DC Power Transmission Systems
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Lecture - 63
Design of single tuned filter: Part 1

In the last class we were trying to see the requirement of a filter because of the problems of harmonics. So, we will study very simple design of what is known as a single tuned filter.

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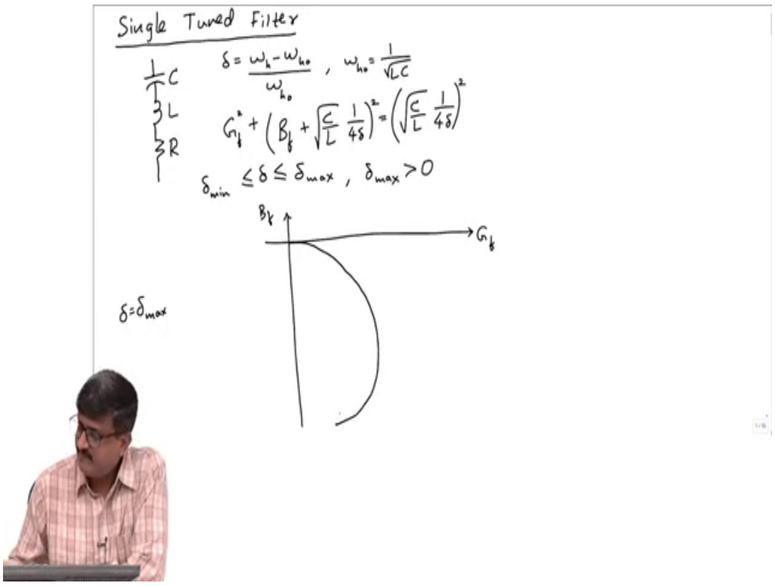

So, as the name suggests single tuned filter is designed for minimizing one particular harmonic frequency. So, single means one frequency. So, it is tuned for one harmonic frequency. So, it is a series combination of a capacitance, inductance and resistance C, L, R. So, we saw that there are some situations where the values of L and C chosen may not meet the requirement. So, the that is actually quantified by defining a quantity called delta. So, the original definition of delta is omega h minus omega h o divided by omega h o.

So, omega h is the actual angular frequency sorry, omega h is the angular frequency omega h o by definition is 1 by root L C. So, let me rewrite that particular equation. So, I will not go through all the steps. The last equation that we got was G f squared plus B f plus square root of C by L, 1 by 4 delta whole squared is equal to root C by L 1 by 4 delta whole square ok.

So, for a given value of delta, this appears to be I mean; this actually an equation of a circle in the complex plane with on the real axis I have G f, on the imaginary axis I have B f ok. Now, if you look at delta, delta actually lies in a range, delta min is the lower limit and delta max is the upper limit ok. So, delta is within a certain range. Suppose, I take delta max delta max is greater than 0.

Now, if I try to plot the curve given by this equation in this plane where I have an one axis G f and the other axis is B f. Now, when it comes to showing the where I mean the graph of this equation. So, for what I will do is, I will try to take delta equal to delta max. See there are two extreme values of delta min and del I mean two extreme values of delta min and delta max these are the worst case values.

So, I will take the one on the higher side delta max. So, if delta is equal to delta max which is greater than 0, then this is an equation of a circle ok. But one thing to notice I mean let me take the circle. So, this centre of the circle is minus root C by L, 1 by 4 delta so, it lies on the B f axis. And the radius is root C by L 1 by 4 delta ok.

So, it appears as if the circle is in the third quadrant and fourth quadrant, but G f is positive. So, G f is positive to be more precise G f is non negative; G f is non negative ok. So, what I can do is I mean I can just show the relevant part of the circle which is just a semicircle.

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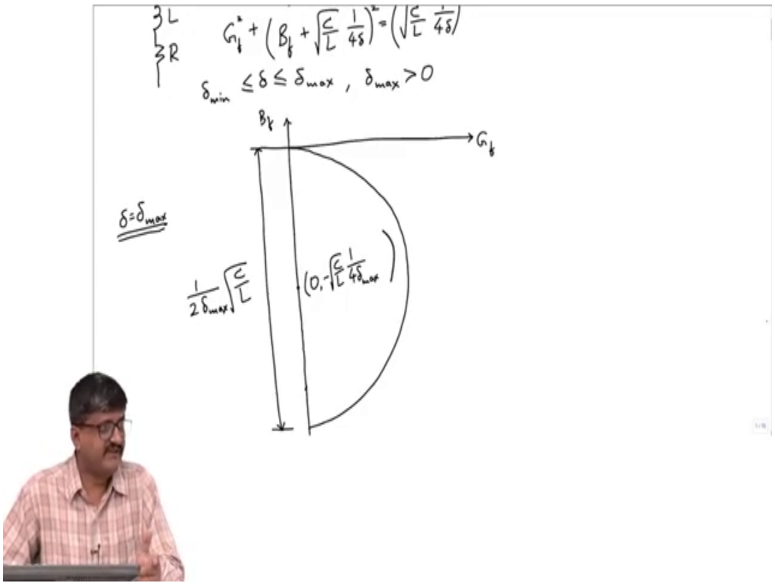

So, if I take this length, so this length is the diameter of the circle. So, the diameter of the circle; please note I am trying to consider one particular value of delta which is delta max. So, this is 1 by 2 delta max under root C by L so, this is the diameter. Radius is root C by L 1 by 4 delta max.

So, the centre of the circle is somewhere here. So, centre is 0, the value of G f is 0 there at the centre and the value of B f is minus root C by L 1 by 4 delta max. So, C and L are positive, we are taking the positive square root and there is a minus sign and delta max is positive. So, the filter admittance at the harmonic frequency it should lie at some point on the semicircle that is the point.

So, we have to design the filter. So, we do not have the exact value of G f or B f may be that is how is designed. So, getting the value of R L and C or in other words getting value of G f and B f is designed. Now, for the sake of filter design, what we will do is; we will consider an equivalent circuit.

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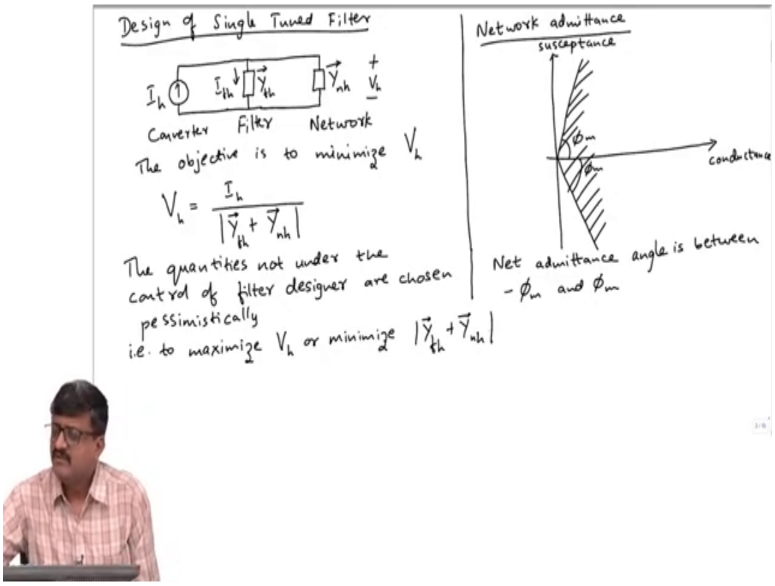

So, let us do the design of single tuned filter. So, the model considered here is for the converter, we just take the harmonic frequency which has to be minimized. So, the harmonic is in the current. So, the converter is represented by a current source, I mean; it has a current source I h. Then there is a filter which is represented by an admittance and there is a network, the external network see this network is the network on the AC side ok.

So, I have converter here represented by a current source, I have between the network and the converter, there is a filter represented by an admittance and this is the network ok. So, let the admittance of the filter. So, we have already given a notation for this, the admittance of the filter at the harmonic frequency for which it is designed is Y f h.

And let the admittance of the network Y n, n for network and since it is at the harmonic frequency Y nh. So, the current that actually flows through the filter has a magnitude say I f h. And the voltage across the converter or filter or network at the harmonic frequency has a magnitude say V h by magnitude I mean the RMS value ok.

Now, when we want to design something of course, we try to take some parameters and try to minimize or maximize a few quantities you know. So, that is what is all about design of one of the parameters I mean one of the quantities that we minimize is of course, cost. See when it comes to design there are two things that matter our performance and cost. So, we need to somehow have good performance at the same time we want a least cost, which we will get that performance ok.

Now, when it comes to performance; the objective is to minimize, see please note the converter has a harmonic current source I h. So, due to the converter there is a harmonic current. Now, if that should not affect the network, then it means V h; V h is the effect of I h. See if I h is not there only fundamental is there then V h is 0. See V h means it is the RMS voltage at the harmonic frequency. So, if only fundamental is there V h is 0.

So, essentially we want to minimize V h, the objective is to minimize V h. So, what is V h? So, if I look at the expression for V h, I can write V h as the converter current I h divided by the admittance of the parallel combination of filter and network. See V h is the voltage across network or filter or converter. So, I can write this as I h divided by the magnitude of Y fh plus Y nh.

Say when I have two admittance in parallel the affective admittance in some of the admittances ok. The magnitude of the admit affective admittance into the magnitude of the current gives mag into magnitude of the voltage gives the magnitude of current ok. So, now, let us see how this Y nh takes values. So, network admittance.

So, when I take network admittance, that is Y nh. So, again I take the complex plane. So, the complex plane the real part is the conductance of the network admittance and the imaginary part is the susceptance. Now the question is where will this network admittance lie which quadrant or which quadrants? It is possible to have values in all the 4 quadrants.

Student: (Refer Time: 12:08).

First and?

Student: Second.

Second.

Student: Sorry first and forth.

First and forth because. So, conductance is?

Student: (Refer Time: 12:19).

Positive ok. Now, susceptance can be positive or negative now why?

Student: Mostly inductor.

Now, if it is only inductive then where it will lie?

Student: Forth.

Forth, but the network consists of transmission line transformers. If we take transmission line, it is not just inductive there is a shunt conductance also. So, there is a shunt sorry not shunt capacitance as well. So, whenever there is a capacitance, there is a possibility of positive susceptance. So, it can lie in the first quadrant and the fourth quadrant.

So, it does not lie in the entire first or fourth quadrant, it can be shown that this lies in this sector. So, there are two straight lines passing through the origin. So, if I take the intersection of the areas to the right of these two straight lines, then the network admittance will lie in this area. So, this angle is called phi m. Similarly, the angle here is also phi m. So, there are 2 straight lines make an angle of phi m with respect to the conductance axis. So, it is an infinite region.

So, essentially the network admittance is having a phase having an angle which is between minus phi m and plus phi m. So, network admittance or in fact, impedance both have the same phase angle, see both have the same face angle range ok. One is the reciprocal of the other. So, network admittance angle is between minus phi m and plus phi m ok.

So, we just saw that the objective is to minimize V h as far as the performance is concerned. Now, when we try to minimize V h, please note what is and under the control of the designer. So, when I say design of single tuned filter, the only values which the designer will decide are?

Student: L C; L C.

L C and R, nothing more than that ok. When it comes to network; the designer has no control over the network. Designer has of course, has no control over I h, I h is known we know what is the harmonic current in the converter ok. So, when it comes to the quantities which are not under the control of the designer, but they are not fixed as well, they keep varying. Then one has to choose a value many a times, so we cannot just take the range as it is for some of the quantities. We have to takes 1 particular value ok. So, if that quantity which is not under the control of the designer is within a range, which value do you take?

Student: The one which corresponds to the most usual case.

That is a one possible answer. Do you do that will you talk? Student: Worst case.

When you design, always design for worst case. So, when it comes to I mean maximizing performance, you want to see that it performs very well even in the worst case ok. So, worst case is something which is chosen if you have the performance in mind. So, right now, I am talking about performance ok. So, objective is to minimize V h means it is somehow maximizing performance. So, we take the worst case for all the quantities which are not under the control of the designer, but with which vary over a certain range ok.

So, the quantities not under the control of the designer; designer means just filter designer. So, we are not doing any other design, only filter design filter designer are chosen pessimistically; that means, we are choosing the worst case pessimistic. So, that means, to maximize V h. So, see our objective is to minimize V h, pessimistically means? Ok, I will remove the comma here to maximize V h.

So, maximizing V h is actually equivalent to minimizing the denominator in the expression for V h, for a given I h is constant ok. So, here what I am trying to say is Y n h, I have not given the value of Y n h. Y n h, I have just said it lies somewhere in the first quadrant or fourth quadrant, I have shown the region also. So, which value to be taken in order to design ok. So, to maximize V h or minimize the absolute value of Y fh plus Y nh.

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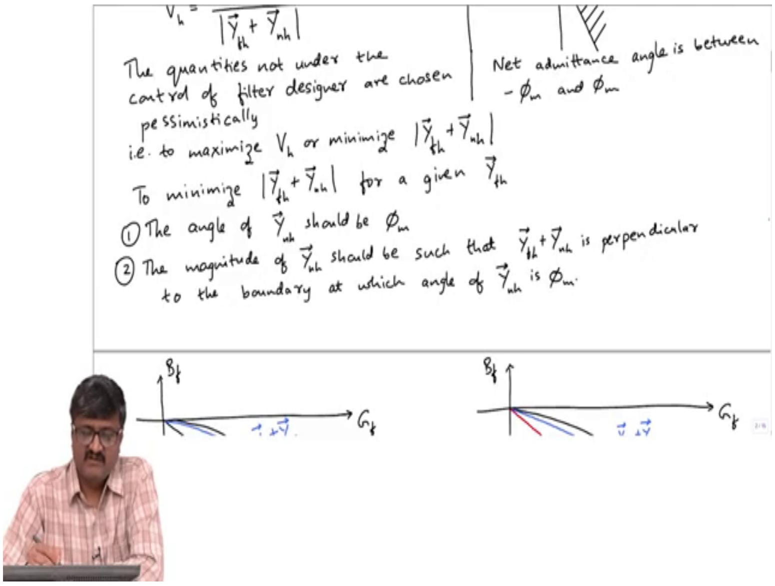

So, if I want to do this. So, let us say how to minimize this, how to minimize the absolute value of Y fh plus Y n h? Now, what I will do is, we will try to take the worst case of Y n h, but Y fh is yet to be designed. Now, suppose I take the worst case for Y nh for a given value of see please note we have not yet decided Y f h. So, for a given Y f h, I will take this next page.

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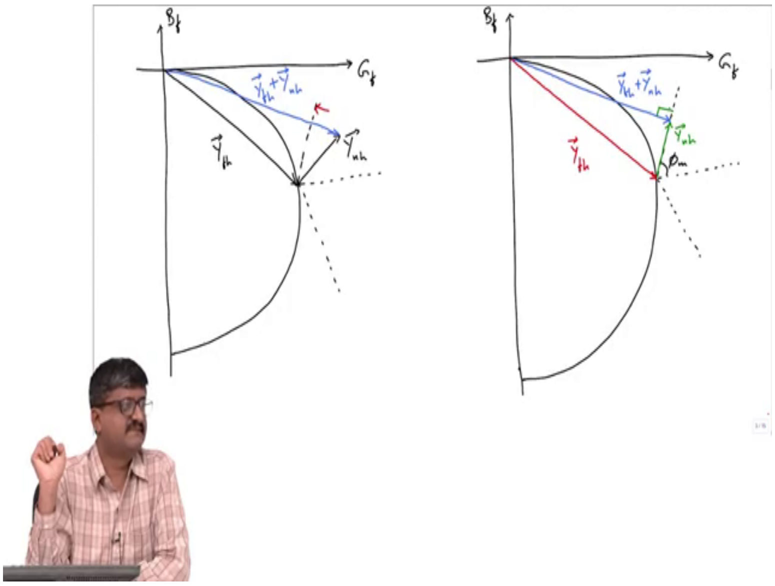

So, G f this is B f, so I have this semicircle ok. So, Y fh is given; that means, this Y fh first of all should lie on this semicircle. So, it is somewhere on the semicircle. We do not know where it is. So, let us assume that a some value is given. So, if Y fh is given suppose, this is Y fh ok; this is Y fh. Please note G f and B f are real and imaginary parts of Y fh.

Now, to this, I have to add Y nh. Now what I will do is; I will just take this region see the network admittance is lying in the first or fourth quadrant. So, I will take the origin of this network admittance and shift it to this point Y fh. So, that is essentially saying that so, to Y fh I am adding Y n h. Suppose, Y n h; I have to take between these two these dashed line which makes an angle phi m and another dashed line which makes an angle minus phi m.

Suppose, I take Y nh to be this ok, then Y fh plus Y nh. So, I will try to use different colour so, that it will not cause confusion. So, this blue complex number is Y fh plus Y nh. So, my intention is for a given Y f h, I should minimize Y fh plus Y nh magnitude, magnitude of Y fh plus Y n h.

So, is it clear that Y nh should be on the boundary? See the boundary is this dashed line and it should be on the boundary which makes an angle phi m with respect to the conductance axis, not the minus phi m. See what I am trying to say is; is it clear that it should lie on this boundary.

Student: Yes.

Ok, but where at which point on this boundary, this is I mean school geometry. I have to take a point on this lane which is having the shortest distance from the origin.

Student: Passing that G f s where it cuts (Refer Time: 22:18).

Is it?

Student: Draw perpendicular.

Drop a perpendicular. See I have a point I have a straight line, I want the point on the straight line which is having the minimum distance with from the given point. So, I have to drop a perpendicular from that point to the straight line that is all ok. So, it is essentially like this ok, let me re draw it. So, suppose this is Y fh.

Now, in order to find the least magnitude of, I mean; in order to find Y nh of that it results in least magnitude of Y fh plus Y n h, what I should do is; first drop a perpendicular from the origin to the boundary which makes an angle phi m ok. So, the boundary is this which makes an angle phi m. So, that should give the least value of the magnitude of Y fh plus Y nh yes.

Student: Sir if Y nh is 0 then (Refer Time: 24:41).

If Y nh is 0.

Student: (Refer Time: 24:44).

Then it will results in least magnitude of Y fh plus Y n h. See we are adding two complex numbers, Y fh and Y n h. So, we want to minimize the absolute value of this sum of the two complex numbers. So, if Y fh itself, see it is possible that I can have the sum of these two complex numbers smaller in magnitude compared to the just the magnitude of Y fh ok.

So, I can choose the Y nh in order to get a value which is smaller than Y fh. So, if this is Y fh blue complex number is Y fh plus Y nh and the red 1 is Y fh so; that means, the difference between these two is Y n h. So, if I take this is Y nh. So, here this sum of Y fh and Y nh is perpendicular to this boundary which makes an angle phi m, right ok. Now, please note what we have done here is chosen the value of Y nh pessimistically, that is a worst case value.

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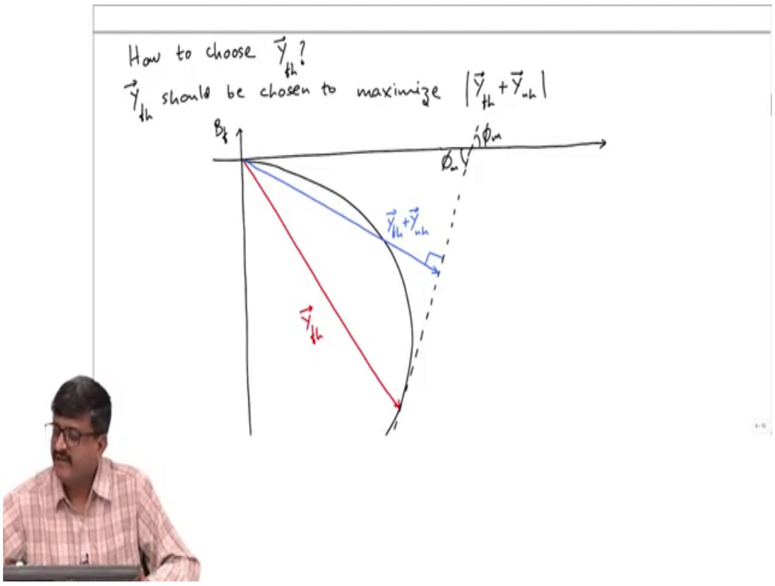

Now, how to choose Y f h? Now, Y fh is under the control of the designer, how to choose Y fh? How to choose Y fh? Yeah as far as the performance is concerned I want to maximize the performance that is minimize the value of V h or its essentially saying mini maximize the value of the denominator in the expression for V h.

So, how to choose Y fh? See in the previous case for some arbitrary value of Y fh we know how to choose Y n h. Now, how to choose Y fh itself. I do not think, I am asking a very tough question. See Y nh is not under the control we take worst case, Y fh is under the control of the designer, so we take the best case. So, how to get the best case? Worst case means; the one with that minimizes the absolute value of Y fh plus Y nh.

So, the best case is the one that maximizes the absolute value of Y fh plus Y n h. So, Y fh should be chosen to maximize Y fh plus Y nh, absolute value ok. Now, how should 1 choose

Y f h? So, please note in the previous the last figure that I got Y fh was taken to be some arbitrary value. Now, the question is how to take this? So, how to find Y fh which actually maximizes the absolute value of Y fh plus Y nh. See the same rule holds as far as Y nh is concerned.

So, when it comes to Y nh ok. So, let me summarize how I have chosen Y nh. To minimize Y fh plus Y nh for a given Y fh what 1 should do is the angle of Y nh should be phi m. Then, the magnitude of of Y nh should be such that; should be such that; Y fh plus Y nh is perpendicular to the boundary.

So, perpendicular to the boundary means; which boundary there are two boundaries, there are two boundaries; one which corresponds to the angle of the admittance being equal to phi m. So, the boundary at which I you are answering the other question ok. So, the boundary at which angle of Y nh is phi m. So, that is how we chose Y n h. So, we still maintain this method of choosing Y n h, but how to choose Y fh is the question now.

Again we have the objective here the objective is to maximize Y fh plus Y nh yeah. Any answer? How to choose Y f h? Now first I have to choose Y fh from then I can show Y nh. Once I know Y fh then, I know how to choose Y nh that is what we discussed just now, but the question is how to choose Y fh in order to satisfy this objective, maximize the magnitude of Y fh plus Y n h.

Student: (Refer Time: 31:57).

See one point to notice this complex number Y fh plus Y nh is always perpendicular to the boundary, is always perpendicular to the boundary. Now, as the boundary goes further from the origin, we get a higher value of the absolute value Y fh plus Y n h. So, what is the maximum distance to which the boundary can move, so that I get a maximum value of this magnitude Y fh plus Y n h?

Student: (Refer Time: 32:44) and this is tangent to (Refer Time: 32:46).

When it when the when the boundary is tangent to the semicircle.

Student: Semi circle.

Is that clear? Is that obvious or not? Simple I mean; simple geometry nothing more than that. So, once the rule is fixed for using Y nh, it should be always the sum of these two complex number is Y fh plus Y nh should be always perpendicular to the boundary. So, I have to choose the position of the boundary itself such that it this perpendicular distance is maximized ok.

So, that means; I have to choose the boundary perpendi I mean which choose the boundary as a tangent to the semicircle. So, of course, there are many many tangents, I mean which see tangents can be taken anywhere. So, which tangent has to be taken.

Student: Y fh which tangent following that Y fh which (Refer Time: 33:49).

Y f h makes yes. So, the boundary should make an angle phi m with respect to the G f axis ok. So, if I extend this tangent, so it intersects G f and it makes an angle ok, let me show this. So, first I should take the tangent. So, the tangent should be the one which is chosen like this. So, what is this angle?

Student: Phi m.

Phi m, this is phi m. See, the idea is very clear here. If I take this angle this is phi m. So, this is also phi m. yeah I chosen the tangent. Now, where is Y fh? It is point common to the semicircle and the tangent. So, what I used red, so, I will show Y fh. So, this is Y fh ok, then getting Y fh plus Y nh is very simple drop a perpendicular from the origin to this boundary that is all.

So, I have used what colour blue. So, just drop a perpendicular. So, this will give Y fh plus Y nh. So, once I know Y fh plus Y nh and also Y fh I can find easily what is Y nh. So, this is the worst case value of Y nh that I am taking green. So, this is Y nh ok.

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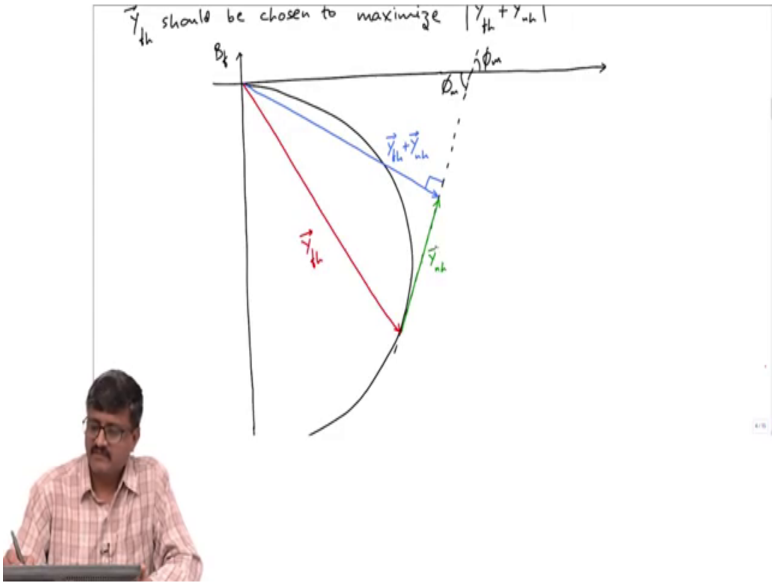

Now, please note just by choosing Y fh will not give me the values of the parameters of filter, there are three parameters of the filter; R L and C ok. Y fh will give me only two parameters. So, essentially I am not getting the parameters of the filter see Y fh will give me what is G f and what is B f. It will not give me what is the resistance, what is inductance, what is capacitance, it is still not given me. So, see please note even if you take impedance, if I know the resistance and the effective reactance it does not mean I know what is L and what is C. I just know what is X which is omega L minus 1 by omega C that is all.

I still do not know what is L what is C. Now, there are infinite values of L and C which can be chosen to get a effective x for a given value of effective x. So, the same thing is here. So, just by knowing the value of Y fh, I do not have the parameter values. So, how to get the parameter values? So, so far we considered performance. So, these are the things which have to be done in order to meet the performance or maximize the performance.

Now, we will see how to actually do further design, I mean; we are not completed the design see design is completed only when we have the value of R L C ok.

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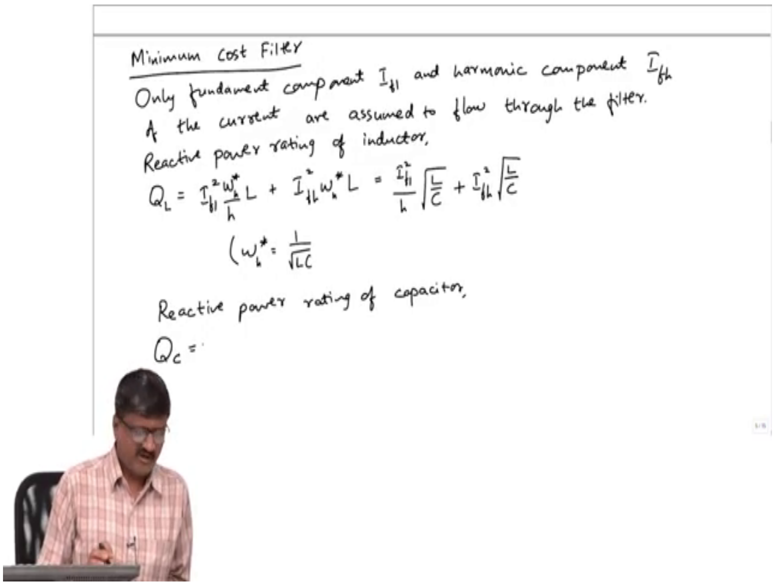

So, for that, we will minimize the cost and get the values of R L and C, minimum cost filter ok. Now, when it comes to the filter, what is the, what are the frequencies that will flow through the filter? What is the frequency of the currents that will flow through the filter? It is designed for?

Student: (Refer Time: 39:10).

A particular harmonic frequency I h, I h will flow then, any other current will flow. Actually, it is not I h please note we have used a different notation here 1 has to be careful while see if you look at this figure the current through the filter is not I h the current through the converter is I h, the current through the filter is I f h ok. So, the two are not same ok, I f h is a current which will flow through the filter. Any other current any other harmonic current will flow.

Please note, it may not offer infinite impedance to other frequency though it is very large impedance to other frequencies, it is not infinite so, it may flow. So, what about fundamental? It will not offer even infinite impedance to fundamental frequency also, but in practice what happens is; the harmonic current for which it is designed will flow in addition to that the fundamental will be significant. Whereas, the other harmonics for which it is not designed, I mean; there the magnitude of the current will be negligible.

So, then the significant components of the current that will flow through a filter are the harmonic frequency current for which it is designed and the fundamental. The remaining harmonics I mean the filter will offer a very large impedance. So, it is insignificant. So, we will make an assumption that only fundamental component. So, I will use a notation I f 1, f for filter 1 for fundamental.

Please note this fundamental component is not the fundamental component of current through the converter, this is the current through the filter. Only the fundamental component I f 1 and harmonic component I fh of the current are assumed to flow through the filter. Now, when it comes to cost, cost is dependent on what? If you take any electrical equipment, can I say the cost is almost proportional to one particular rating of that equipment. What rating?

Student: (Refer Time: 42:02).

Let me take for example, transformer. If I say the cost is proportional to some rating of the transformer, what rating? Voltage rating, current rating.

Student: (Refer Time: 42:13).

It is volt ampere rating, it is actually volt ampere rating. Now, when it comes to filter, what rating? Again so, filter is having electrical equipment it is again the volt ampere rating. Now, when you if you see the filter it is essentially L and C, R is something which comes for some reason. So, R is not a very significant part of the filter. So, it is only L and C, when it comes when it has only L and C, there is only reactive power.

So, it is proportional to the reactive power rating. The cost of the filter is proportional to the reactive power rating. So, what is the reactive power rating? So, there is an inductor there is a capacitor. So, let us try to take the reactive power rating of the inductor and capacitor separately, reactive power rating of inductor. So, I will use a notation for this Q L, L for inductor.

So, can I get an expression for the reactive power rating? See we have made some assumptions that we are neglecting the other harmo harmonic components. So, only I f 1 and I f h flows ok. So, there is only the fundamental current and the harmonic current for I mean for which the filter is designed. So, based on this, can we get an expression for the reactive power. Now, please note reactive power is something which is difficult to define in the presence of, see reactive power has a well known definition in the I mean when there is only fundamental component.

Of course, there have been attempts to generalize the definition of reactive power in machine theory they use I mean the Perkins transformation can be used. But, when it comes to steady state, there are attempts to give other definitions. One particular definition is the one given by a person called Budeanu. I do not know if you have studied power quality, you may and how many of you studied power quality. Have you heard of this Budeanu's definition of reactive power?

Student: Yes.

There are many other definitions Budeanu is one particular. So, he I mean there are many ways in which we can define reactive power. So, one of them is Budeanus definition. So, what is the reactive power according to Budeanu in this case? What will, what is that in that particular definition? You take each frequency find the reactive power and add them that you say that is the total reactive power, that is what is the Budeanu's definition ok.

So, if I take only the fundamental and harmonic, there are only two when it comes to filter there is only the fundamental and harmonic, there are only two frequencies. So, find the reactive power for fundamental, find the reactive power for the harmonic frequency and add them. So, what is the reactive power corresponding to fundamental? See the current is I f 1. So, how do I get reactive power from current?

Student: I f (Refer Time: 45:49).

No no I it is not necessary to get into complex

Student: I f square.

I f.

Student: Square (Refer Time: 45:55).

Yeah I f 1 square into, into reactance. The square of the current into reactants gives reactive power right ok. So, what is the reactance? Now please note we are calculating the reactance depends on frequency. So, we are calculating at fundamental. So, what is the fundamental reactance?

Student: (Refer Time: 46:18) 1.

In terms of the quantities that we have used.

Student: Ok.

L is the inductance ok.

Student: Yeah.

There is inductance L, what is fundamental angular frequency?

Student: 100 by L.

We have not used any specific value of frequency. Using the notations that we have used. We have used notations omega h star divided by. See omega h star is the harmonic frequency for which the filter is designed divided by h, this is the fundamental, is that is that plus, now please note I am just taking the ideal value of omega h. So, ideal value is omega h star. So, in practice omega h will deviate. So, because of that the reactive power rating will slightly be within a band. So, I am I am trying to take the ideal value of the frequency and compute the reactive power.

Then if I take the harmonic frequency it is I f h squared into reactance. So, in this case it is omega h star into L ok. Now this can be written as I f 1 square by h, omega h star is 1 by root L C, Is 1 by root L C. Omega h star is 1 by root L C. So, please note omega h star is 1 by root L C. So, using this I can write this as root L by C, the first term. Similarly, the second term is I f h square into root L by C.

Student: (Refer Time: 48:17).

Go back to.

Student: (Refer Time: 48:21).

So, we are doing a very simple design, this is a very simple design where we are ignoring the effect of chain variation in the inductance and capacitance, we are taking only one. So, if we consider that it will become even more complicated ok. So, similarly, I can define the reactive power rating of capacitor. So, reactive power rating of capacitor Q c is a notation.

So, again I can use the Budeanu definition of reactive power and write the reactive power rating as sum of two reactive powers; one for fundamental, one for harmonic. So, I will stop here continue from this point in the next class then complete the design.