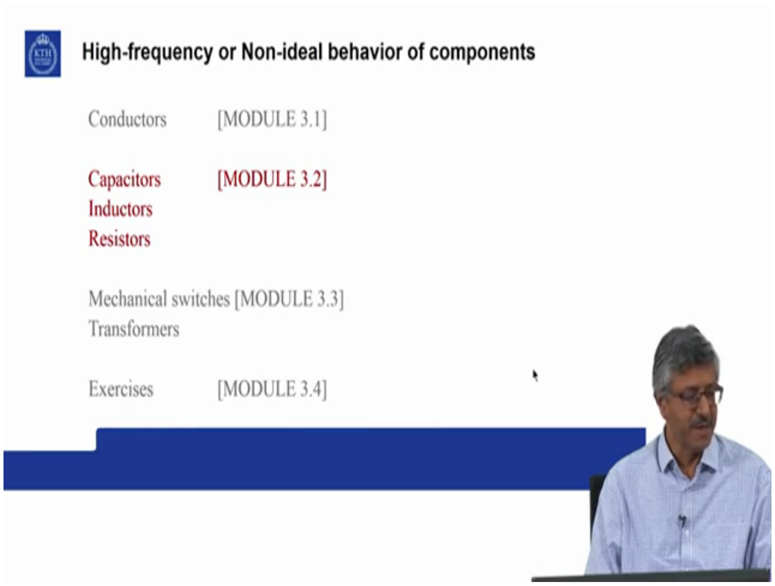
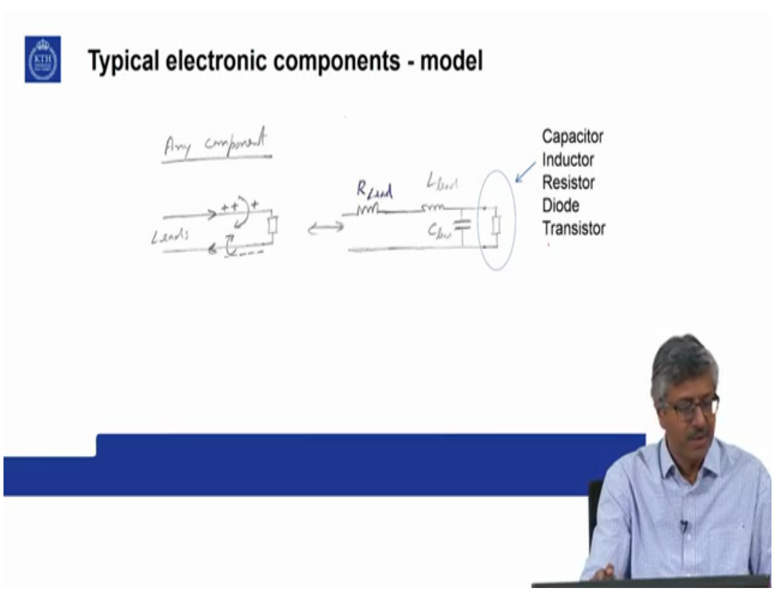
Electromagnetic Compatibility, EMC
Prof. Rajeev Thottappillil
KTH Royal Institute of Technology
High-frequency behavior of electrical components - Capacitors, inductors, resistors

(Refer Slide Time: 0:40)



Okay, we go to module 2 of chapter 3, continuing with high-frequency behavior of electrical components. So in this module, we will handle capacitors, inductors and resistors under high frequencies how they behave and what are the models we can make to reflect this behavior.

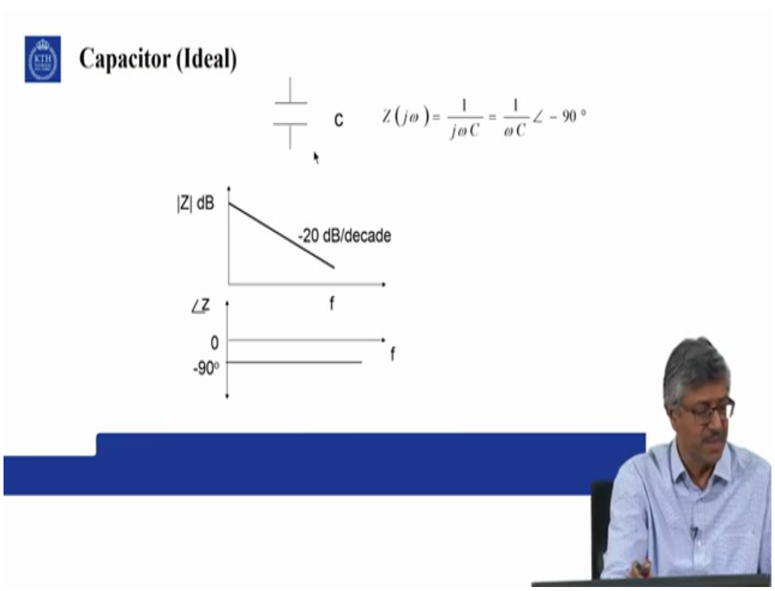
(Refer Slide Time: 0:55)



Now take any component, so usually this component will have some lead which is in the form a small round wire connected to the component. Then the moment you have conductors, we have seen in the previous module that it has some electric field around it, some magnetic field around it. So you think of some parasitic capacitance and parasitic inductance associated with it. Parasitic means that like a parasite. It is not supposed to be there but of course it is there in that sense. So it is kind of unwounded, like a wheel.

So we have some inductors and some capacitors and that is, and some resistors also because they are not ideal conductors, so any lead will have a resistance, lead resistance, a lead inductance you will have and a lead capacitance, a parallel element. So these are the parasitic elements. And after that, you have the your real idealized component. So it can be a capacitor or inductor, resistor, diode or a transistor. It can be anything. So here we will consider the first three, capacitor, inductor and resistor. Then you may have some more parasitic elements depending upon the type of construction used in creating these components.

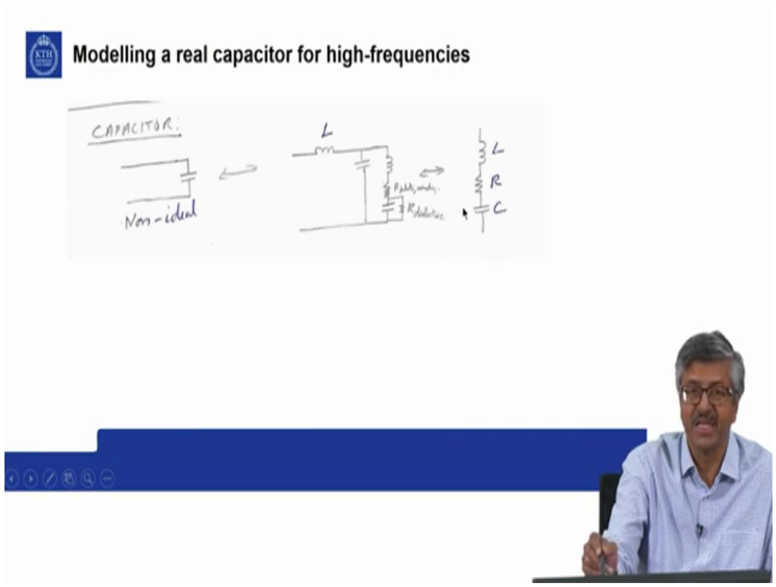
(Refer Slide Time: 2:42)



So we take the ideal capacitor. What is an ideal capacitor? Well, it has a symbol like this. So this is the ideal capacitor and it has a impedance which is a function of frequency. We know that it is 1 by J omega C or in polar form we write 1 by omega C and minus- 90. It means that the impedance is voltage divided by current. So voltage and current are 90 degrees face shifted and the current is leading the voltage by 90 degree. So that is why you have this minus- sign, or 1 by J, from that also you get a minus- sign.

You can look at in that way also. So if you convert it into dB, you can immediately see that as the frequency is increasing, the impedance of an ideal capacitor is decreasing by 20 dB a decade. It means that for every 10th times increase in frequency, so if the frequency is increased 10 times, then impedance is decreased from the previous level by 20 dB. That is the meaning of minus- 20 dB per decade. So this is an ideal capacitor and this is the angle, minus- 90 degree. Now if you take real capacitor, what would be, what are the other components we have to add to get the realistic model for the capacitor?

(Refer Slide Time: 4:49)

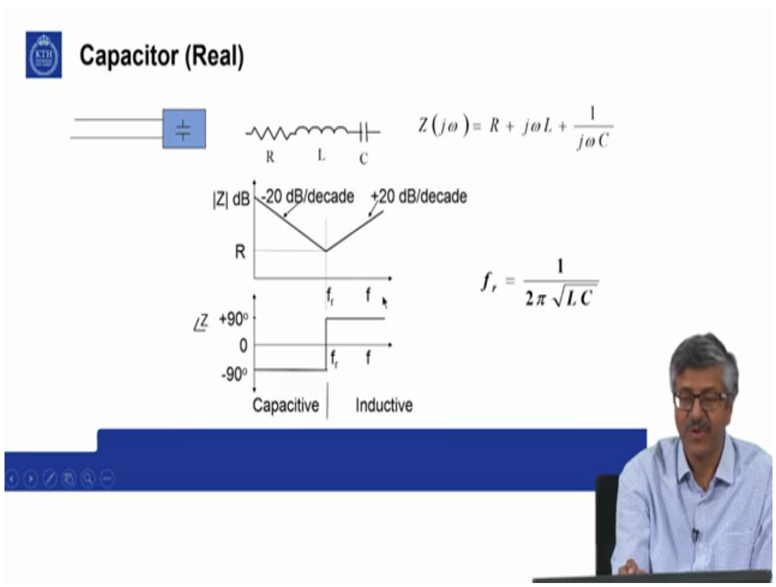


So we take a non-ideal capacitor. First of all, we take the lead parameters, you have lead resistor also but impedance of the capacitor is there only so high, you can most often neglect the lead resistor which will be very small or combine that into the resistor of the plate and windings of the capacitor if it is one capacitor. We can absorb that into this. Then similarly internally we can have an inductance and the dilated resistance of the capacitor across C but also is quite high. So that also can be neglected.

So you can neglect some things in this because usually this capacitance have high values. So finally you end up with, and this capacitance can also be neglected or absorbed into the, because we are looking at a capacitance value which are the only high compared to the lead capacitance.

So you get as an approximate of presentation a series network of L, R and C. So C is the idealist, idealized part of the capacitor. And R and L are mostly contributed by the leads or maybe even from the, R mostly from the capacitance itself. So this may be an idealized capacitor. So it is a series resonance circuit. Sorry, this is not an idealized capacitor. This is a real capacitor as opposed to an idealized capacitor C.

(Refer Slide Time: 6:58)



So if you write the impedance of this real capacitor, then we get R plus+ J omega L plus+ 1 by J omega C. Now you can do a Bode plot, a frequency plot or Bode plot of this. So we are, at the corners we are doing this idealization and we are assuming sharp turnaround at the corners just for easiness, so let us take this impedance. You increase the impedance from 0 hertz, 0 frequency and so then it is only R plus+ J omega L is 0. So this part is 0. And this part is omega equal to 0, infinity, idealized.

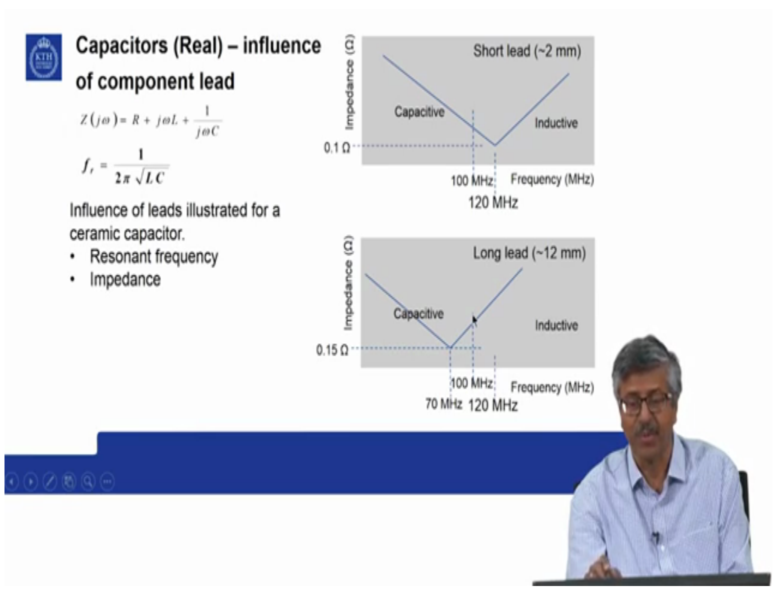
So you assume from some very high impedance, you are coming down from very high impedance for the capacitor, for DC because DC is completely blocked by this capacitor. Then as the frequency is increased, this becomes a finite value but since frequency is small, this is a high number compared to J omega L. This is such a small and R is kind of constant. So as the frequency continue to increase, you see that this impedance from the inductive part is increasing whereas this impedance from the capacitive part is decreasing. So inductive part increasing, capacitive part decreasing and at some point both will become equal and cancel each other.

So because this is J omega L, this is 1 by J. 1 by J is minus- J, so these two, the sum of this value is decreasing all the time as the frequency is getting increased. So finally, that impedance comes down. So during this regime, it is acting as a capacitor. So at this frequency, when impedance of this part and this part are equal, total impedance become the resistance R, then beyond that this part is dominant. Inductive part is dominant. So then from that time onwards you have approximately 20 dB per decade increase in impedance as you would expect from inductor.

Same thing will happen with the face also, minus- 90 here it transition into plus+ 90 as if it is an inductor. So this transitional frequency or resonance frequency is given by when these two are equal, J omega L equals 1 by J omega C, and that is given by 1 by 2 pi square root of LC when these two terms are equal. So that is the resonance frequency. So above the resonance frequency, the idealized capacitor is not really acting as a capacitor. It is acting more like an inductor. So while selecting a capacitor, you have to know what is the resonance frequency of that capacitor and you have to know the operating frequency where the capacitor will be employed.

And the operating frequency should be much less than the resonance frequency. You can use it at any frequency. Then how do you reduce or how do you increase the resonance frequency?

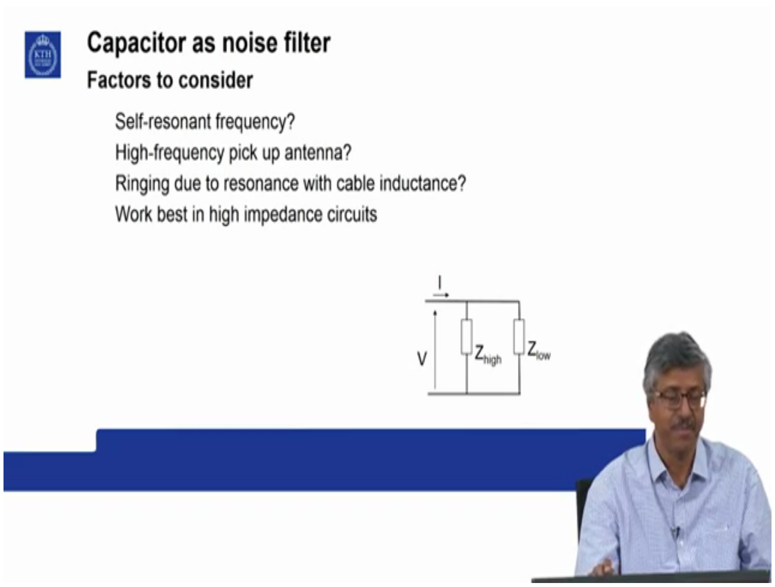
(Refer Slide Time: 11:26)



If you make the leads of the capacitor as small as possible, you can do so. That is shown in this view graph, it is influence of component lead. So here a short lead capacitor, same capacitor in one before soldering these leads are cut off, and only 2 millimeter is retained, the other you keep a long lead, 12 millimeter. Then you compare the impedance as a function of frequency. Then you can see that the short lead, the resonance frequency in this particular case may be at around 120 megahertz. And at that time it may have a resistance of 0.1 ohms.

So you can operate easily at 100 megahertz without any problem, it will be like a capacitive element. Whereas another person taking the same component for the same application may have a long lead and then the resonance frequency of that will be, because parasitic inductance is now larger, resistance is also larger. So it is at 70 megahertz and resistance is 0.15. So if you try to operate it at 100 megahertz, it will not succeed because it is not behaving as a capacitor, more like inductor it is behaving. So the circuit will not work properly.

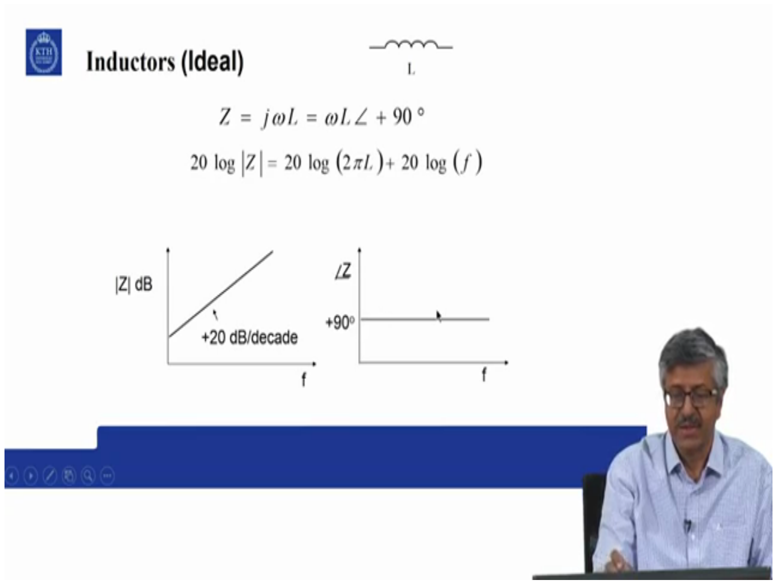
(Refer Slide Time: 13:13)



One is the self resonant frequency of the capacitor, the operation should be below that frequency. Then since capacitor is kind of a high impedance element, and along with the leads, it can act as a pick up antenna for high frequency ambient noise. So that one has to be aware and that can be ringing due to resonance with cable inductance. If the cable used in correcting this capacitor, then it works best in high impedance circuits. Suppose you want to reduce the noise in the circuit, everyone knows that capacitor is more like a bypass element because at high frequency it shorts out, high frequencies.

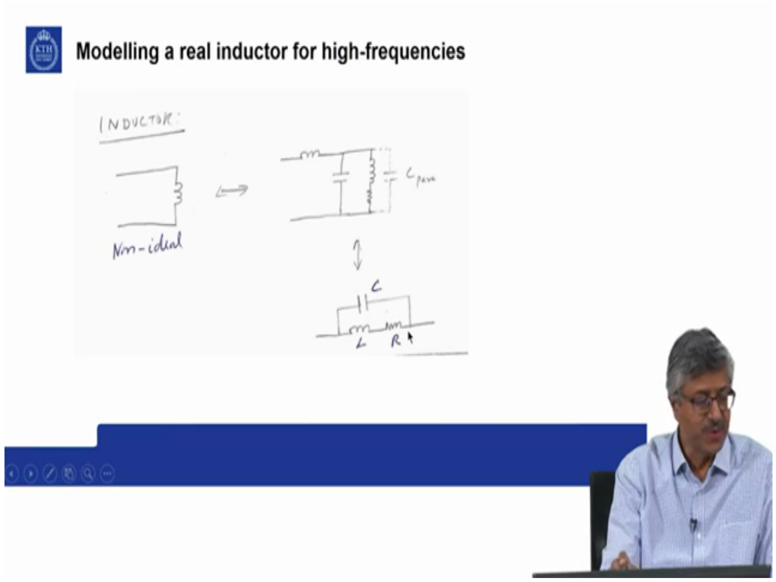
So it is ideal thing to use, the input terminals of the equipment you want to protect or the circuit you want to protect. But if your circuit is of, already of lower impedance, it may not work very well because your capacitance impedance under noise condition has to be even lower than the circuit impedance to be effective and that will be at really high frequencies. So capacitance has a noise filter works best with other high impedance circuits, not with the low impedance circuits.

(Refer Slide Time: 14:56)



Though inductors, this is the representation of an ideal inductor, impedance is J omega L. Omega is the frequency and angle 90 degree or the face difference between voltage and current. So the current is lagging behind the voltage by 90 degree. So 20 log Z equal to 20 log 2 pi L plus+ 20 log f. So you see that it is 20 dB per decade increase in impedance as the frequency 10 times increasing, you can see then 20 dB increase in impedance. This part is constant and 90 degree. So this is the ideal inductor.

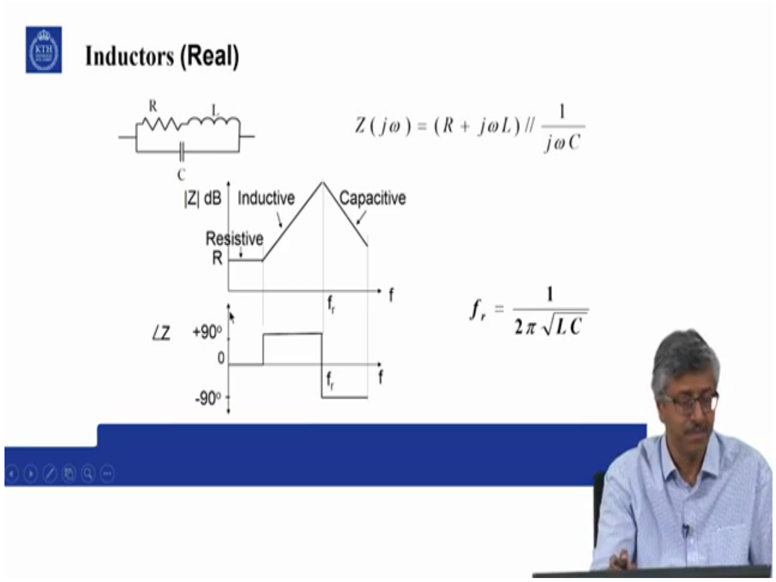
(Refer Slide Time: 16:04)



So we again model this ideal inductor, you have a lead. We can have some resistance, then inductor, and capacitance, then you can have from the inductance winding you can have some resistance also and a parasitic capacitance across the inductance if it is wound inductor or across the terminals or internal terminals of the inductor. So many of these things can be combined together and you can, so basically, essentially you have an L and R in parallel with a capacitance C. So this is the minimum high frequency of inductor.

Depending upon the applications one can have even more complicated models but usually this would be sufficient. Now let us how it will behave as the frequency is increased.

(Refer Slide Time: 17:11)

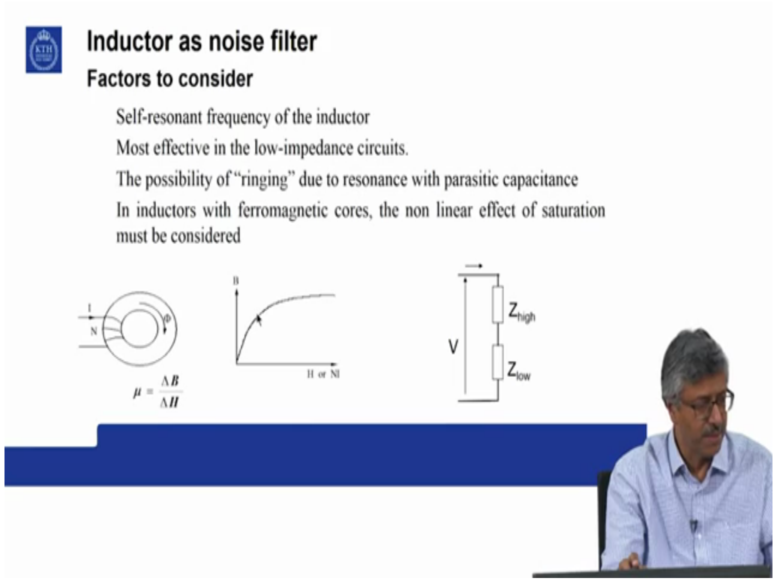


Now in the form a bode plot, so this is the real inductor. Impedance is R plus+ J omega L for this branch in parallel with the capacitive branch, in parallel with 1 by J omega C. So you can write out the expression for inductance, expression for the impedance. What we are mostly interested is how the impedance varies with the frequency. So again following the same exercise from almost very small values, when omega is extremely small, this is small, so this is in parallel with this one. So this is the high impedance, so this is mostly dominant one.

So this parallel branch is not very dominant, it is almost like an open circuit. So initially it is R, then it is J omega L, that is dominating. Then at one particular point, J omega L and 1 by J omega C become equal, so that it is resonant frequency. So now this is high, this is parallel resonance, so it is high impedance at resonance. Whereas previously in series impedance it is, series resonance it is low impedance at resonant frequency.

So after that, after resonance the capacitor part is dominant and 20 dB per decade decrease. So corresponding phase angle, so this is an ideal inductor. So you can operate the inductor in this frequency band, below this resonant frequency.

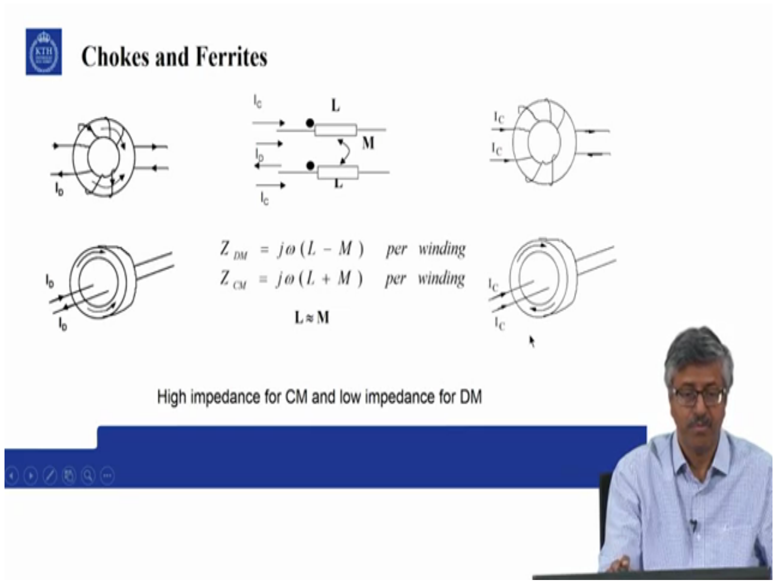
(Refer Slide Time: 19:17)



So inductors are also used as noise filter. So here what are the factors to consider? One is, the self-resonant frequency of the inductor. And inductor is most effective in the low impedance circuits because inductors are connected in parallel. So as the frequency is increasing, the inductor, inductor impedance is also increasing. And it should be much higher than your normal impedance and it is easy to be higher than the normal impedance of the circuit if your circuit already is having low impedance.

So this is most effective in the low impedance circuits. The possibility of ringing due to resonance with parasitic capacitance is another factor to be considered. And inductors with ferromagnetic cores, the non-linear effect of saturation must be considered. Say this is a ferromagnetic core, so mu is defined as changes in flux density to magnetic flux intensity. So this is the saturation region, so it should not operate in the saturation region, it has to be somewhere here. So these are the factors to be considered while selecting inductance as noise filter.

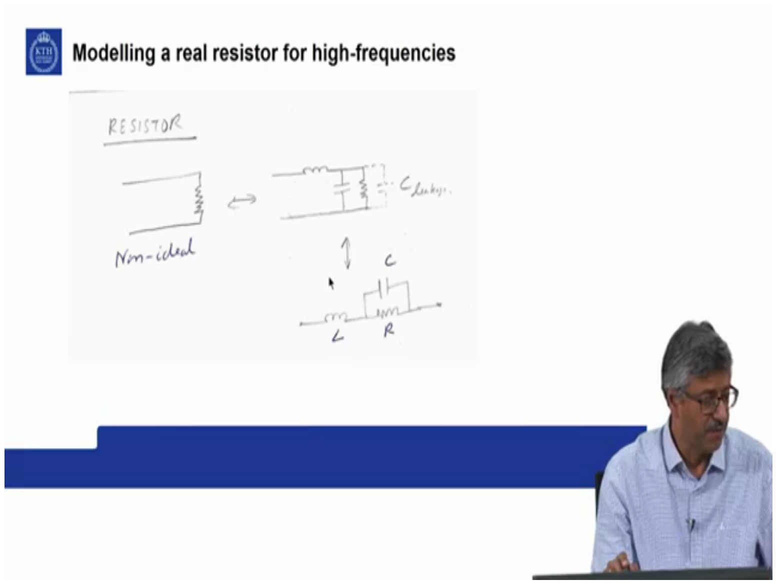
(Refer Slide Time: 20:58)



And often we use chokes and ferrites in electronic components. So if you connect a monitor, sometimes you can find round heavy thing on the cable itself and that is high frequency choke. This is for filtering out the noises coming from supply or for preventing the noises going from your device to the power lines. So these are the differential mode currents, so with the normal winding, the fluxes are opposing to each other. So it is a very low impedance because total flux is almost 0. So you have a low impedance, differential mode impedance for winding.

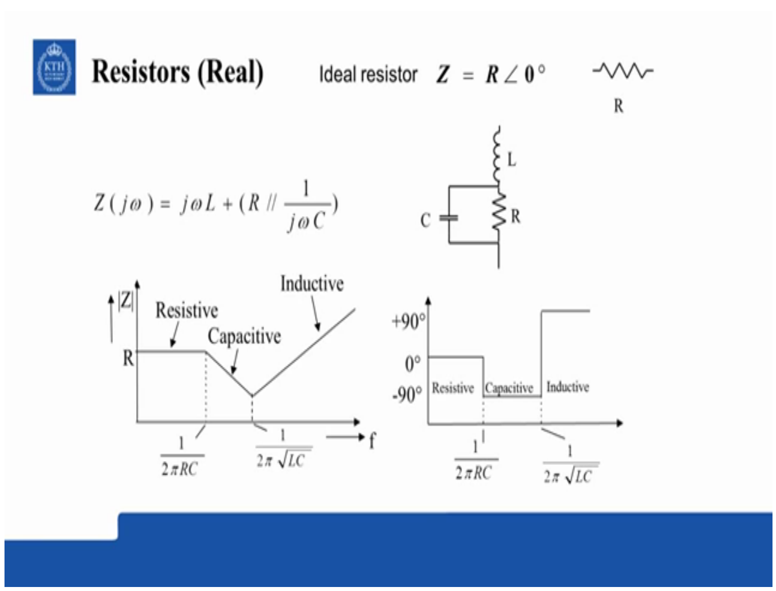
Now this is say single primary, this is several turns. Now for common mode type of currents where the current interactions are the same in both, both fluxes aid each other and you have then high impedance per winding under common mode noise currents. So then it will kind of introduce high impedance in the circuit and you block the noise.

(Refer Slide Time: 22:37)



Now modeling a real resistor for high-frequencies, again we do the same exercise of including the parasitic elements of the component leads, inductor and capacitor. Or there can be a leakage capacitance across the register also which we can combine with this parasitic element. So you get circuit in which we have inductor, then we have a capacitor and resistor connected in parallel. So this will be the minimum model for a real resistor under high frequency.

(Refer Slide Time: 23:22)



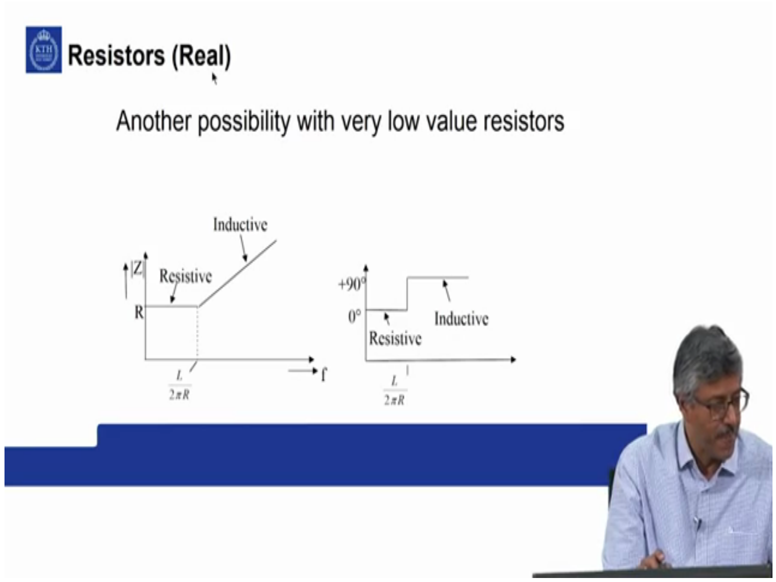
Consider a real resistor R, it has got due to the leads and due to the construction of the resistor some parasitic inductance L and some parasitic capacitance C. Now as the frequency is increasing, or DC value of the parasitic capacitive impedance is very high and the parasitic capacitive impedance reduces as the frequency is increasing. And at the same time the parasitic inductive impedance is increasing as frequency is increasing. Now as you move away from the DC value, you can see that at one point the resistance R become equal to 1 by J omega C.

And that point is given by this, so the capacitive impedance is coming from very high value, so they are in parallel combination. So at this point, both of them become equal, R equal to 1 by omega C. So that frequency corresponds to 1 by 2 pi RC. Beyond that it becomes capacitive. So the resistance remain as resistive only below this particular frequency of 1 by 2 pi RC. After that it becomes capacitive. When inductive impedance is also increasing, capacitive impedance is decreasing and at some point of frequency both become equal and we have a resonance.

And that resonance point is given by here, 1 by 2 pi root LC. And beyond that resonance point inductive impedance is much more than capacitive impedance. So it behaves as a inductor. So all these three phases you can find at over here. The resistive phase, so this is where the resistor should operate. Then after that you can have a capacitive and inductive phase also. So resistor is not supposed to operate in this area. Only below this frequency it is supposed to operate.

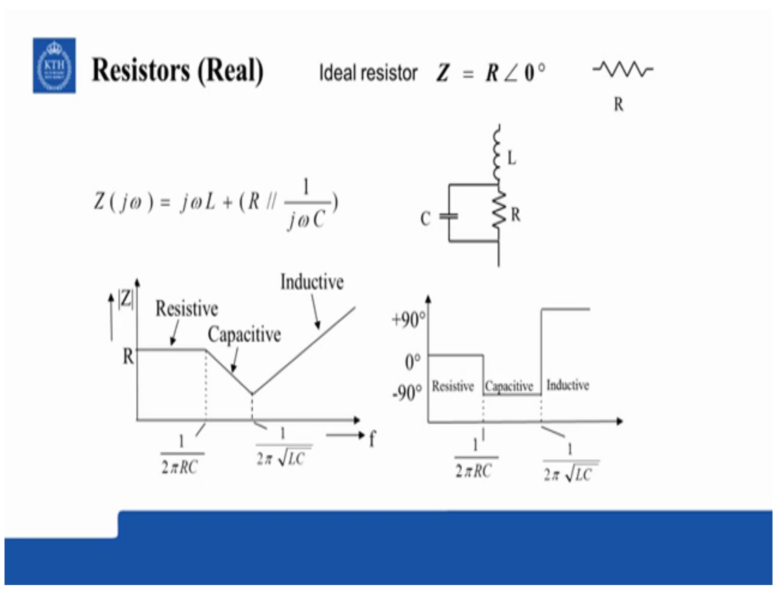
We would say in the next slide another case also where you do not have this capacitive phase in which resistance directly go from resistive to inductive phase. This happens mainly with low value resistors. That we will see in the next slide.

(Refer Slide Time: 26:19)



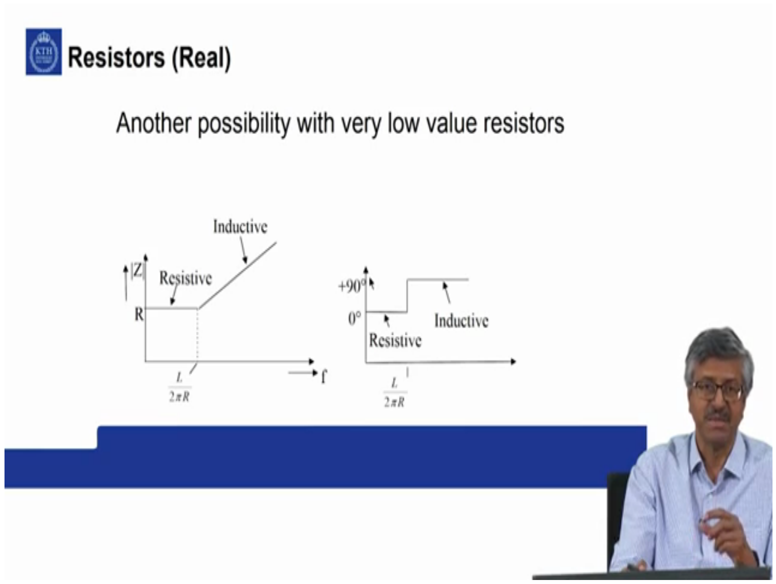
Resistors, real value of resistors, let us consider another possibility with very low value resistors.

(Refer Slide Time: 26:33)



Now that possibility comes when your inductance impedance first become equal to R and capacitive impedance still becomes, that is the parallel branch, that becomes still very large. So what happens in that case? So this is still very large. So this is negligible. You have only L and R in the circuit.

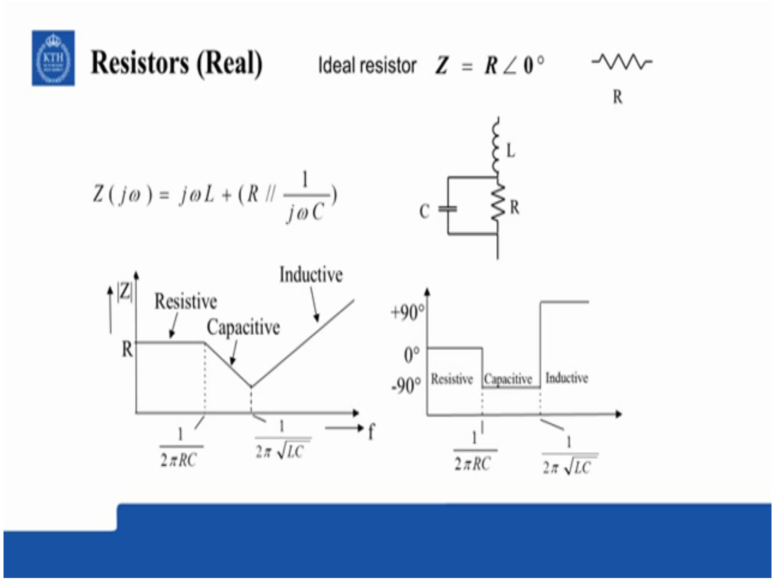
(Refer Slide Time: 27:05)



So in that case at this frequency when R equal to 1 by 2 pi f, R is equal to 2 pi f L, then beyond that, beyond this frequency you have inductive 20 dB per decade increase, inductive increase. So from resistive to inductive it is going directly without going through the capacitive phase. So you have resistance and you have inductance, the phase angle. So this is another possibility with the resistor. So we often say that if you are selecting for an implications, very low value resistors you have to be extremely careful about parasitic inductor, parasitic inductance, not really parasitic capacitance.

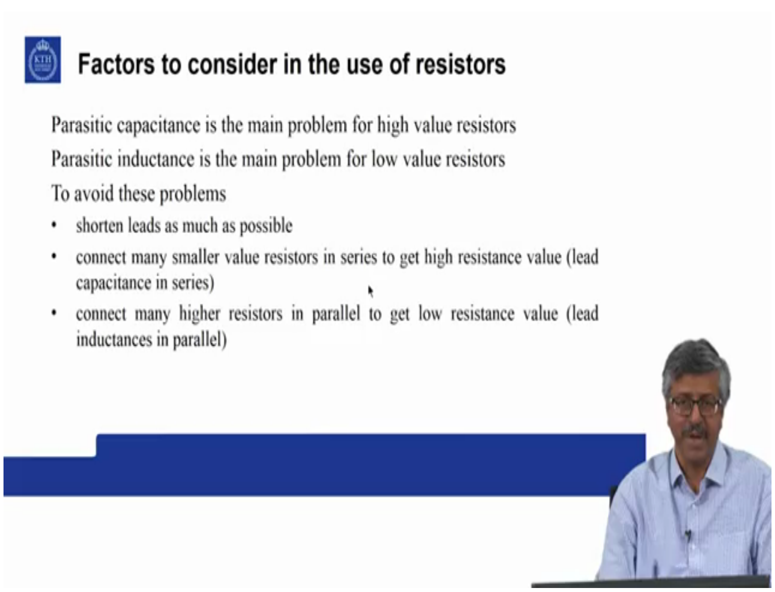
That is where you have the main problem that happen because this will be the bode plot corresponding to it. From low value of resistor immediately you go into the inductive part of it, whereas if you have very high resistors, say thousands of ohms, then parasitic capacitance becomes more problematic.

(Refer Slide Time: 28:31)



So then bode plot will be something like this. From resistance to capacitive it will go into. So depending upon the application area, depending upon the low value or high value of the resistor one of these two parasitic, one of these two bode plot will be more appropriate to be applied so two different models are possible for resistor.

(Refer Slide Time: 29:02)



Factors to consider in the use of resistors: One is parasitic capacitance is main problem for high value resistors. Parasitic inductance is the main problem for low value resistors. To avoid these problems, shorten the leads as much as possible. When you reduce the parasitic elements both your parallel inductance, parasitic resistance and parasitic capacitance, connect many small value resistors in series to get a high value, resistance value.

So suppose you need to have a high resistance value, so instead of using say 20 mega ohm or 1 mega ohm resistor directly, you can take 10, say 100 kilohertz, 100 kilo ohm resistors and connect them in series, so then parasitic capacitance values are coming in series, so effectively you are reducing it. Now if you want a low value resistor, you can take certainly high value resistors and connect them parallel because then you are parallel connecting all the parasitic inductance, effectively reducing the inductance problem. So these are the two techniques you can use in circumventing the effect of parasitic elements. So that is the end of module 2.