# Power Electronics and Distributed Generation
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## Lecture - 36
## LCL Filter Design

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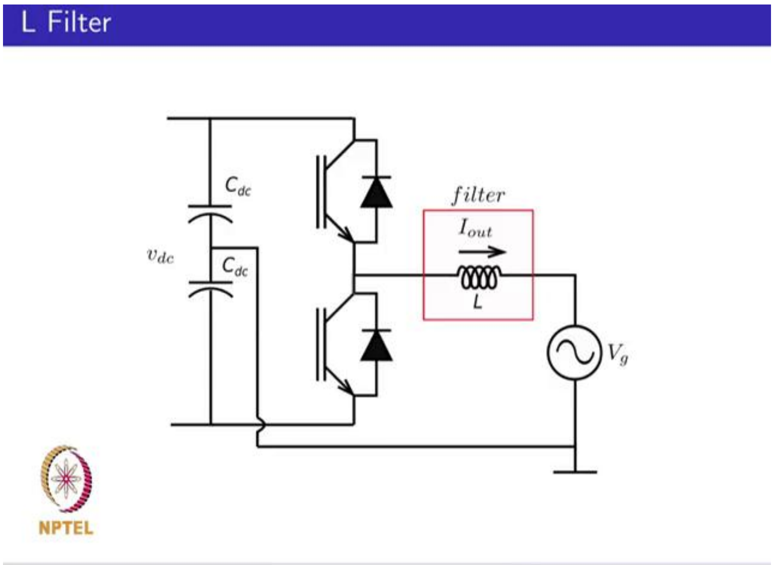

L Filter

Welcome to class 36 of topics in power electronics and distributed generation. So, we have looked so far at an example of an L filter for a single phase inverter. And based on the R M S current calculations, we saw that the ripple that gets injected into the grid would not meet the standard recommendations. And we can get a similar result based on a similar conclusions based on a more exact Fourier analysis.

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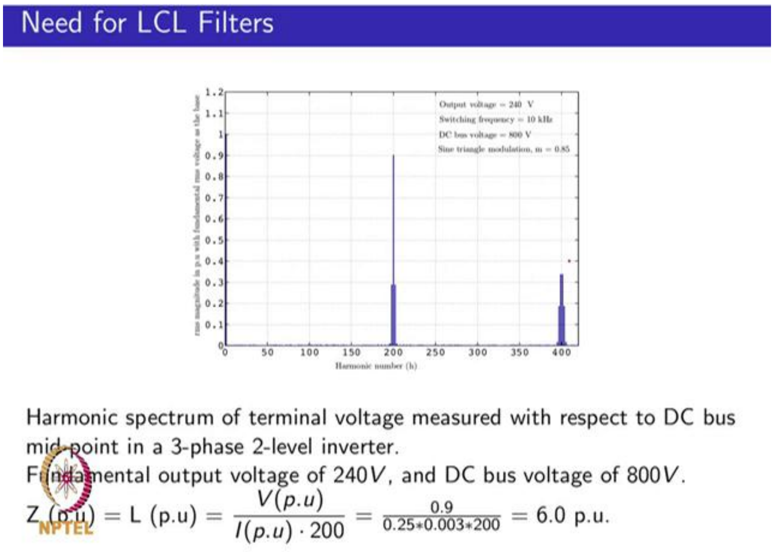

## Need for LCL Filters

Harmonic spectrum of terminal voltage measured with respect to DC bus mid-point in a 3-phase 2-level inverter.

Fundamental output voltage of $240V$, and DC bus voltage of $800V$.

$$Z\,(p.u) = L\,(p.u) = \frac{V(p.u)}{I(p.u)\cdot 200} = \frac{0.9}{0.25*0.003*200} = 6.0 \text{ p.u.}$$

So, what we what is shown here is the Fourier spectrum of a 3 phase 2 level voltage source inverter; its output voltage is 240 volts R M S; which is taken as the base quantity. And switching at a frequency 10 kilo hertz with a D C bus voltage of 800 volts with sine triangular modulation; so the modulation index is 0.85. So, if you do the Fourier analysis your fundamental is a having a magnitude of one per unit; if you look at 10 kilo hertz that would correspond to the 200th harmonic. And the amplitude at the R M S value of the amplitude at the 200th harmonic is around 0.9.

So, if you then look at what the specifications recommendations of the standards would be; you would like the to have the per unit in value of your filter inductor to be equal to V per unit divided by I per unit; that is allowable at the 200th harmonic; one thing to notice in the standard recommends given harmonic to be a 25 percent of the harmonic. So, your standards say 0.033; so 25 percent of that is essentially what is recommended. And the excitation at the 200 harmonic would correspond to 0.9 amps; so the required value of the of your inductance would be 6 per unit.

So, clearly showing that you would exceed what would be realistic for a practical power converter. One thing to keep in mind is so you can see that the given harmonics is restricted to 25 percent of the odd harmonics; this becomes especially important if your switching frequency is low of the order of 1 kilo hertz which might be a more common at a very high power levels. So, it might actually make sense to actually shift your harmonics. For example, instead of 10 kilo hertz if it was 9750 kilo hertz; then that would be correspond to the 195th harmonic; so you could then you need the factor of 0.25 in the denominator over there.

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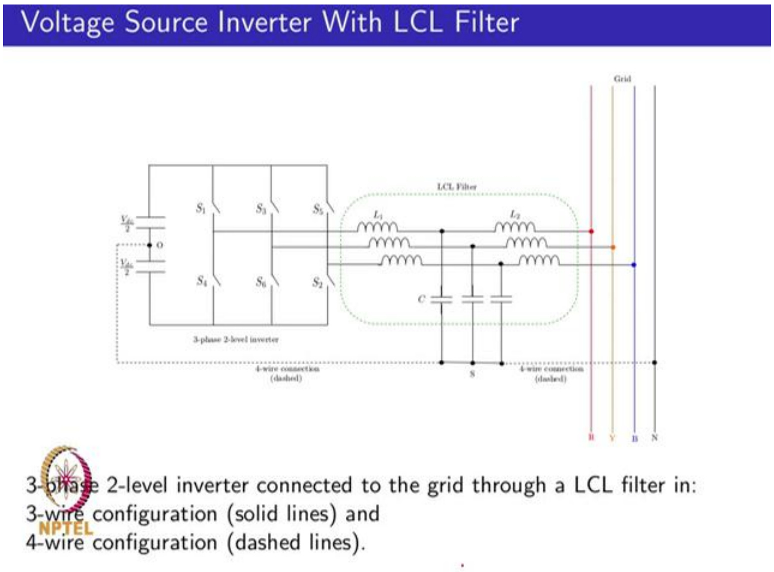

Voltage Source Inverter With LCL Filter

3-phase 2-level inverter connected to the grid through a LCL filter in:
3-wire configuration (solid lines) and
4-wire configuration (dashed lines).

So, based on this we can see that having just a inductive filter may not be possible to meet the standard requirements. So, one could consider a higher order filter such as L C L filters; so what is shown in this schematic over here is the for a voltage source inverter in connected to the grid; where a L C L filter. So, you have L 1 connected to the inverter side L 2 connected to the grid side and capacitor C. And you can have this as a 3 phase 3 wire configuration in which case these dotted lines would not be present or we can have it as a 3 phase 4 wire configuration with capacitors under tap; in which case the dotted lines would be connected with physical wires. So, one question that can be asked is why did you go from a L filter to a L C L; which is the third order filter, why not just a L C filter? So, we could consider what happened if you use a L C filter?

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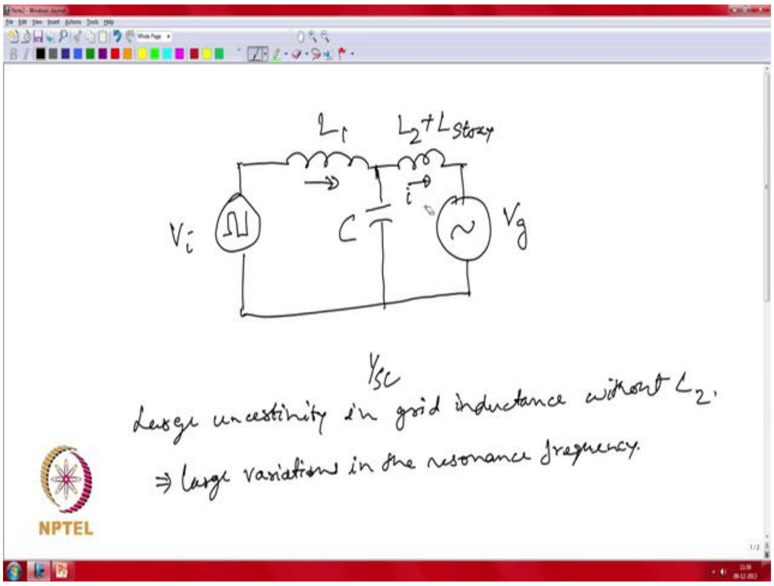

Large uncertinity in grid inductance without $L_2$.

$\Rightarrow$ large variations in the resonance frequency.

So, suppose you have the inverter which can be represented as a pulsed voltage source V I; and if you consider the L filter and then you have the grid voltage V g. So, the first question is where to place the C you could not definitely place the C on the inverter side; because you have to switch from a voltage source to a current source. So, you cannot have a capacitor here; so you think about possibly connecting the capacitor here. And you know that the impedance; if you consider the voltage source as ideal we know that the dynamic impendence of a voltage source would be 0; whereas the dynamic impendence of the capacitor would be 1 by S C. So, whatever ripple would come in the inductor, would actually flow through into the grid?

So, this is for a ideal grid; so you can see that there is no benefit for adding a capacitor; in a practical grid you would not just have a solid connection ideal 0 impedance source would have some strained inductance; it could be of the lines transformers etcetera going back to the grid; in each case this reduces to a L C L filter. So, this is actually a L C L filter. So, practically you would end up with an L CL filter if even if you just connect the C; but having in the L C L filter where one of the dominant impedances be governed by a stray parameter is not a great idea. Because the resonances of this particular filter would vary over a wide range depending on what the value of the strained inductance is. So, it would be it would not be possible to accurately predict; where the resonant frequencies lie; in such a situation so a more practical situation would be to physically add a second inductor. And then whatever non ideal inductance is there on the grid would be essentially considered part of your inductance L 2. So, your L 2 can be designed in such a manner that it dominates over the stray inductance.

So, whatever variation exists because of the stray inductance in the grid can be accommodated in a in add over tolerance range by appropriately designing the L C L filter. So, you can see that there will be large uncertainty without L 2. And the implication of this is that you would have large variations in the resonance frequency. So, if you look at the circuit that we seen for the L C L filter. So, this would accommodate for the configuration for both the 3 phase 3 wire and the 3 phase 4 wire; what one would typically C is that the ripple that is going out into the grid is essentially your grid current ripple is higher in a 3 phase 4 wire converter compared to a 3 phase 3 wire converter. Because you have now additional parts in the 4wire case for the 0 sequence components to flow. So if you have a filter design that meets the standards for the 3 phase 4 wire phase; it would typically meet the requirement for the 3 phase 3 wire situation also. So, we have to consider the 3 phase 4 wire power filter to be typical filter; which would then look at in detail.

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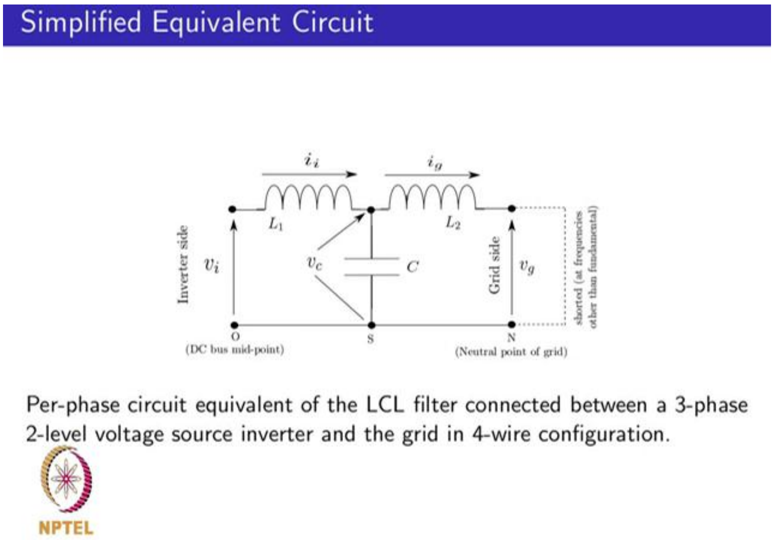

Simplified Equivalent Circuit

Per-phase circuit equivalent of the LCL filter connected between a 3-phase 2-level voltage source inverter and the grid in 4-wire configuration.

So, if you look at the L C L filter now for the 3 phase 4 wire power converter; we can then look at it on a per phase equivalent circuit basis. So, on one side is essentially the inverter voltage V i between the output of your phase leg and the midpoint of the D C bus followed by the L C L filter; on the grid side you essentially have the grid voltage

Vg which at frequencies other than the fundamental can be considered a short circuit. And whatever stray inductance impedances are there in the grid can be accommodated along with L 2. So, the grid side can be considered a short circuit we are looking at frequencies at rather than the fundamental frequency. So, with this simplified single phase equivalent circuit you could go about analyzing the L C L filter.

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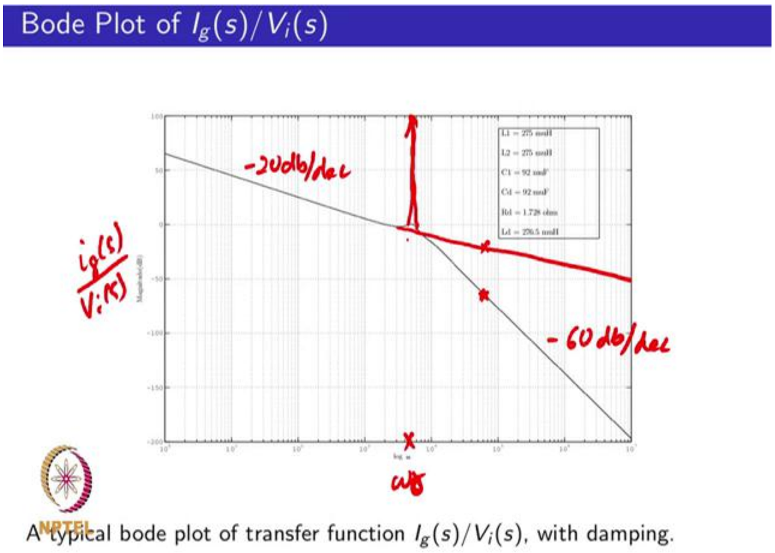

Bode Plot of $I_g(s)/V_i(s)$

A typical bode plot of transfer function $I_g(s)/V_i(s)$, with damping.

You can then take look at typical magnitude response plot of the grid current injection divided by the inverter side voltage. So, essentially you are looking at a transfer function I g (s) divided by V i (s) and you are looking at the bode plot. And if you look at the low frequencies below your resonant frequency; you are attenuation of V s corresponds to minus 20 d b per decade. So, this would be similar to the attenuation characteristics of a simple inductive filter; beyond the resonant frequency the attenuation of the L C L filter would correspond to minus 60 d b per decade, which would correspond to a third order L C L filter.

So, if you take a what is shown over is the frequency in radiance per second and the magnitude of I g by V i transfer function which is essentially a admittance transfer function; if you had essentially a L filter it would continue all along the higher frequencies at the same minus 20 d b per decade. So, if you are considering say a frequency such as say 10 kilo hertz; so this would correspond to around 6 into 10 to the power of 4 radiance per second.

So, you are looking at essentially at this point on the L C L filter and this point on the L filter you have a attenuation difference of about 40 d b. So, you get a improvement in attenuation by a factor of 100 for the L C L filter compared to a L filter. So, you know that you could actually meet it is feasible to meet the attenuation requirement of suggested by the specifications with the L C L filter. So, what is shown over here is not an ideal L C L filter; where the resonant peaks would actually go of to a very large value; this shows a damped L C L filter where the resonant frequency is managed the gain at the resonant frequency is managed by lower level.

One could then use the to look at the transfer function I g by V i (s); we can actually get it from the simple equivalence circuit of the L C L filter. So, from the L C L filter network one can actually calculate what is i g as a i g (s) divided by V i (s); and that can be done with just a looking at the impedance values.

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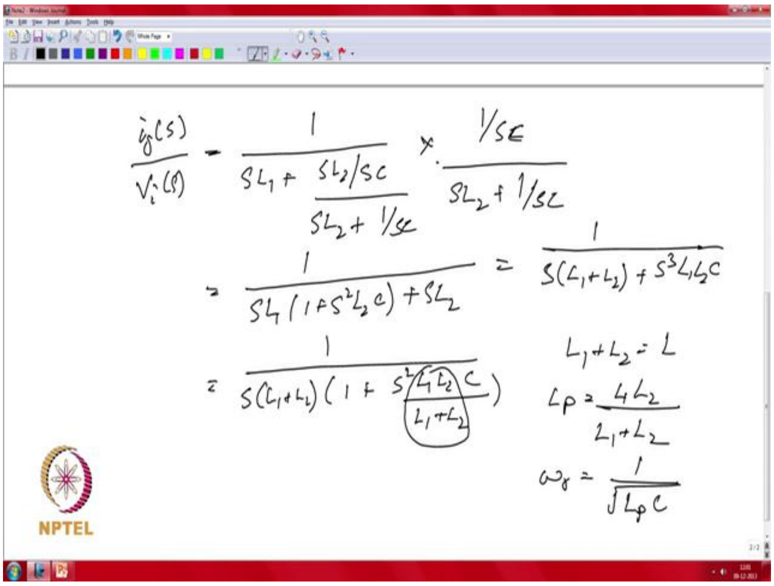

$$\frac{i_g(s)}{V_i(s)} = \frac{1}{sL_1 + \frac{sL_2/sC}{sL_2 + 1/sC}} \times \frac{1/sC}{sL_2 + 1/sC}$$

$$= \frac{1}{sL_1(1+s^2L_2C)+sL_2} = \frac{1}{s(L_1+L_2)+s^3L_1L_2C}$$

$$= \frac{1}{s(L_1+L_2)\left(1+s^2\boxed{\frac{L_1L_2}{L_1+L_2}}C\right)}$$

$L_1+L_2 = L$

$$L_p = \frac{L_1L_2}{L_1+L_2}$$

$$\omega_r = \frac{1}{\sqrt{L_pC}}$$

So, i g (s) divided by V i (s) is 1 by S L 1 plus the series value of S L 1 plus the impedance of C in parallel with L 2. So, essentially you have S L 2 by S C and then whatever current flows through your inverter side splits between these 2 branches depending on the ratio of the impedances. So, you can write it as 1 by S C divided by; so this is equal to 1 by this can also be written as 1 by S L 1 plus L 2 into 1 plus S square L 1 L 2 C divided by L 1 plus L 2. So, the quantity L 1 plus L 2 can be thought of as L. So, essentially the inductor is patented to L 1 plus L 2; if you had a first order filter then essentially the capacitor connection would not be there; you would have essentially just L 1 plus L 2. Now, that you add a capacitor in between you get the add additional attenuation provided by this term over here. Now, this term over here is essentially the parallel L 1 and L 2 in parallel. So, L p is and your resonant frequency is 1 by root L p times C.

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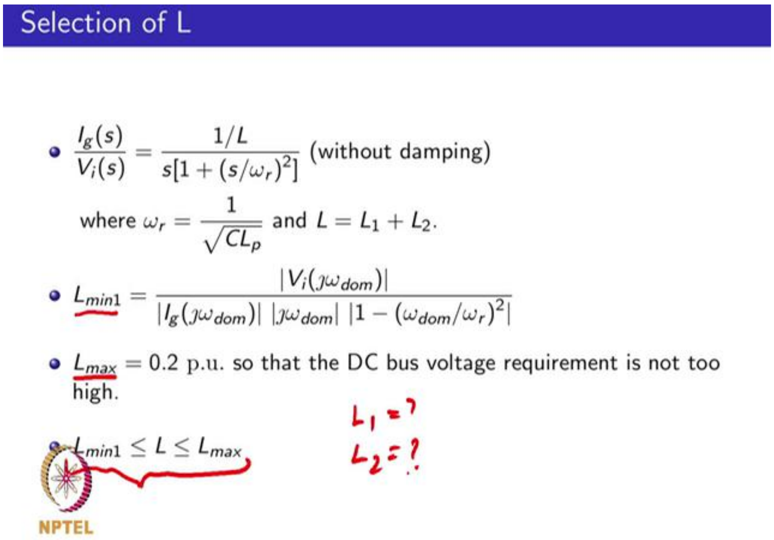

## Selection of L

- $\frac{I_g(s)}{V_i(s)} = \frac{1/L}{s[1+(s/\omega_r)^2]}$ (without damping)

  where $\omega_r = \frac{1}{\sqrt{CL_p}}$ and $L = L_1 + L_2$.
- $L_{min1} = \frac{|V_i(\jmath\omega_{dom})|}{|I_g(\jmath\omega_{dom})|\ |\jmath\omega_{dom}|\ |1-(\omega_{dom}/\omega_r)^2|}$
- $L_{max} = 0.2$ p.u. so that the DC bus voltage requirement is not too high.
- $L_{min1} \leq L \leq L_{max}$

$L_1 = ?$

$L_2 = ?$

So, this relationship can be used then to obtain this transfer function i g (s) by V i (s); so this is the ideal L C L filter without any damping. So, you have very high gain at the resonant frequency and you have the definition of what is resonant frequency and the L value is; we can actually make use of this to actually the turn in what would be one of the limits for this particular filter design.

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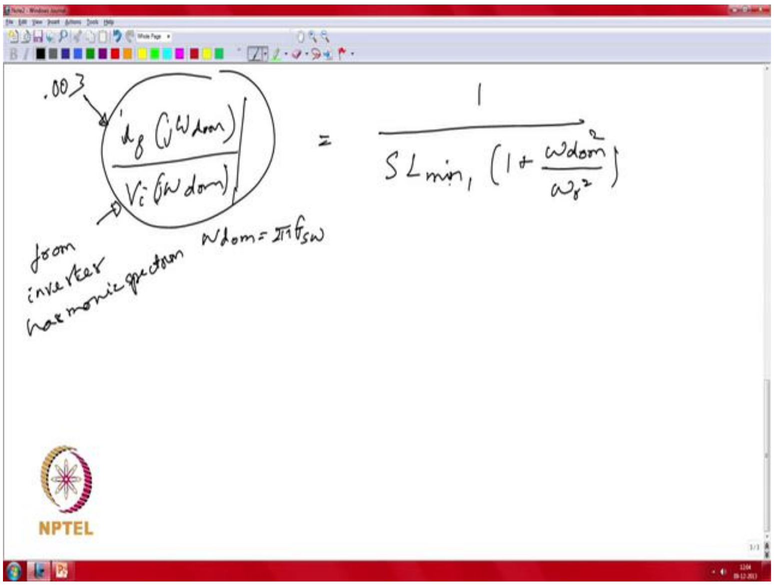

$$\left|\frac{i_g(j\omega_{dom})}{V_i(j\omega_{dom})}\right| = \frac{1}{s L_{min,1}\left(1 + \frac{\omega_{dom}^2}{\omega_r^2}\right)}$$

.003

from inverter harmonic spectrum

$\omega_{dom} = 2\pi f_{sw}$

So, if you look at essentially this particular expression over here; we can write this particular term as i g at your down line frequency. And your omega dom we saw from our previous spectrum it is essentially 2 pi switching frequency; and this would correspond to 1 by S L 1 times 1 plus omega dom square by omega resonant. So, we know that your i g has a value of 0.003 on a per unit basis and your V i can be obtained from your Fourier inverter harmonic spectrum.

So, one could then a rewrite this particular expression in terms of we know what this quantity it is. And assuming at this point we know what the resonant frequency is; we could make use of this particular expression and put in the form of determining L minimum in terms of quantities that are known; you know what the dominant frequency is we will discuss on; how we could select the resonant frequency. So, you have essentially minimum limit for what your inductive term is; you also have a maximum limit for what L 1, L max is; what is the maximum value of L 1 plus L 2 is? And this is based on the d c bus voltage requirement.

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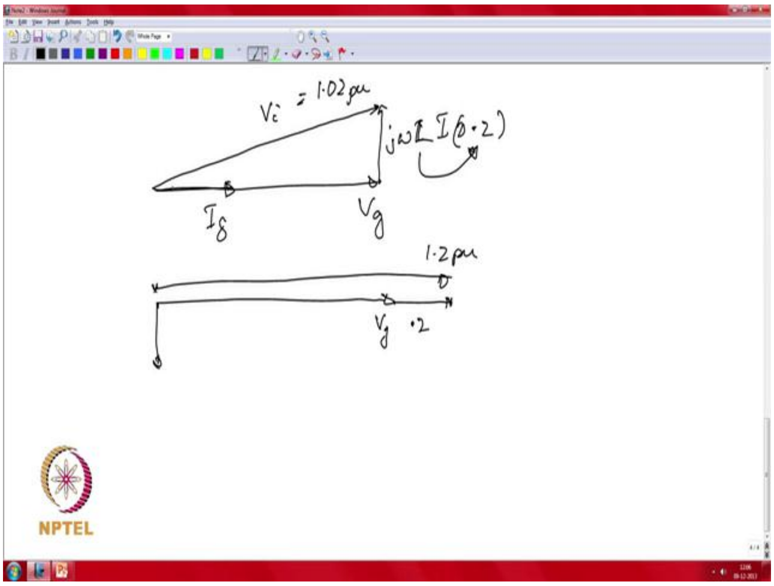

So, if you look at essentially typical power converter that is connected to the grid; if you consider a power converter operating with a 20 percent impedance, filter impedance value of L being 20. And operating say unity power factor i g; then essentially at fundamental frequency your voltage drop is j omega L l times i and i is 1 per unit say V g is 1 per unit.

So, you have a drop a voltage drop of 0, 2 per unit assuming L is 0.2. So, then if you look at what would be the inverter voltage V i this would be actually 1.02 per unit. So, it is not very different from V g if you are operating at relative power factor; if you are operating say the power converter is a start com. So, supplying a reactive power then essentially you would have V g and i g; and the voltage drop would now be having a value of 0.2. And your inverter voltage required would be now 1.2 per unit which would be at the higher on the higher side. Suppose that you are not operating as a either as a stat com or even though you are operating as a in a unity power factor mode typically for a d g.

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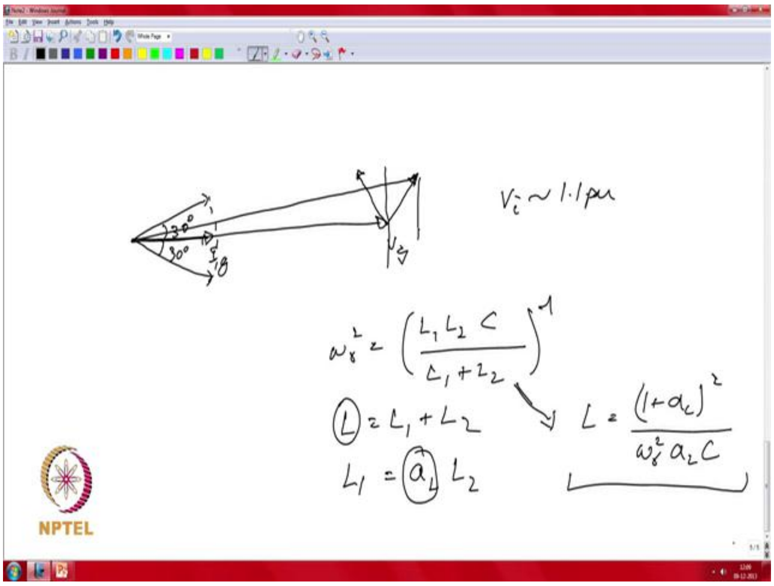

$V_i \sim 1.1\,pu$

$$\omega_r^2 = \left(\frac{L_1 L_2 C}{L_1 + L_2}\right)^{-1}$$

$$\boxed{L} = L_1 + L_2$$

$$L_1 = \boxed{a_L}\, L_2$$

$$\searrow \underbrace{L = \frac{(1+a_L)^2}{\omega_r^2 a_L C}}$$

You might consider say some variation in the in the power factor; when you are operating this particular power converter say you have the grid voltage V g. And say you have your i g that you would ideal ideally like to use it in unity power factor and say you have a range of i g going say 30 degree reed to thirty degree lag. And then if you look at what would be the say the voltage that would be required at the terminal of the power converter.

So, when you are trying to inject leading volts you need high terminal voltage; when you are trying to inject lagging volts you would require low lower terminal voltage. So, you could you could require say about 10 percent more for D C bus voltage where when you are operating say a range of a such conditions; you might be required to operate in such a condition under dynamic situations when you have phase joints, frequency shifts etcetera your controls take time to actually react. So, you might need some margin to actually accommodate the filter. So, if so keeping in mind what would be a upper limit of the D C bus; you would then be able to obtain a range of value of the inductance between say L min and say L max. So, your value of the inductance would lie in this particular range; we could also think about say in this particular case we are looking at what L is. But what we are really interested in is what L, 1 should be and what L 1, L 2 should be? So, the question is how should we split the L between L 1 and L 2.

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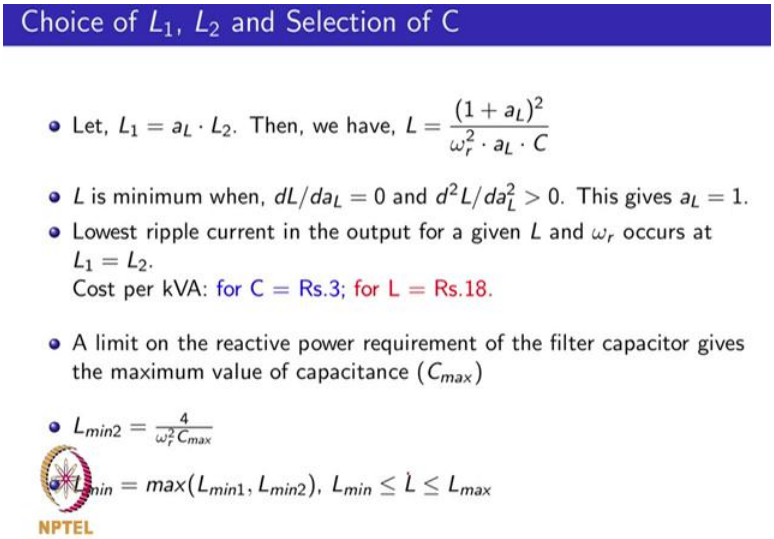

### Choice of $L_1$, $L_2$ and Selection of C

- Let, $L_1 = a_L \cdot L_2$. Then, we have, $L = \dfrac{(1+a_L)^2}{\omega_r^2 \cdot a_L \cdot C}$
- $L$ is minimum when, $dL/da_L = 0$ and $d^2L/da_L^2 > 0$. This gives $a_L = 1$.
- Lowest ripple current in the output for a given $L$ and $\omega_r$ occurs at $L_1 = L_2$.
  Cost per kVA: for C = Rs.3; for L = Rs.18.
- A limit on the reactive power requirement of the filter capacitor gives the maximum value of capacitance ($C_{max}$)
- $L_{min2} = \frac{4}{\omega_r^2 C_{max}}$
- $L_{min} = max(L_{min1}, L_{min2})$, $L_{min} \leq L \leq L_{max}$

So, one thing that you could then do is look at the expression omega r square is equal to L 1 L 2 C by L 1 plus L 2 inverse. And then look at L to be equal to L 1 plus L 2 and define say L 1 to be equal to a times a L times L 2. So, for example if a L is closed to 0; it means that the entire inductance is L is equal to L 2; if a L is equal to 1 it means L 1 is equal to L 2 and if a L tends to infinity it means the entire inductance is L is in L 1 and L 2 is negligible. So, you could then write this particular expression for the resonant frequency in terms of L in this particular expression and a L; you would then get an expression of the form L is equal to 1 plus a L the whole square divided by omega r into a L C. So, you can then look at this particular expression which is a constrain between the value of L a L and omega r and C; and look at a few minimizations ok.

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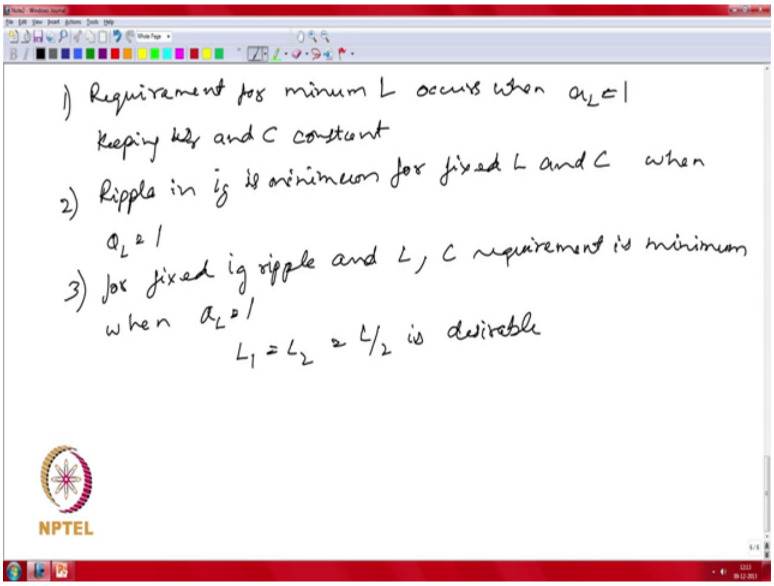

1) Requirament for minum L occurs when $a_L = 1$
keeping $\omega_r$ and C constant

2) Rippla in $i_g$ is minimum for fixed L and C when
$a_L = 1$

3) for fixed $i_g$ ripple and L, C requirement is minimum
when $a_L = 1$

$L_1 = L_2 = L/2$ is desirable

So one thing you might ask is what is the requirement for minimum L; when a L is equal to 1 keeping omega r and C constant. So, if you take the previous expression and differentiate L with respect to L; we could then equate it to 0 either at the minimum or the maximum; take the second derivative to see whether it is minimum or maximum. And look at what are the relationship which you could get; and you would see that the requirement for minimum L is when a L is equal to 1 keeping omega r and C constant. Another property that you would observe is that it you the ripple in i g is minimum; for fixed L and C; when a L is equal to 1. So, keeping other parameters like L, C and omega r constant; you can then take the expression for i g. And take the derivative with respect to a L and you see that the ripple in i g is minimum at this particular point of a L.

Another point that you could observe is that for fixed i g ripple and L comma c requirement; if you put L the so keeping i g ripple fixed and keeping L fixed you are allowed to vary L. But keep L 1 plus L 2 equal to L as a fixed parameter; you will then see that C requirement is minimum when a L is equal to 1. So, from all these properties it is actually seen that a L 1 is equal to L 2 is equal to L by 2 is desirable. And in a practical situation you may not be equal to exactly make L 1 equal to L 2; because L 1 might be a physical inductor that you might add; L 2 might be a inductance of a interconnection transformer you might try to make the values close. But you may not be able to exactly match but you know what is the desirable direction.

So, you can see that keeping things like you could actually look at the minimum of these functions and keeping things like the value of L to be small is desirable. Because in a filter if you look at the cost of energy storage; if you look at point number 1 which we just wrote keeping the L value L minimum given other parameters to be constant would be actually important; from your cost prospective the cost per k v of capacitors etcetera is actually much lower than that of a inductor. So, it is actually desirable to actually keep your inductive components to be as cost effective as possible; you also have one more constraint on in the L C L filter.

So, if you look at the L C L filter; you while operating the power converter if you now look at the operation at a fundamental voltage you have say 240 volts over here and 240 volts R M S over here. But the voltage across the capacitor resistance would be actually close to 240 volts. So, we are talking of approximate value of the voltage in the filter network. So, there is actually reactive power which is being drawn by the filter capacitor; and you do not want that reactive power to be excessive. So, you that would actually form another constraint on the on the filter design.

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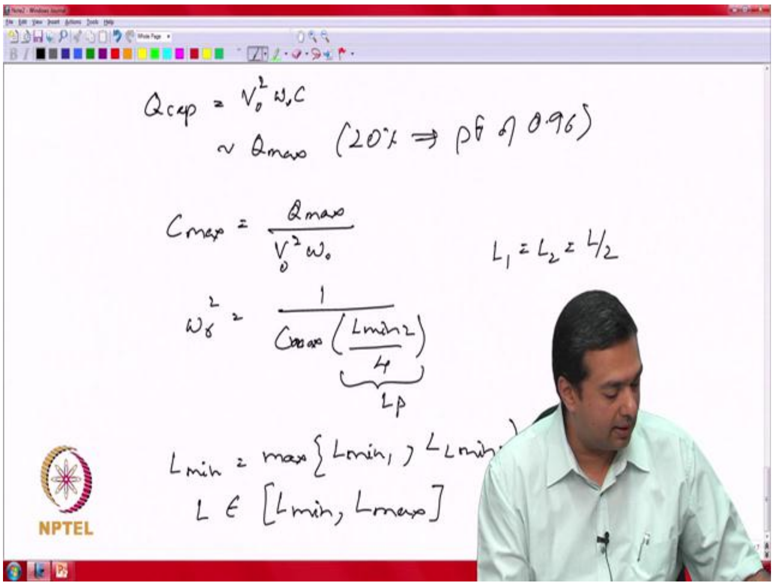

$$Q_{cap} = V_0^2 \omega_0 C$$

$$\sim Q_{max} \quad (20\% \Rightarrow pf\ of\ 0.96)$$

$$C_{max} = \frac{Q_{max}}{V_0^2 \omega_0}$$

$$L_1 = L_2 = L/2$$

$$\omega_r^2 = \frac{1}{C_{max}\underbrace{\left(\frac{L_{min2}}{4}\right)}_{L_p}}$$

$$L_{min} = \max\{L_{min1}, L_{min}$$

$$L \in [L_{min}, L_{max}]$$

So, we know that Q of your capacitor is equal to V naught omega naught C. And if you keep this to be a limit Q max say 20 percent; 20 percent power Q would correspond to a power factor of 0.96. So, under operation you do not cost a large a say offset in your power factor because of the introduction of the capacitor. So, you have C max and we know the constrain that omega r square is equal to 1 by C max and the corresponding L would correspond to L min. And we will called as l min 2 by 4; because we know that L 1 is equal to L 2 is equal to L by 2 is essentially the value. And if you then look at L p which is essentially the parallel combination of L 1 plus L 2 this would be L by 4; so the corresponding constrain would be L min 2 by 4.

So, on the minimum side there're two constraint one constraint is about the ripple current being injected into the grid; the second constraint is on the amount of the reactive power that is being consumed by the filter. And you could then say your L min might be the upper limit of your L min 1 and L min 2. So, by selecting this you are ensuring that both the constraints are being meet. And then your final inductance is would be belong to the range between L min and L max. So, the another question is what would be how to actually go about the selection the value of the inductor which is ranged between your minimum and maximum.

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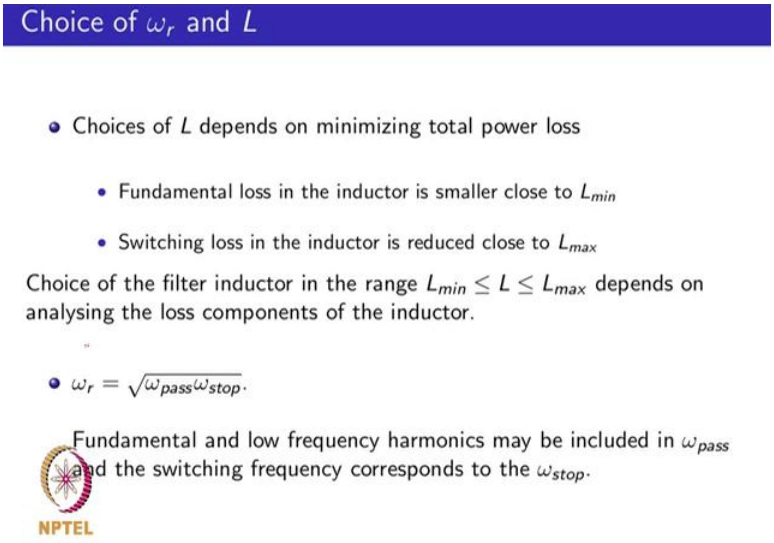

### Choice of $\omega_r$ and $L$

- Choices of $L$ depends on minimizing total power loss
  - Fundamental loss in the inductor is smaller close to $L_{min}$
  - Switching loss in the inductor is reduced close to $L_{max}$

Choice of the filter inductor in the range $L_{min} \leq L \leq L_{max}$ depends on analysing the loss components of the inductor.

- $\omega_r = \sqrt{\omega_{pass}\omega_{stop}}$.

Fundamental and low frequency harmonics may be included in $\omega_{pass}$ and the switching frequency corresponds to the $\omega_{stop}$.

And, the actual choice of the value of L between minimum and maximum could be based on minimizing the power loss in your filter. If you look at the power loss in a filter in your value of power loss at fundamental frequency plus the value of power loss at the switching frequency is what you are trying to minimize. And if you look at the trend of the power loss at the fundamental frequency it would actually increase; if you have a larger value of inductance. Because you need more terms, more length of the wire winding may be a larger core. So, you would end up with a fundamental loss which tends to increase and so it is desirable to operate closer to L min from the fundamental loss prospective; if you look at the switching loss in the filter inductor your switching repair current tends to reduce at as you increase your inductance. So, the losses also would reduce as you are your ripple current through the filter reduces. So, from your switching loss prospective it is actually decidable to operate close to L max.

So, then you look at the overall picture to actually see what point would correspond to the lower loss and will look at a issue in a in the subsequent slides; to actually determine optimum value of your inductance between the L min and L max range depending on analyzing your loss components within the filter inductor. So, one item that we still need to figure out is what the resonant frequency was.

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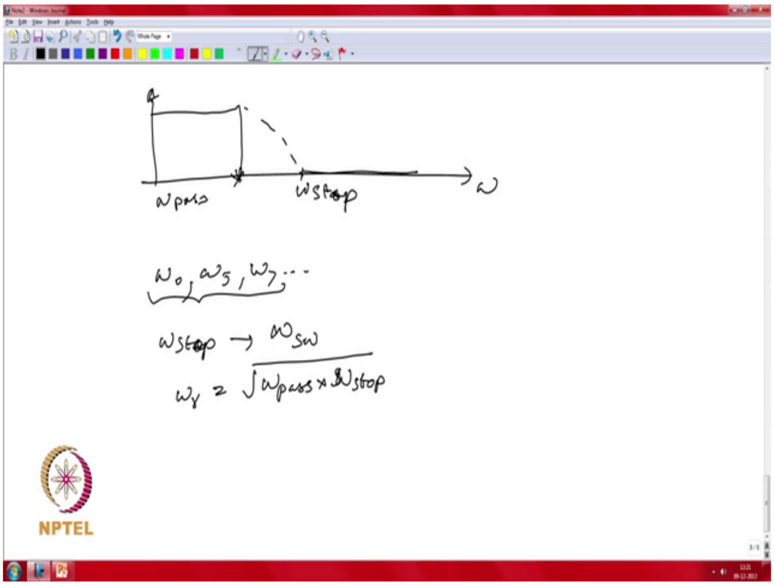

$$\underbrace{\omega_0, \omega_5, \omega_7}, \dots$$

$$\omega_{stop} \rightarrow \omega_{sw}$$

$$\omega_r = \sqrt{\omega_{pass} \times \omega_{stop}}$$

And, if you look at a typical filter designs you are your essentially having a filter where you have a pass band. And you essentially have a stop band; and essentially you would like your filter to transition from your pass band to your stop band; when you are actually going between this particular range. So, the question is what belongs to your pass band? Your pass band might have frequencies you definitely have the fundamental frequencies see in your pass band; you might have say your 5 th, 7 th harmonic, etcetera, your harmonic frequency is in your pass band especially if you are trying to build a active filter; which is trying to inject and control the harmonics in an accurate manner;

you might also say for example, try to reject the harmonics that the grid is putting on a power converter; by active actively insuring that your bandwidth includes your harmonic frequencies. So, your pass band may just be your fundamental frequency can actually extend for the rout depending on your bandwidth tower gets for your power converter; your stop band would correspond to your switching frequency and its side bands and harmonics. And you are trying to ensure that all that is in the stop band; and then you could actually select your resonant frequency to be a geometric mean between a pass band and stop band.

So, with this choice you now have essentially obtained all the components of your L C L filter; you know your resonant frequency you know the choice of L you know L 1, L 2. And once you know your omega r knowing L 1 and L 2 you automatically fix your capacitance; because it is related through your resonant frequency. So, the next thing that one could consider is then what does this design procedure address; there are multiple constraints in filter design.

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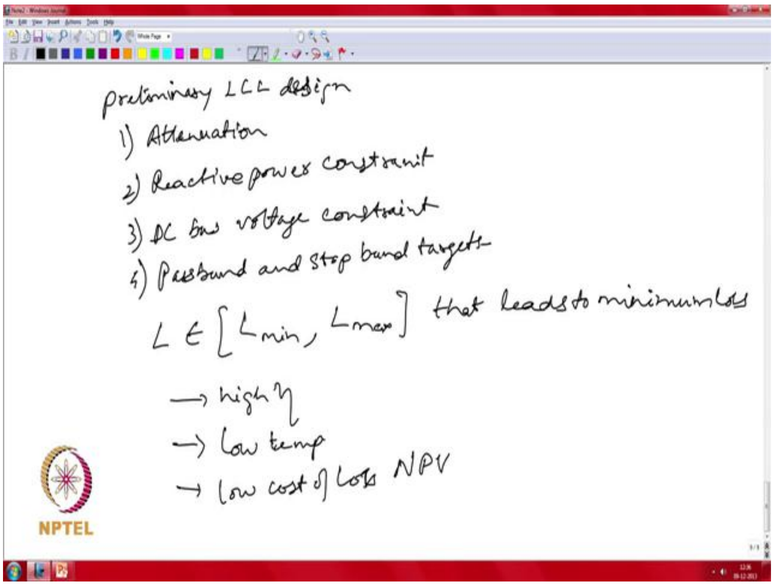

preliminary LCL design

1) Attenuation
2) Reactive power constraint
3) DC bus voltage constraint
4) Passband and stop band targets

$L \in [L_{min}, L_{max}]$ that leads to minimum loss

→ high $\eta$
→ low temp
→ low cost of loss NPV

So, you have essentially at this point a preliminary one issue that it address is it definitely address the attenuation requirement; it looks at the reactive power constraint, it looks at the D C bus voltage constraints and it looks at your pass band and stop band targets. So, the actual value of now that we have your preliminary L 1, L 2 and C.

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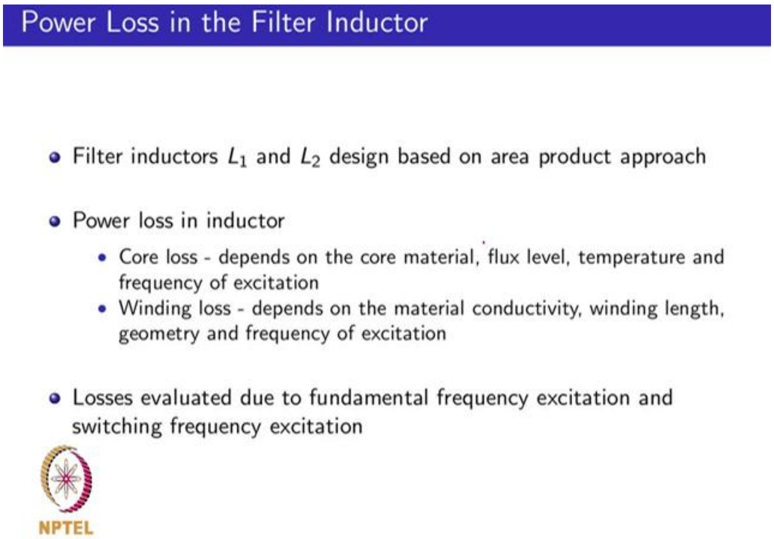

## Power Loss in the Filter Inductor

- Filter inductors $L_1$ and $L_2$ design based on area product approach
- Power loss in inductor
  - Core loss - depends on the core material, flux level, temperature and frequency of excitation
  - Winding loss - depends on the material conductivity, winding length, geometry and frequency of excitation
- Losses evaluated due to fundamental frequency excitation and switching frequency excitation

NPTEL

The next question is what is the actual value of L 1, L 2 that can be designed; and the procedure to design the L 1and L 2 is based on the area product calculations; that we had discussed previously. And we need to choose a L 1 and L 2 from keeping in mind the power loss in the filter inductor. And we have seen that the power loss in the filter inductor consists of core loss component and the winding loss; the core loss depends on the type of material that is selected with the flux level, the temperature because the cross parameters would the properties of the materials would change with temperature; also the frequency of excitation, the winding loss would again depend on the material conductivity, the material conductivity can again change with temperature, the winding, length, the geometry, geometrical parameters, number of layers etcetera and frequency of excitation.

So, both these terms of core and winding loss terms can be then evaluated at the fundamental frequency excitation and the switching frequency excitation; to look at what would be the components on the loss components L 1, L 2 and the other parts of the filter; and we can actually do that.

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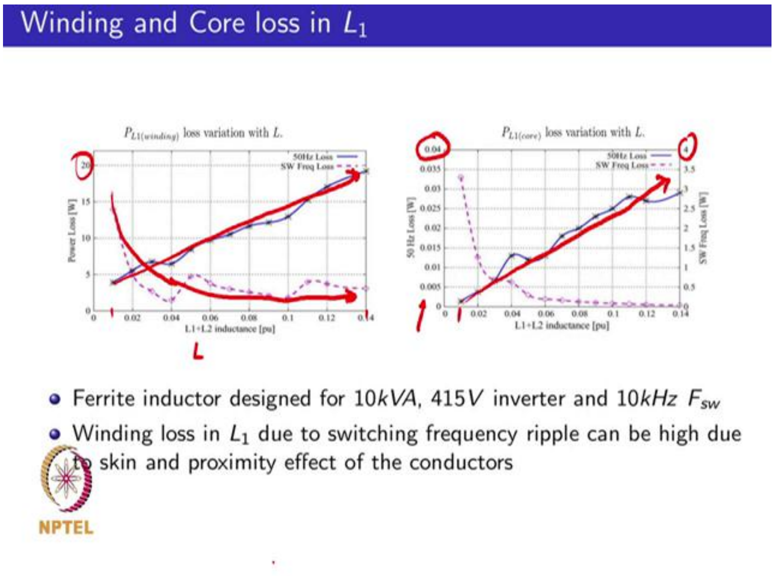

Winding and Core loss in $L_1$

- Ferrite inductor designed for $10kVA$, $415V$ inverter and $10kHz$ $F_{sw}$
- Winding loss in $L_1$ due to switching frequency ripple can be high due to skin and proximity effect of the conductors

So, if you look at the filter inductor L 1 this is actually an example of a 10 k v, 415 volt inverter switching at 10 kilo hertz; what is shown in these figures are essentially what is plotted is the power loss in a inductor L 1; the first figure over here shows the winding loss as a function of L which is L 1 plus L 2 ranging between say 1 to1 percent to 14 percent. And the next figure shows core loss again L is varied between 1 and 14 percent and you are looking at the loss in the core with a variation of L loss in the core of L 1 when L 1 plus L 2 is varied.

So, you can see that if you compare this 2 figures; this is actually for a right inductor. So, you would expect it to be used at very high frequencies; it is being used at 10 kilo hertz over the core loss is actually much lower than the winding loss. So, if you look at the winding loss the components you are looking at numbers of the order of 20 whereas if you are looking at the core loss you are looking at numbers the range of these particular plots has a maximum of 4. So, you can see that the winding loss in this particular due to the selection of this particular material; the winding loss dominates over the core loss; potentially if you had used steel lamination rather than fluorides; you could get much higher losses in the core rather than the winding. So, you could then look at the trends between the core loss and the winding loss; if you look at the core loss in this particular case; you can what is plotted on the to y axis; one is the 50 hertz loss. So, this is the 50 hertz loss shown in this particular axis; you can see that the maximum value of the 50 hertz's loss is in the range of 0.04. And then you look at the core loss at the switching frequency you have a value of 0.4. So, if it actually plotted on the same axis, the core loss at 50 hertz would be almost a straight line at the very bottom.

So, it would not affect the overall loss characteristics significantly but you could see the underline trend the 50 hertz component of the loses has a increasing trend; as you increase the value of L total. And if you look at the switching frequency term at low value of L the switching ripple is large. So, you are having higher losses but as you increase the value of L the switching ripple reduces.

So, your losses come down as your L is made goes to a larger value; if you look at then the winding related loss again you have a similar trend, if you look at the 50 hertz loss in the winding it has again a increase in trend. Whereas if you look at the switching ripple related loss you would end up with decrease in trend as you are increasing the value of L. And so the overall trend for the losses would be to select a value which tends to give you the lowest losses which would lie in between this range; you could you can see that in this particular example the even though the trend is can be seen from the curve the actual value of the loss is having a up. and down characteristics; this is because each of these point corresponds to a different inductive design.

So, L being one per unit correspond to one particular inductor L being 0.2 or 0.3 or 0.4 your different inductors. So, if you go beyond say a value of L; you might need to go the next larger size core or you might need one more layer in your windings. So, the these junks that you see is because of discontinuities, because of you are changing your physical inductor from one particular value selection into a next selection; which makes this curve have a non uniform, non uniformity in it. But the overall trend can be seen under underlying this non uniformities; where at the wind low values of L your switching related terms should dominate. And at the very large values of L it would be your fundamental related terms that would dominate.

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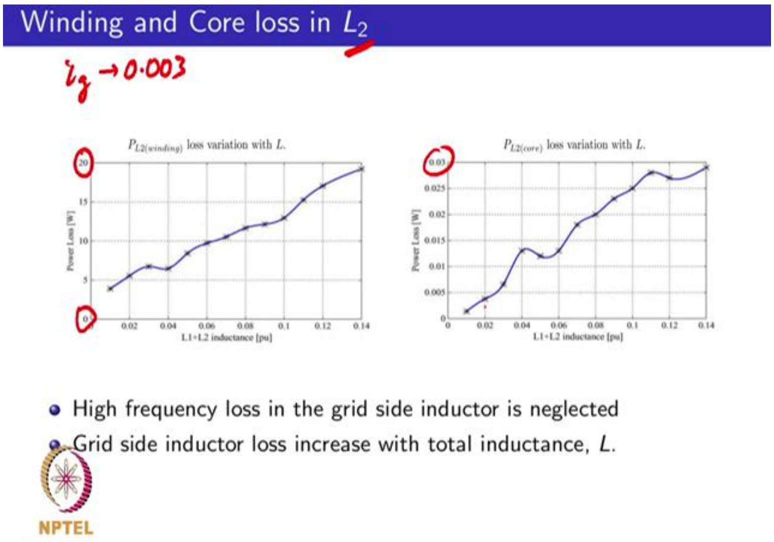

## Winding and Core loss in $L_2$

$i_g \rightarrow 0.003$

- High frequency loss in the grid side inductor is neglected
- Grid side inductor loss increase with total inductance, $L$.

So, once you so this is for loss in inductor L 1 you could then do a similar analysis for inductor L 2. If you look at the inductor L 2 the we know that our your ripple current in the grid that is being specified i g rippled at the switching frequencies to the 0.003 per unit. So, in terms of the ripple current flowing through inductor L 2 there is almost no ripple. So, if you look at the high frequency loss in the grid side inductor; it can actually be neglected you can think of it essentially a fundamental frequency which is flowing through the inductor L 2.

So, then if you look at the fundamental frequency loss term in the inductor L 2; again you can see the underline characteristics the core loss is in the range between 0 and 0.03; the winding loss is in the range between 0 and 20. So, if you look at the overall losses, the winding loss is the dominant term because we are selected a right core inductor. And the over the losses in the total inductance would be the sum of losses in L 1 plus L 2. So, the underline trend in both these cases is actually increasing losses as you are increasing the value of L.

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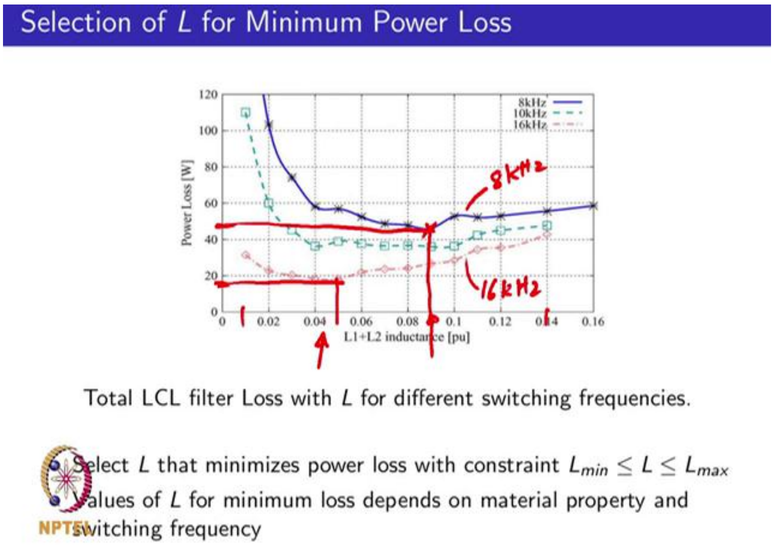

Selection of $L$ for Minimum Power Loss

Total LCL filter Loss with $L$ for different switching frequencies.

- Select $L$ that minimizes power loss with constraint $L_{min} \leq L \leq L_{max}$
- Values of $L$ for minimum loss depends on material property and switching frequency

So, one could then look at what would be the a total loss the in the L C L filter. So, this actually includes not just the losses in L 1 and L 2; it also includes the losses in damping terms in the circuit. So, if you look at the loss term overall as a function of L; so what is shown in this green dotted line is a total loss as a function of L 1 plus L 2; where it is varied in between the 1 percent to 14 percent range. And we are looking at a 3 different frequencies; one is at very low switching frequency. So, this corresponds to 8 kilo hertz; so this would correspond to a low switching frequency and this would correspond to a high switching frequency.

So, this is 16 kilo hertz and what is in between is for the 10 kilo hertz term. So, you could see that when you your loss in the filter design is having this tradeoff between losses at the low value of L and the losses at the high value of L; even for the different frequency ranges. But it is also interesting to see the point at which the minimum occurs is for the low value the high value of switching frequency a desirable range of your minimum loss is occurring around 0.4 around 4 percent value of inductance. Whereas if you look at the case when your operating at low switching frequency; the desired value of L the total inductance L 1 plus L 2 shifts from a lower frequency to a higher frequency of higher value of L t to about 0.9 percent.

So, at 16 kilo hertz you are having a minimum loss of 4 percent, at around 8 kilo hertz switching frequency the minimum loss point shifts up to a larger value of inductance. So, this is what you naturally expect; if your switching frequency is low you need higher value of inductance in your filter. And if your switching frequency is high you need a lower value of inductance in a filter; the other thing to observe is that at the lower value of switching frequency the losses in your filter inductor is actually about 50 volts. Whereas at the high value switching frequency your losses in your filter is lower about slightly lower than 20 watts. So, you could then consider not just the losses in the filter; you could also consider the losses in the filter plus the semiconductor devices. Because you know that you get lower losses in the filter but your losses switching losses in the filter are igbt's and recovery losses in your diodes is going up with switching frequency. So, you could not just look at it from the filter prospective; you could actually look at a minimization in the overall perspective.

So, depending on the frequency you have chosen and you could then consider a value of L. So, you could select a value of L that leads to be in loss that could be a preferred filter design; there are multiple perspectives; one is you have high efficiency. Because you have selecting a filter which leads to lower losses you have a low temperature rise low temperature of the filter components which improves the reliability. So, if you look at it from your net present value basis you are cost of loss is actually reducing in your net present value. And sometimes if you just by the rule of thumb you might have ended up selecting a larger value of filter inductor. But you know that physically because you have done the analysis you might actually be able to select a filter; which is actually having a lower value than initially thought which actually reduces the initial cost too. So, from multiple prospective you can actually end up with a better filter by doing a close analysis of a what would be the power loss and the thermal rise in your filter?

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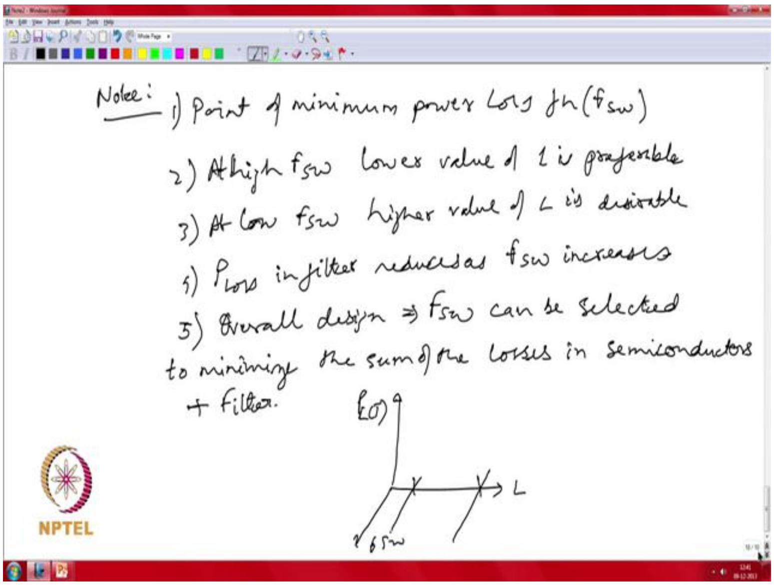

Note:

1) Point of minimum power Loss fn($f_{sw}$)
2) At high $f_{sw}$ lower value of L is preferable
3) At low $f_{sw}$ higher value of L is desirable
4) $P_{Loss}$ in filter reduces as $f_{sw}$ increases
5) Overall design ⇒ $f_{sw}$ can be selected to minimize the sum of the losses in semiconductors + filter.

So, we can also see that at some of the points to note are is a function of switching frequency. The second thing is at high f s w lower value of L is preferable; we saw that at 16 kilo hertz your preferable L was closer to the 4 percent range; and the power loss in the filter reduces as switching frequency increases. So, your overall switching frequency in your overall design can; because in new designs you are often asked what is your switching frequency and you might say 10 kilo hertz or 20 kilo hertz or some number. So, later on you can justify why you selected a particular switching frequency through such a loss calculation; which leads to what is the best switching frequency the power converter can operate?

So, you could select your frequency to minimize the sum of the losses in semiconductor plus filter. So, if you look at the overall characteristics; you can think about the total power loss is a function of what your L per unit is also a function of your switching frequency; essentially you are looking at what is the point that gives you your best desired loss subject to constraints on your total value of L lying between some minimum and maximum range.

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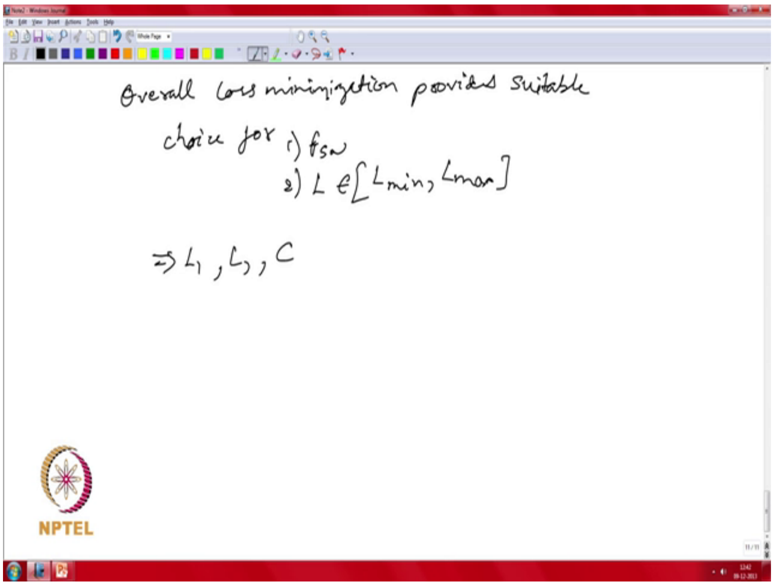

Overall Loss minimization provides suitable choice for 1) $f_{sw}$

2) $L \in [L_{min}, L_{max}]$

$\Rightarrow L_1, L_2, C$

So, at this point we have actually now your selection. So, of a L 1 comma L 2 comma C. And we can actually look at non ideal, non idealities of your power converter; and primary non ideality which you automatically get one if once you go into a higher order filter design is how to deal with filter resonances. So, this is one aspect that we would need to consider?

Thank you.