Power Electronics and Distributed Generation
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Lecture - 40
Balance of Hardware Component for Inverters in DG Systems

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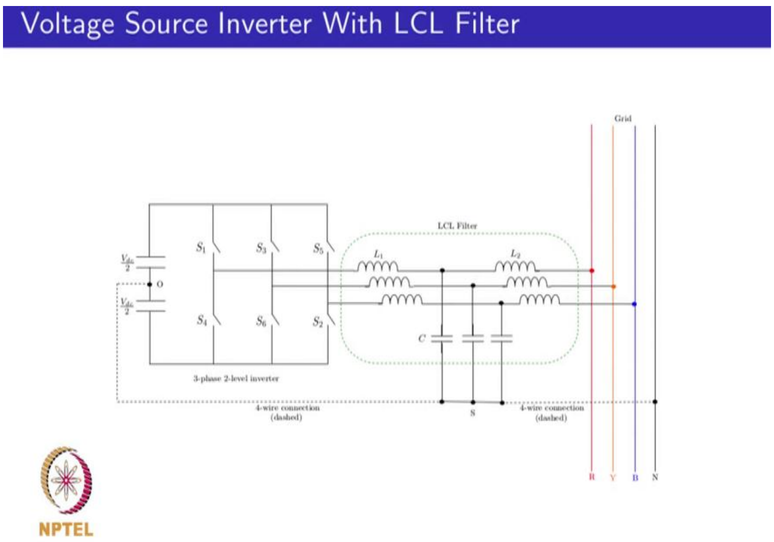

Welcome to class 40 in topics in Power Electronics and Distributed Generation. We have been looking at damping of resonances in LCL filters, and one way to provide damping is passive damping and in passive damping what is done is to add a resistor or a network with a resistor in it to the LCL filter. And the objective of the passive damping is to minimize the quality factor of the filter at resonance, and do that with minimum power dissipation.

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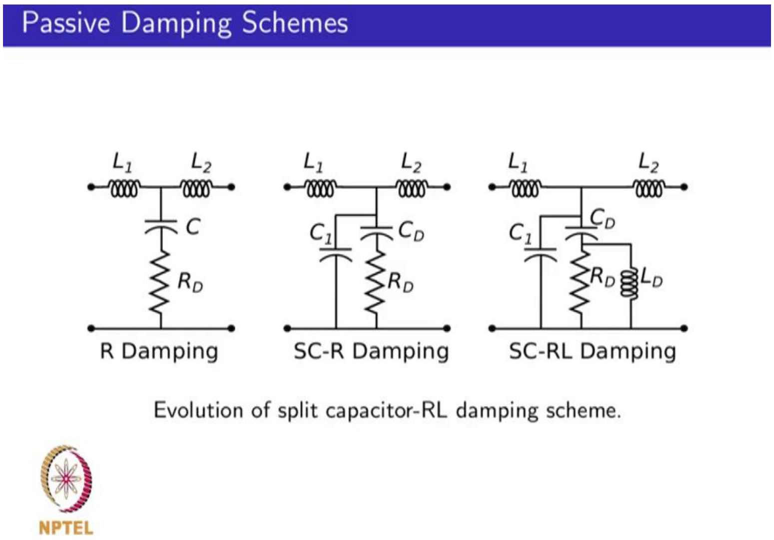

So, we looked at the progression of a possible passive damping schemes starting with a simple resistive damping and then a split capacitor resistive damping and a split capacitor R l damping. And as one goes with higher complexity, it is possible to reduce the power dissipation, but a with the higher complexity, you have more components, it can be more expensive, so there is a trade off in where what could be applicable.

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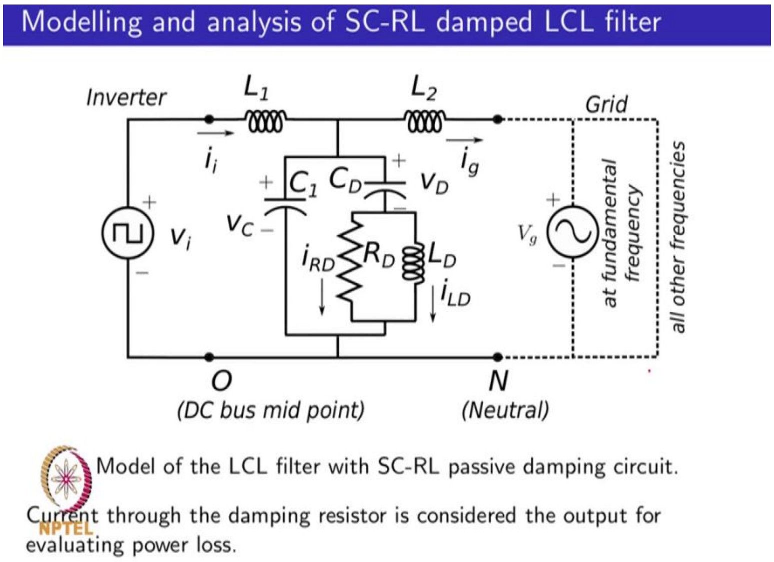

To model such a LCL filter, one can make use of circuit analysis and one could then makes state space models of the equivalent circuit of the power converter a grid connected power converter which dammed LCL filter. The state space models can be used to derive a transfer functions of between different parameter say one transfer function might be the capacitor voltage to the inverter output voltage.

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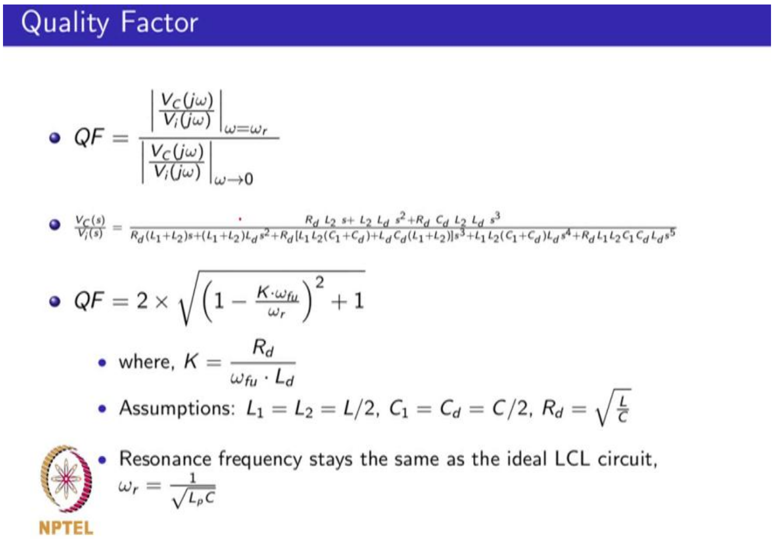

Then, you could look at what the quality factor is and then we derived an expression for a approximate expression for the quality factor using parameters, the parameter K and with certain assumptions. We also can make use of the state space model of the LCL filter with the damping to evaluate power loss.

And the power loss is evaluated at the two major frequencies of excitation which is the fundamental frequency and the frequency at which the major ripple occur which is the switching frequency. So, now you that one can have waste to quantify quality factor and the and the power loss one can then look at how to go about designing the passive damping network.

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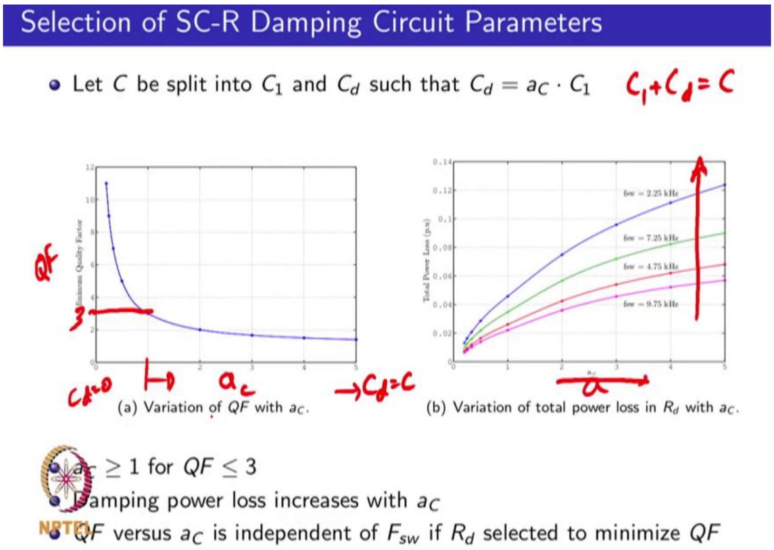

So, the first step that we looked at was we took an example of a 40 KVA, 250 volt, 3 phase per wire inverter with a LCS filter and as a starting point, we had the grid side inductor and the inverter side inductor to be equal to L by 2. And we saw that that was a good choice for Keeping the grid current ripple to minimum given a Constant value of L 1 plus L 2.

Then, the next question was to how to spilt the capacitor between C 1 and C d and C d is taken as a C time C 1 with C 1 plus C d being equal to C and this C is essentially the C selected in the LCL design procedure. So, if you to take a value of a C equal to 0, so what is plotted over here is a C verses the quality factor, the minimum possible quality factor and a C equal to 0 would correspond to a situation where C d equal to 0 and a C tending to large values would correspond to a situation.

Where, C d equal to C and as C d becomes larger and larger, we can see that the quality factor QF comes down, but at again as a C increases the power dissipation increases and you can see that for a range of switching frequency is the power dissipation is increasing with a C and its also increasing as the switching frequency reduces. So, if you select a value of a C greater than 1, the new of this particular curve is close to a C being equal to 1.

So, if you select a C being equal to 1 you will get a quality factor of less than three and with minimum with a small reduction in a in quality factor further as a C is further increased. So, selection of a a C in this particular range might be a reasonable starting point and taking a C equal to 1 might be a suitable design, also one can look at with a C equal to 1.

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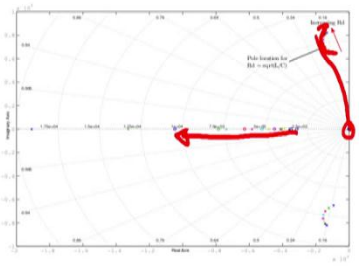
Pole Loci with Varying R_d in a SC-R Damped LCL Filter



Poles of $V_C(s)/V_i(s)$ for R_d variation from (0.6 to 2) $\times\sqrt{L/C}$.

- Two Real poles with one at the origin, and a pair of oscillatory poles
- $R_d = \sqrt{L/C}$ for maximum damping of oscillatory poles when $a_c = 1$

What is the value of R d that can be selected and suitable choice for R d is a square root of a L by C and then, with the state space model, one can plot the poles of this particular filter transfer function. And one can see that as R d is increased, you have one pole at the origin, you have another pole which moves to the left, you have a complex conjugate player and a the maximum damping is obtained when R d is equal to square root of L by C.

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Filter Parameter Values for SC-R Passive Damping

- The combination $C_1 = C_d = C/2$ and $R_d = \sqrt{L/C}$ is good in terms of quality factor and power loss in R_d for an SC-R damping scheme.

Parameter	$L_1 = L_2$	$C_1 = C_d$	R_d	ω_r	ω_{sw}
Per Unit Value	0.02	0.125	0.4	20	195
Physical Value	275μH	92μF	1.728Ω	6283 rad/s	61261 rad/s

Filter parameter values for SC-R passive damping.

SC-RL

$L_d = ?$

So, selection of R d is equal to square root of L by C and .C 1 is equal to C d, we have a suitable design for a starting design for a SC-RL spilt capacitor resistive passive damping for a LCL filter. So, the next question is a how to select the damping in inductor, if you want to go for a SC-RL dammed network, so the question is what should L d be.

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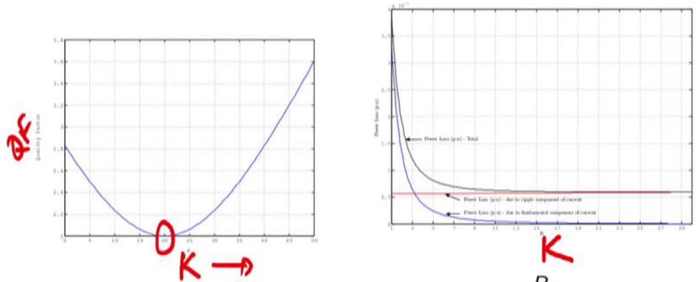
Quality Factor and Power Loss Curves: SC-RL Damping



Damping impedance factor: $K = \dfrac{R_d}{\omega_{fu} \cdot L_d}$

- $QF = 2 \times \sqrt{\left(1 - \dfrac{K \cdot \omega_{fu}}{\omega_r}\right)^2 + 1}$
- Power loss of 0.06% in the damping resistor for $K = 20$

So, to address this particular question one can go back and take a look at the expression for the quality factor and for the power loss. And if we saw that the expression for the quality factor is approximate expression is twice square root of 1 minus K times omega fundamental by omega resonance the whole square plus 1. So, you can see that to minimize this particular function, if you select K to be equal to omega R by omega f u, then this term with in the square would go away and you would get a quality factor close to 2.

And in this particular design, we have the resonant frequency close to 1 Kilo hertz and the fundamental frequency is 50 hertz, so if you plot this particular expression the minimum happens for K close to 20 and what is plotted is the quality factor verses K and if you look at then, the power loss verses K, the power loss consist of 2 terms. The 1 is because of the fundamental power loss which is essentially the broke over here, you have power here due to switching ripple which is the red curve over here, the black curve is the total to you can say that the power loss verses K graph has a Knee close to around K is equal to 5.

So, selecting a value of may be K greater than five would one can have minimal further reduction in power loss, so if you take a value of K may be from 10 to larger than your K there is no a significant reduction in power loss as a value of K is increased and you can see that for this particular design. If you select the K of 20 would get a power loss about ah 05 of around .06 percent for K is equal to 20. So, the pre test expression for the quality factor was a K was based on enough perspiration as we saw we could also determine the exact quality factor numerically.

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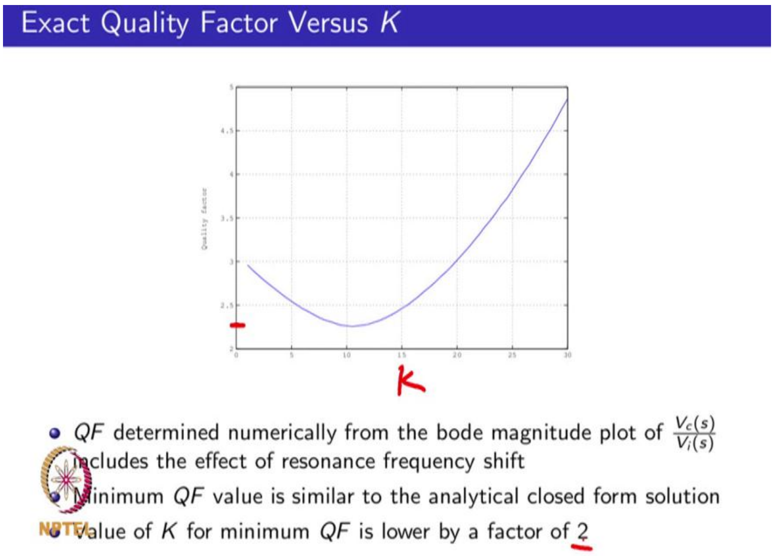

So, if you plot a exact numerical quality factor verses K, we again see this is a curve with minimum and the value of the minimum is again close to available value of 2, but the location of where the minimum occurs has shifted from value of close to 20 to a value of close to 10. So, there is factor of 2 between the approximate and the exact quality factor minimum point, based on a exact numerical analysis of where you would have the minimum value of K. So, you could then make use of this particular factor of 2 and look at evaluate design now at differences in frequencies.

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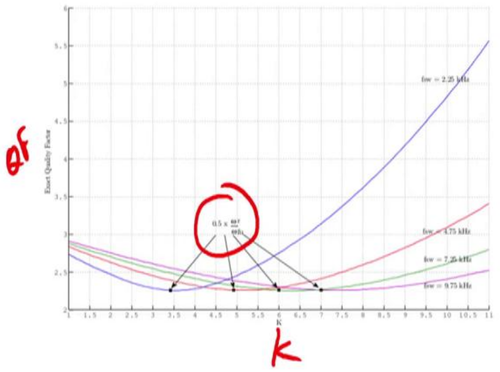
Quality Factor Curves for Varying Switching Frequencies



Numerical evaluation of variation of QF with K for varying values of switching frequency. For all the cases, $\omega_r = \sqrt{\omega_{fu} \cdot \omega_{sw}}$.

So, here what is shown is the point of minimum quality factor verses K for power converter designs, where the switching frequency selected from close to 10 Kilo hertz to 2.25 Kilo hertz. So, for wide range frequency you go to procedure of designing the LCL filter with SCR damping and you look at where the exact quality factor is minimum and that happens at half omega r by omega u.

So, point half omega by omega u coming side with minimum value of the quality factor, the quality factor would process K expression for this range of practical range of switching frequencies selection in a power converter. So, again if you then look at what would be the effect of this reduction of K by factor of 2 in terms of the power loss 1 can again plot the power loss verses K.

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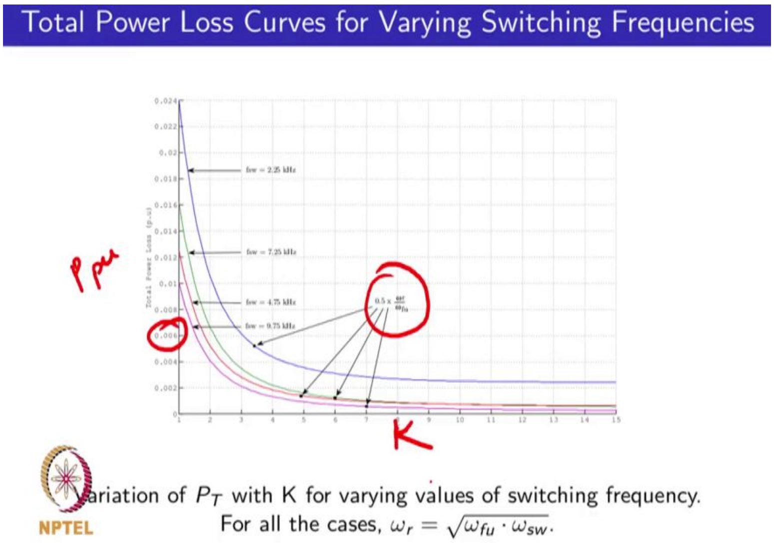

So, what is plotted here is the power loss and per unit verses K for again for range of switching frequency from close 9.75 Kilo hertz to 2.25 Kilo hertz and all cases you can see that for the selection of 0.5 omega r by omega f u. The points of power loss lie beyond a Knee of this particular curve, so even for a low switching frequency such as 2.25 Kilo hertz you are having a power loss of less than 0.6 percent for the selection can given selection of K 1 could also see look at the effect of this particular selection of K is equal to half omega r by omega fundamental.

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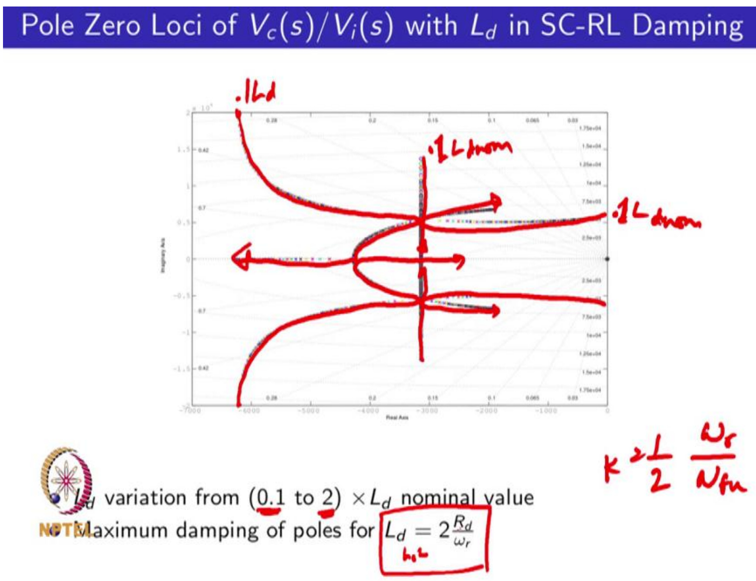

In terms of the location of the pole 0 plots plus using states space models, so from the state space model we could at say for example, the transfer function of capacitor voltage to your inverter voltage and see where the pole locations and say 0 locations, how they vary as the value of L is varied and will take nominal value of L d to be given by this particular expression and that would correspond to L d begin equal to 2 R d by the resonance frequency and if you then vary L d from 1, 10th of this particular nominal value to twice nominal value you get the locus of the pole zeros.

Single starts which say point L d and you get one projector of this pole 0 plot, you have complex conjugate pair and you can see that for value of L d, L d nominal you have very poor damping and again if the value of L d nominal becomes large, again you have to poor damping. Similarly, you have another complex conjugate pole pair which takes the trajectory such as this, so you have this would be 0.1 L d and you have another pair of complex zeros moving from L d’s point 1, L d nom 2 L d having this particular trajectory.

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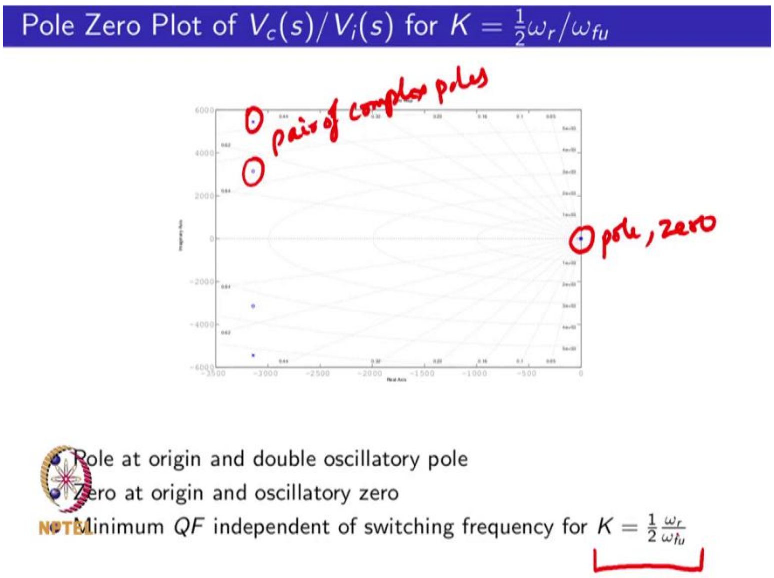

So, if you look at the point at which the L d is equal to this particular value, then at that particular point one can see that there is a one complex pole and a zero at the origin, you have a pair of complex conjugative poles and you have 0 and this would be correspond to the point, where you get the maximum damping again in the explained as to get closer to the 0 omega axis.

So, the damping reduces and a as the closer to the real axis and left half is explained your damping actually good. So, this would correspond to the point of having the best damping and corresponding selection for the given value of L d where K is given by half omega resonant by fundamental frequency. One could another factor in filter design is to look at how the filter would work for a variety of grid conditions in particular the grid condition a grid may be strong.

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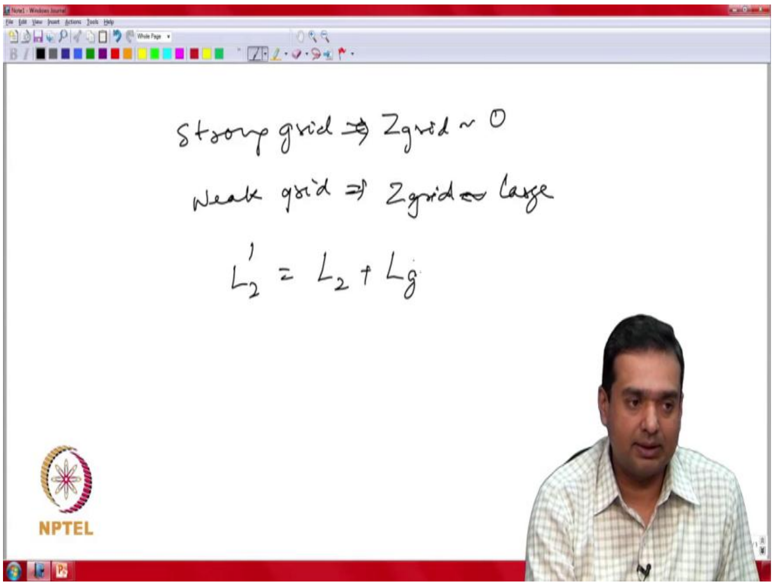

So, this would may imply that your impedance of the grid is close to 0 and or the grid might be weak, would this would imply that your Z grid is large and if you in think in terms of the model that grid as inductance reactance plus resistance then you would think about lamping the grid impedance along with the value L 2 and think of L 2 clime to be equal L 2 plus L grid. One would also think about a resistance in the in the grid interconnection, but the resistance term would only provide additional damping to your filter. So, we consider a situation where essentially Z grid as primarily consists of the inductive term.

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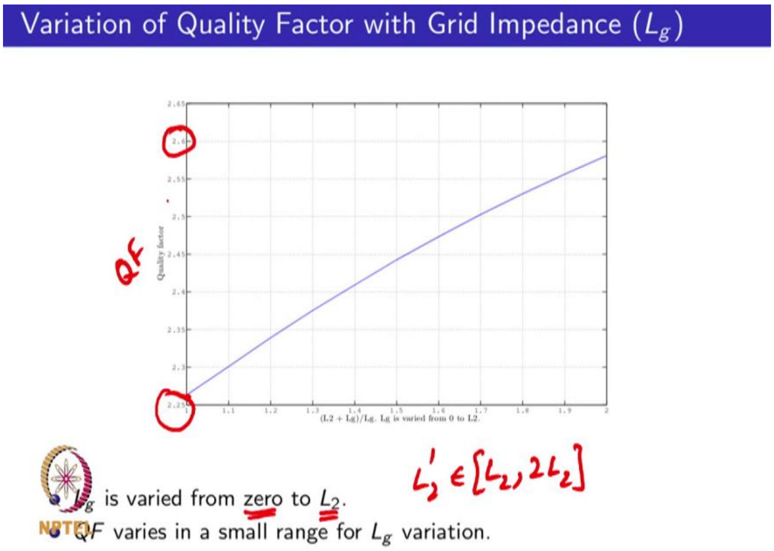

So, if you look at the range where the L grid is varied from 0 two L 2, itself essentially what it means is L 2 prime is varied from the range of L 2 to twice L 2 and one can look at the quality factor as this value L grid is graded over this particular range and you can see that you start off with a number is closer within the quality factor, which is a number closure 2.25 and twice L 2 you underlie with the quality factor which is less than 2.26 there is modern major variation in the quality factor as the grid impedance.

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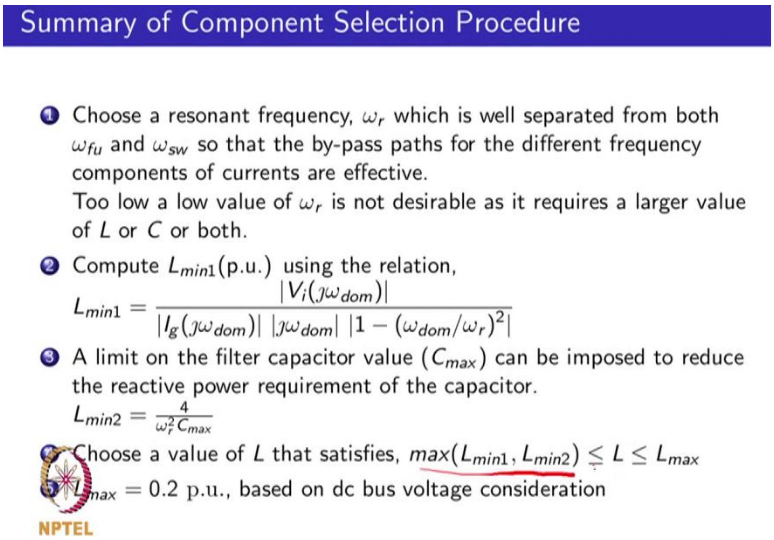

So, this particular design could work over fair a fair range reasonable range of grid impedance, so with this we would then summarize the procedure that we took for the filter design, so one thing we start band and what is your stop band was a fundamental frequency would begin the pass band. Those potentially some other harmonic frequencies, if one is looking at control at those harmonic frequencies, switching frequency would in your stop band and you could use a that to determine what you are resistance frequency is the filter.

And if you take to low value of residence frequency end up with large values of L or C or both next step is to identify a constraint on the value of L minimum and this is again we saw this is from the ripple constrain a mode of ripple that is begin allow to inject the grade, the second constrain minimum value of inductance is from your maximum reactive to power that is drawn by the capacitor.

So, using L 1 and L 2 you could then find what is your L mean which would be the maximum of L 1 or L 2 min, you also have a maximum value of the inductance that you could use in the filter and this is based on your d c bus voltage, because if you have two large filter inductance.

Then, the voltage drop propose the filter would add it to the grid voltage and you would need higher d c bus voltage to be able operate, the power conductor in a linear modulation range. So, you get a range of particular value of the inductance and then in this particular range, one could see what value of conduction is needs to the minimum power loss in your LCL filter and using that you could then, decide the value of L 1 and L 2.

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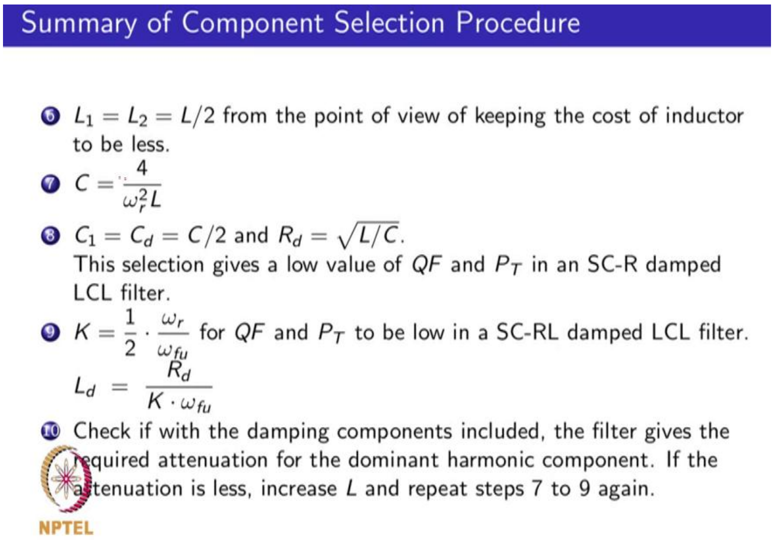

Another condition that can be derived is L 1 is equal to L two is equal to L by 2, would be a good design in from the point of your keeping the cost of the inductor low by minimizing the ripple inject in to the grid by for a given constant value of L 1 plus L 2. So, once you have the selected your resonant frequency and your and then that would gave you good design for capacitor, then for spilt capacitor base damping design could select C 1 is equal to C d is equal to C by 2 and R d is equal to square root of L by c.

This could give you low value of Q factor and total power loss in SCR balance and L C filter, so if you want then go to spilt capacitor R L damping 1 could select a K to be equal to half omega res by omega fundamental begin major excitation which causes loss in this damping grounds and the corresponding value L d would be equal to R d by K omega fundamental.

So, at end of the design you want to go back the validate what you are actuation is the difference performance constrains by begin met, if they are not begin met for example, that we actuation is on the lower side you want to slighting to that equation, you could go increase that value of L and go back and then evaluate the new value of C, go through the design procedure.

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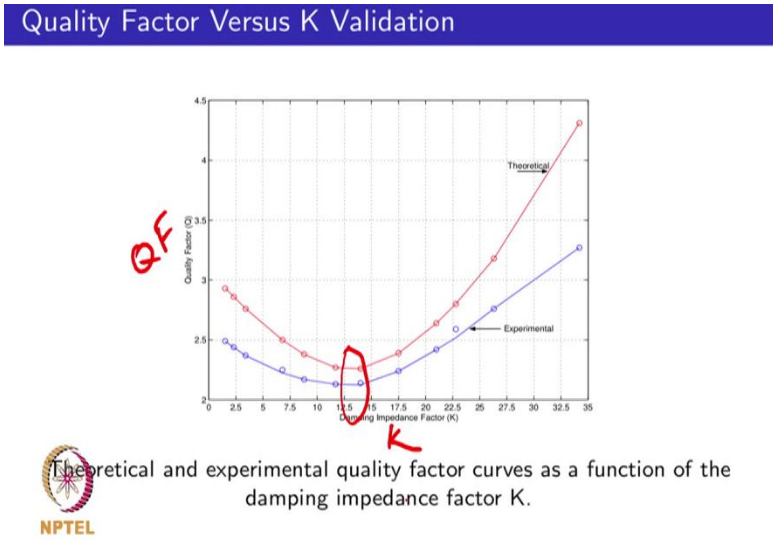

So, at this particular point we also like to see how good this particular procedure is so what is shown over here is the damping factor K verses the quality factor for ha for SC-RL damped LCL filter. So, what is shown in red the analytical value of the quality factor verses K and what is shown in the blue curve is the large majored quality factor.

So, we can see that the shape of the curve of the value at which minimum occurred is similar for the analytical and the it the lab assurance, in the lab the quality factor is reduce a little further is because in practical filter, you would have additional stray resistance in your windings in capacitor is etcetera which provides you au slightly for damping verses value degree are available of damping.

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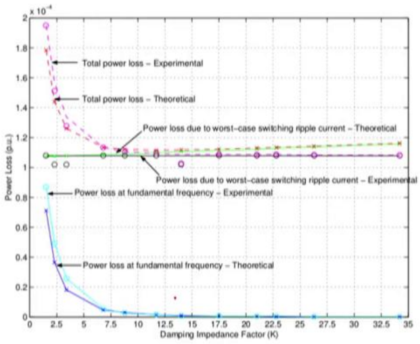
Power Loss Versus K Validation



Theoretical and experimental power loss comparison as a function of the damping impedance factor K. Curves for the fundamental loss component, switching loss component and total loss are indicated.

You could also then look at measurements of the analytical and the measured power loss for the different values of K and you can see that the power loss of the fundamental frequency and the power analytical power loss majored matches each other closely. And similarly further the power loss at the switching in a ripple vary closely with the variation of K, so the overall model can actually match the measurement that you take in ah physical design, so this procedure can be used in realistic manner.

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Major Power Converter Hardware Components

- Semiconductors, dc bus capacitors and output filters
- Contactor, circuit breaker, surge arrestors, precharging circuit
- Enclosure, busbar and cabling, cooling loops and equipment
- Circuit boards for protection, gate drive, control power, sensing, controller

So, at this particular point we have actually looked at range of things in a factors in this curve, we have looked at distribution system from the point of view of what at power converter can except, when it is interface to a distribution system. In terms of the distribution system, in terms of the distribution protection, the time face in which protection act, the type of voltage distribution that one can accept around the feeder etcetera and see whether the power converter can actually operate.

In the particular connects to the to a system, rather than assume the grid to be power constant value of the voltage source, we can re find actually further by including some of the aspect. So, the distribution system along with the model of it distributed generation inverter, the second part that we look at is how to how that is electronic system can be evaluated in terms of the life cycle cost and when you consider the life cycle cost the factors such as efficacy, reliability, aging that concern to play.

When you are revaluated the cost and that then we use in the design of the power converter, so you have absent cost, the efficacy related factor and reliability factor, so with this we then looked at the mean components of the inverter. So, the major components in the power converter would be the power semiconductor devices your d c bus of a voltage source inverter discuss points to the d c bus capacitor and we are also looked at the output filter.

There many other hardware components that are going to a power converter such as circuit breakers, contactors, surge arrestors, that is pre-charging circuit etcetera which also can be looked at closely. You also have to think about issues like how the enclosures built how cabling and best bar connection is made within the power converter, what are the cooling loops, what is the air exchange mechanism or if there is a water cooling what is the where how the water cooling loop is built and associated with a equipment.

You also have important aspect which is related to the control of the converter and in terms of control their to two aspect one is the hardware related aspect which might involve circuit boards for protection. The gate drive how you feel the control power the voltage and the current sensing, the controller often in today, the controller of high power converter is would we be digital controllers and you also.

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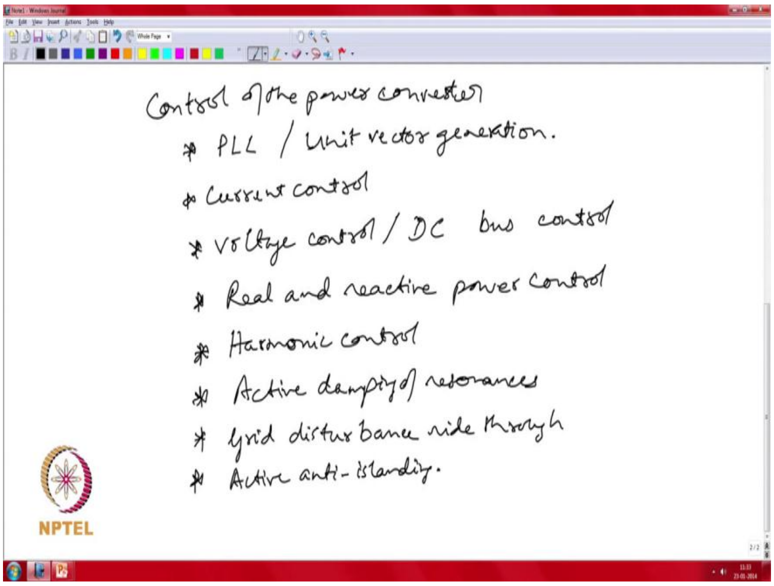

Than have the same where the algorithm related aspects and then somewhere algorithm aspects be so one would be the sis lock loop or unit vector generation, so the important task is to find out where the what the frequency the amplitude the phase fundamental component is a three phase system, you might to want to Know what where the angle f the positive sequence, fundamental voltages, yours to have current control, you have voltage control.

Often, you need to control your d c bus voltage, you also have to look at what the broader real and reactive power control how that is begin achieved in some applications harmonic control might be important. If you are looking at inactive filtering or trying to damping harmonics etcetera, you we just looked at design of the passive damping. It is also possible to control the active damping of the resonance also a major aspect of the power control is how to deal with the distribution grid.

We saw that contractor the grid protection can occur in a longer time frame and big challenge is to have right through of the power converter, when there is grid disturbance and the disturbances might be longer term. Where voltage regulation frequency shapes etcetera or it might be shorter term sags swells shortages for shorter durations and variety of the situations can the power converter ride through the disturbance and help reenergize the system when the grid recovers.

You also have issues like active anti-islanding and many such control related issues. So in this course we are not looking at the details of the control related issues, a starting point for looking at some of the control issues would be a course on electric drives that would be available on NPTEL, so at this point will wrap up this course and I hope you have found it useful.

Thank you.