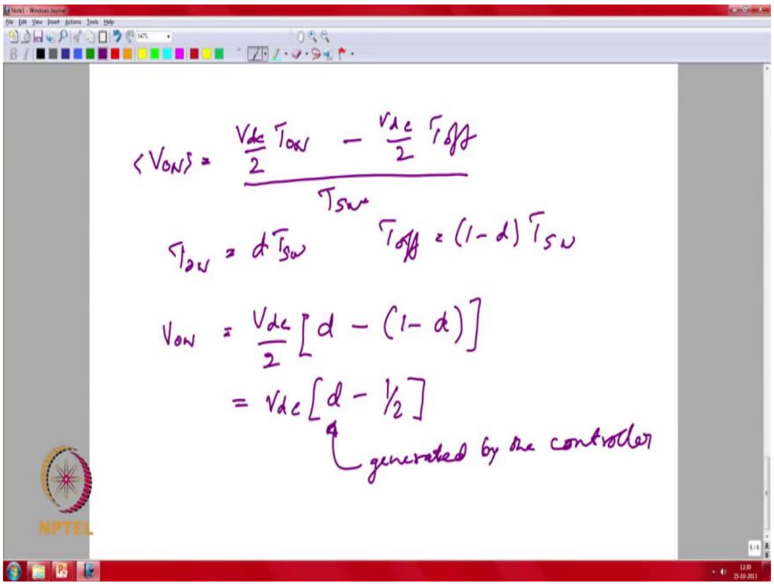

Also T on can be related to your switching duration T s w through your duty cycle d and T off is 1 minus d times T s w. So, if you look at then what is the this average voltage is applying over the period, your V on is V d c by 2 into d 1 minus d substituting from T on from T off. So, you can see that this is equal V d c into d minus half, so you can think about you are single face inverter as a amplifier, were essentially your having a gain having of V d c on an average bases that is getting multiplied by the duty cycle with some of set depending on a the value of a duty cycle being in the range 0 to 1.

So, that half corresponds to the mid value of the particular range, so you can see that essentially in this particular situation your P on d is generally generated by your controller it can be a PI controller or some of the other type of controller or it can be some open loops type of the structure, which is giving a way form, which belongs to the duration 0 and 1. So, this is actually a signal that can be thought of a generated by a controller and if you look at then way from your S plus has a value of either 0 or 1, if you look at the average value of your S plus over at switching period.

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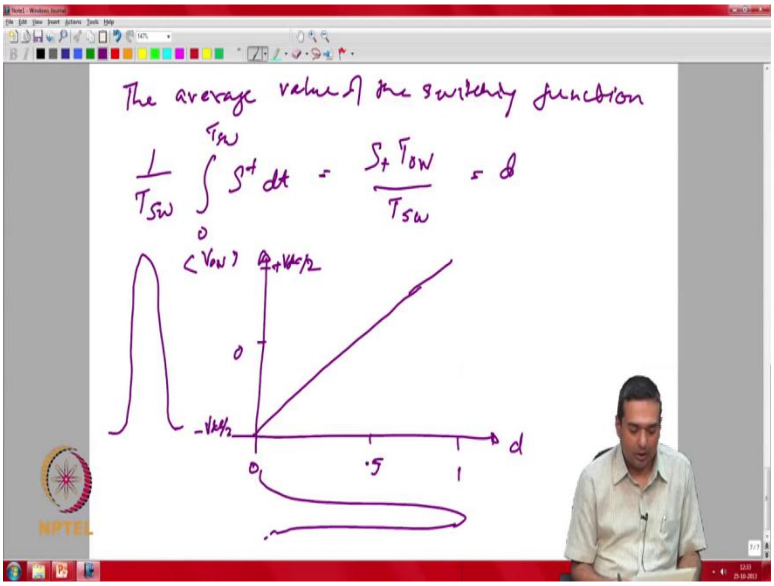

The signal S plus is also referred to as a switching function the average, so over a duration S plus d T s w S plus is on for T on has a value of 1 during T on by T s w. So, you can see that the switching function and the duty cycle give information back and forth, so knowing the duty cycle, you know what is switching function is. And knowing what is switching function is you know what is the duty cycle is, so you can go back and forth between your switching function and your duty cycle.

Also, if you look at the average voltage expression V on average and you look at your duty cycle between say d belongs to range 0 to 1. So, when you are duty cycle is 0 you have output voltage, which might be minus V d c by 2 when your duty cycle is close to plus 1, you are having a value plus V d c by 2. So, depending on your duty cycle, you can actually think about an average of voltage, which is being applied and essentially a your single face leg of the converter acting essentially as an amplifier from your voltage plus perfective.

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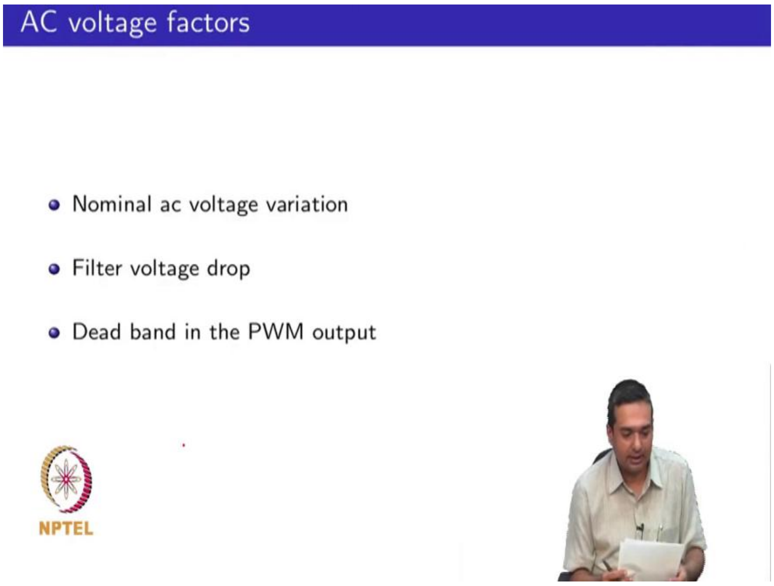

Now, once we have a feeling for what the voltage can be generated on a single faces bases in such type of converter, we could then ask the question in what would be the voltage level that could be considered appropriate for a given application, often we are interested in connecting to the AC grade. So, will see that important factors is factors are what is a nominal voltage and what is the rage around nominal voltage that one has to consider. What is the filter voltage drops that one as to consider and also effects such as dead band plays the important role, in determining how much margin you need to have over and above your typical voltage when your selecting your given DC bus value in your inverter application.

Thank you.