Switched Mode Power Conversion
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Lecture- 7
Capacitor

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Good day today. Today, we will see on the last component which we have listed has the devices for efficient power conversion. We had seen in the earlier lectures, the other devices namely the switches, inductors, transformers and so on. And the lossless electrical circuit element which is still remaining to be covered in our lectures is the capacitors and that is the 4th component, forth device which are used in efficient power conversion. So, in this lectures we will try to see the basic properties of capacitors, different types of capacitors available, how does one understand the process of energy storage in the capacitors, how do we specify them, how do we test them and so on.

The switches we had seen in the first set of lectures are used in a efficient power conversion for the purpose of control. Control and flow of energy is being carried out by the presence of switches. We had seen that the inductors could store energy and smoothen the flow of energy in power converter circuits. The transformers we saw were used to match voltage levels to step up voltages or step down voltages to give electrical isolation and so on. The last element that we are going to see in this set of lectures is the capacitors. Capacitors store energy and their purpose is also to smoothen the flow of power from the source to the load. The switches which are used in power converters necessarily introduce discontinuities in the flow of power and the energy storage elements which are the inductors and capacitors which are used in power converters are used mainly for smoothening the flow of power. These are energy storage elements. The capacitors store energy; just like inductors, the capacitors also can store energy. The energy stored in the capacitor is in the form of an electric field. We saw that the inductors were storing energy in the form of magnetic field. In the capacitors, the storage is done in the form of electric field. And in power converters, in order to smoothen the flow of energy from the source to the load, capacitors are used for that purpose.

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Capacitors are also used in protection circuits. The switches we had seen that are subjected to large voltage and current stresses and it is necessary to protect them against store voltages and over currents during switch on and switch off. We had seen that, during switch on over currents are prevented by introducing inductors in the circuit and inductors by the nature of their capacity to limit the d i by d t, rate of rise of current provide protection against turn on process in the switch. In a similar way, capacitors are used as switching aid elements in order to provide protection during the turn off process. This protection is to prevent very large over voltages occurring in the circuit much more than the supply voltage. The capacitors are able to suppress over voltages in that capacity in many power converters, capacitors are used as switch protection element. We have seen 2 functions: One is to smoothen the flow of energy and the second one is to protect the devices during the turn off process from over voltages.

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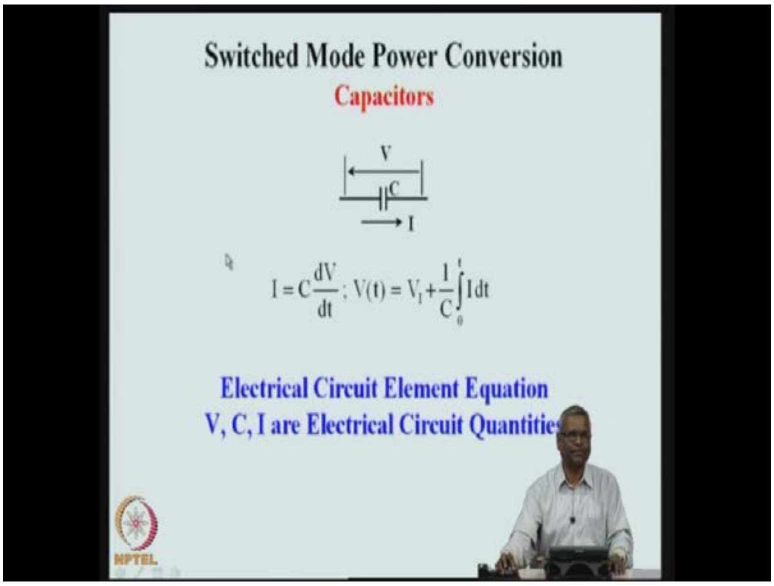

The capacitor is a circuit element and as a circuit element it can be defined through the voltage across the capacitor V and the current through the capacitor I. What you see here as V and I. And the relationship between the current and voltage can be expressed in the form of a differential equation or in the form of an integral equation. The first one relates the current to the rate of change of voltage. The current through the capacitor is capacitance times the rate of change of voltage across the capacitor. The inverse relationship of this is that the voltage across a capacitor is equal to V I, the initial voltage at any instant t equal to 0 plus the quantity of charge that is supplied to the capacitor divided by the value of the capacitance. So, this relates given the current function and the initial voltage, it is possible to find out the voltage across the capacitor. And in the other equation current voltage if we know, what is the voltage that is applied across the capacitor, it is possible to find out the current through the capacitor. These are the circuit equations and these equations are the once switch we use in order to develop several designed relationships.

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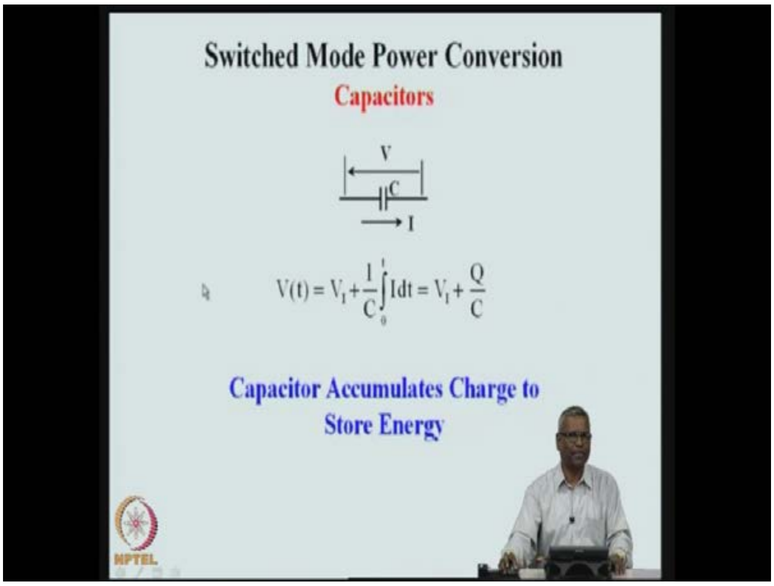

The capacitor accumulates charge in order to store energy. The integral form of the equation between V and I in the capacitor is restated here. The voltage across the capacitors a function of time is the initial voltage V I plus the capacitor the charge that is supplied to the capacitor divided by C integral 0 to t I d t is nothing but, the total charge that is supplied to the capacitor Q. So, we see that the voltage across the capacitor is the initial voltage plus the charge supplied in any time divided by the value of the capacitance. So, you can see that this relationship indicates that the capacitor is capable of accumulating charge in order to store energy. The charge is accumulated on the plates of the capacitor and it appears in the form of voltage and a charged capacitor will have a certain voltage and the stored energy is a related to the voltage and the capacitance.

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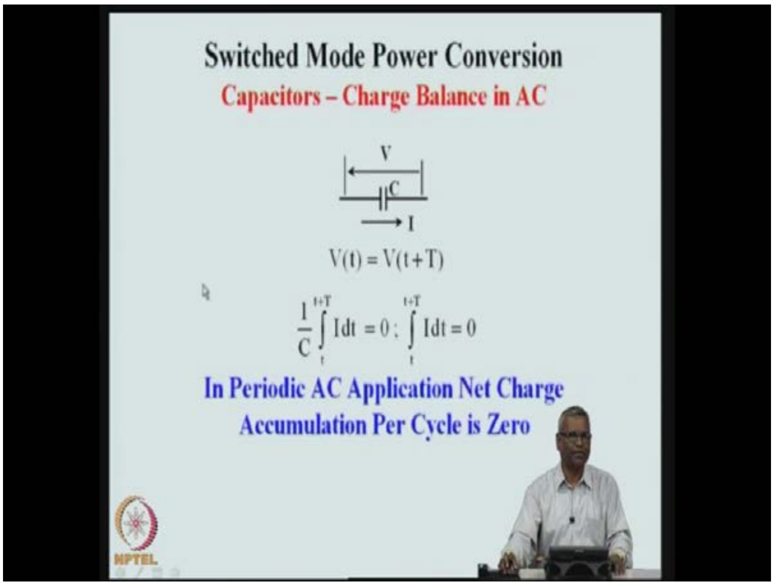

When we use capacitors in a periodic circuit, in an AC circuit or a periodic circuit, what we notice is that, the voltage across the capacitor will be a periodic function V of t is V of t plus capital T Where, capital T is the period of the circuit. And if this is true then, over one cycle from t to t plus T, over one cycle whatever is the capacity the charge that is accumulated by the capacitor has to be 0. Because, at the end of the cycle, the voltage remains the same as it was before. And the result of this, the consequence of this is that in a periodic circuit one can use the relationship that, in one period the charge that is accumulated on the capacitor is 0. Or, in other words the integral of I and d t or ampere second. This is also mentioned as ampere second integral over one cycle and that is 0. Many times this relationship is useful in order to find out several study state performance, figures for a capacitor in any typical switching circuit. In periodic AC application, the net charge accumulation per cycle is 0, which is another way of stating that the under periodic conditions every cycle the voltage keeps on repeating the same as the previous cycle.

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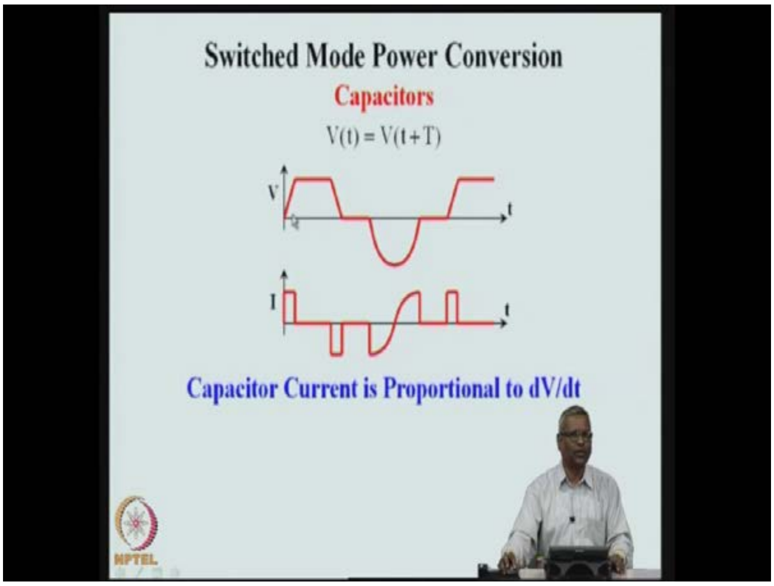

The relationship in a periodic circuit, I have written a drawn a typical periodic current and voltage across a capacitor where, the time function of voltage is a periodic function. What you see here, it keeps repeating every cycle. There is a ramp up of the voltage and flat voltage constant voltage then, ramping down and then, some kind of a sinusoidal voltage on the capacitor in the reverse direction and then, no voltage for some duration and then, the cycle repeats. This could be a typical voltage waveform on a capacitor. The relationship of V equal to C d v by d t can be seen here, that during the ramp time when the voltage across the capacitor is increasing linearly, you will see that the capacitor current is constant. C times the slope here will give the positive charging current on the capacitor. During the time the capacitor voltages is constant, we find that the current here is 0 and during that time when the capacitor voltages is linearly falling down to 0, the capacity is discharging or the current through the capacitor is negative value of constant magnitude.

And during that time when there is no change in the capacitor voltage, the current in the capacitors is again 0. The sinusoidal voltage change in the capacitor voltage will have a co-sinusoidal current change because the current is the derivative of the voltage. You see that large negative slope here, results in a large negative current in the capacitor. As the capacitor reaches a peak value here at this point d v by d t is 0, the current is 0 and as the current is charging back to 0, the positive slope here corresponds to the positive charging current here and then, the cycle repeats. The capacitor current in any circuit is proportional to d v by d t and that proportionality constant is a value of the capacitance. It is possible in many situations from the sketches of the voltage to draw the sketches of the currents and if we know the mathematical relationship, it is possible to differentiate it and get the current values.

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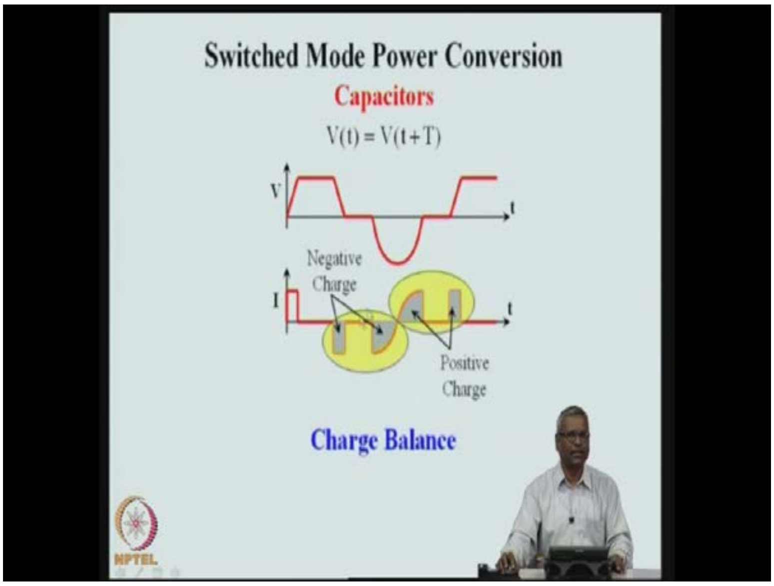

Now, in a periodic circuit we had seen that there has to be charge balance. And what we see here, from this instant to this instant; over one cycle, there is no net change in the voltage. Whatever was the voltage at this point is the same here. So, the voltage that was lost here during this part is gained here. So, the net voltage drop is the same as the net voltage rise. And voltage drop is equal to the charge that is taken away from the capacitor. What you see here as the areas is indicated by the negative charge and the area shown here as the positive charge corresponds to the time when the capacitor is regaining its voltage. Charge balance simply indicates that the negative charge during a part of the cycle has to be equal to the positive charge during other part of the cycle so that over one cycle there is no net accumulation of charge or net accumulation of voltage across the capacitor.

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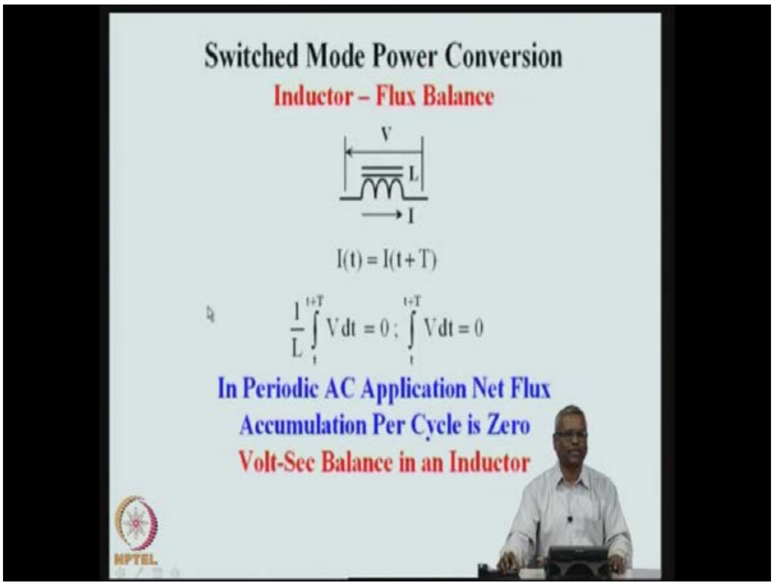

This property is a dual property to what we see in an inductor. In an inductor which is working in an AC circuit in a periodic circuit where, the current follows a periodic waveform I of t is I of t plus capital T. Where, capital T is the periodicity of the circuit. In such a circuit from one cycle to the next cycle there is no net accumulation of current, there is no net change in current and this can be expressed in this in this integrally equation 1 by L integral t to t plus T over one cycle, the voltage applied to the inductor volts seconds applied to the inductor is 0. The volts second apply to the inductor is what is responsible for the flux accumulation in an inductor. So, what this indicates? In a periodic circuit from cycle to cycle there is no net flux accumulation or net flux accumulation in per cycle is 0. This is also referred to as, volts second balance in an inductor, this is a dual property of charge balance in a capacitor when it is excited by a periodic circuit and steady state is reached.

We come back to the same charge accumulation property; it is possible to express V as an initial voltage plus the accumulated voltage. The accumulated voltage is the charge that is supplied to the capacitor divided by the value of the capacitance. We can say that, the capacitors stores energy by accumulating charge. As more and more charge is accumulated in the capacitor more and more energy is stored and this relationship is given by one half of C V square.

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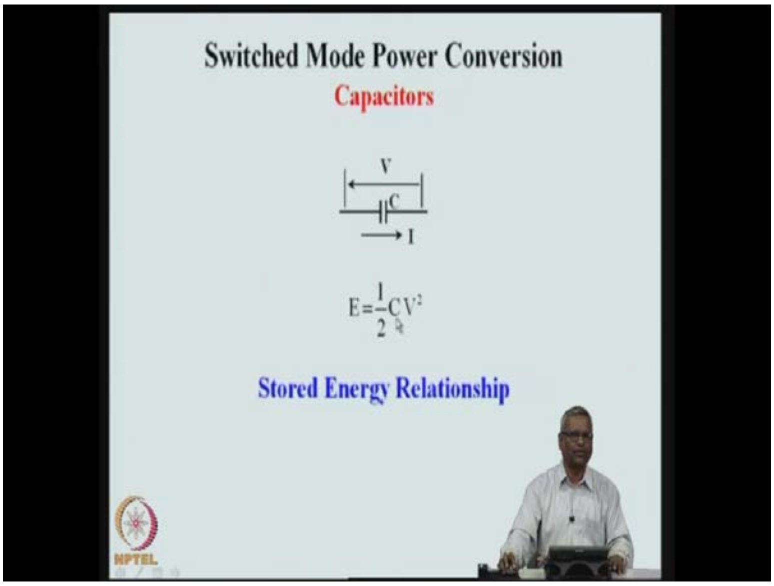

If a capacitor of value C is charged to a voltage of V then, the stored energy is 1 half of C V square and this is a relationship between the stored energy and the capacitor voltage. The capacitors normally are not designed by power electronics engineers for any specific application but, they are selected from manufacturers catalog depending on what the value of capacitance needed; the voltage it has to withstand; the amount of energy it has to store and so on. We will see some of those points here.

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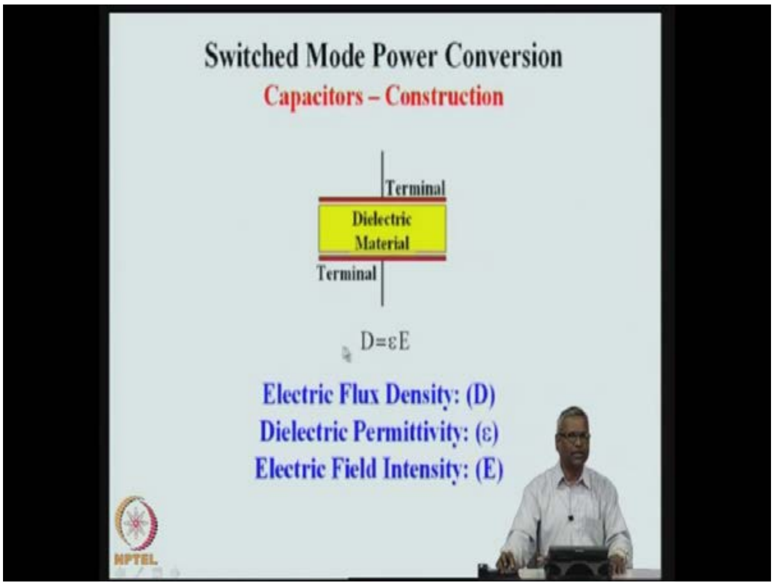

The construction of a capacitor consists of 1 terminal as you see her conceptually, it can be seen as terminal 1 and terminal 2 and in between a dielectric material is placed and this configuration is capable of storing charge and on account of this stored charge can store energy also. So, in this configuration of a capacitor it is possible to charge these terminals, top terminal can be charged with respect to the bottom terminal. On account of the charges that are going to stay on the plates there will be an electric field introduced in the dielectric material. That electric field is what we see here as capital E, this epsilon is the material property of the dielectric material it is called the permittivity of the dielectric material and D is the electric flux density. The electric flux density that is set up in the dielectric material is the product of the permittivity of the material and the electric field density field intensity that has been established. This equation is also a complete analog to the magnetic flux density being equal to permeability time multiplied by the magnetic field intensity. We had seen that relationship when we were studying about the inductors. This is the relationship which relates the electric flux density to the electric field intensity through the permittivity of the dielectric material.

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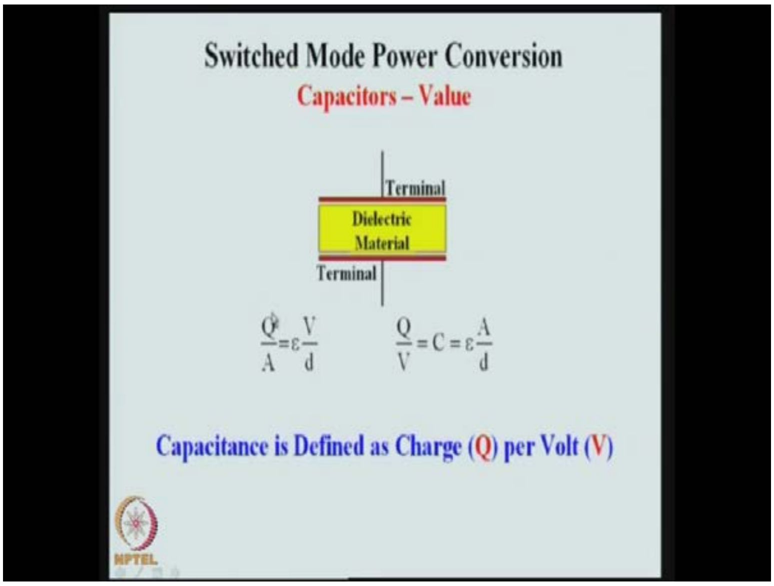

Now, the electrical flux density is defined as the in a symmetric circuit of this nature, whatever is the total charge on the terminals divided by the area of cross section of these dielectric material will give us the electric flux density epsilon times. And electrical field intensity is the voltage across the terminal divided by the distance between the terminals. So, I have written the same equation in terms of charge and voltage and this gives rise to the relationship that Q by V is C, which is how capacitance is defined. Capacitance is defined as charge per volt in an electrical circuit configuration. The amount of charge that can be held in relation to the voltage that is built up on the capacitor. Charge per volt is the definition of capacitance and this is also related through the dimensions of the capacitor and the property of the dielectric material. The area of cross section of the electrical field and the distance between the plates of the electrical field and the permittivity of the permittivity of the dielectric material in decides what will be the capacitance value. Epsilon time's area of cross section divided by d, this is a relationship which relates the capacitance. This also is very similar to the way inductance is defined through the geometrical properties of n square by reluctance, we had seen in the earlier relationship. This relates capacitance to the dimensions of the electrical field circuit.

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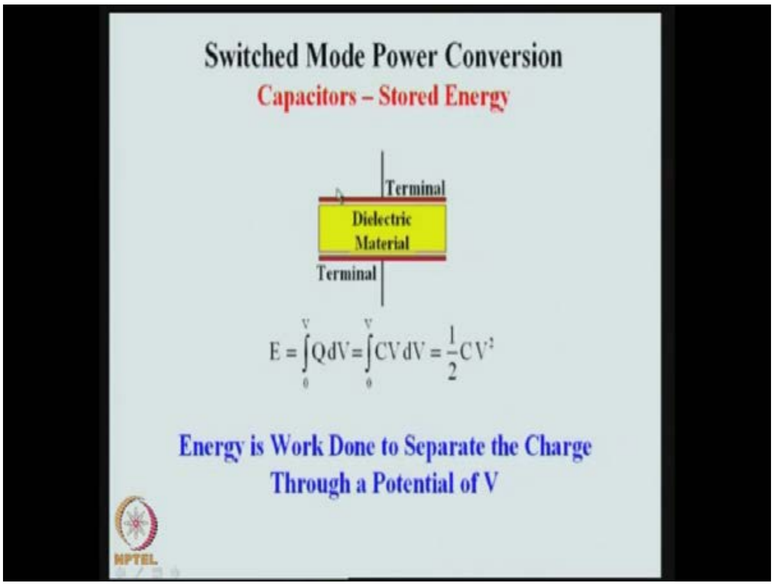

Now, here what we see is the total energy that is stored in that. This can be very easily worked out as the work done in order to separate the charge through the potential. We have a total charge of Q from the negative plate to the positive plate and the voltage across the plate is V. So, if you take a charge from this end and take it all the way down to the bottom plate or a charge which is from the bottom plate pulled out and brought to this configuration. The work done is the energy that is required in order to move this charges through a field voltage of V Q into d V integrated over 0 to V is the total energy store and this Q itself is C into V and this gives rise to the famous relationship that the energy stored in a capacitor is half CV square.

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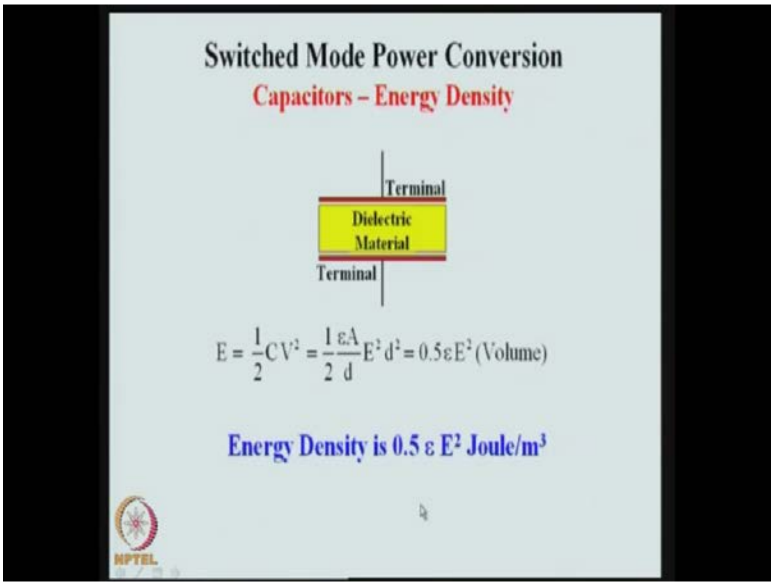

And if we substitute these numbers very interesting results come here, we can see that the energy stored in a capacitor is the electrical field intensity, permittivity of the material and the volume of the capacitor; the area of cross section and the distance of separation. So, if you try to find out, what is the specific energy storage in a capacitor that is, per meter cube of volume how much energy can be stored, that number is nothing but 0.5 epsilon E square, energy density is 0.5 epsilon permittivity of the material and the electrical field intensity that can be established.

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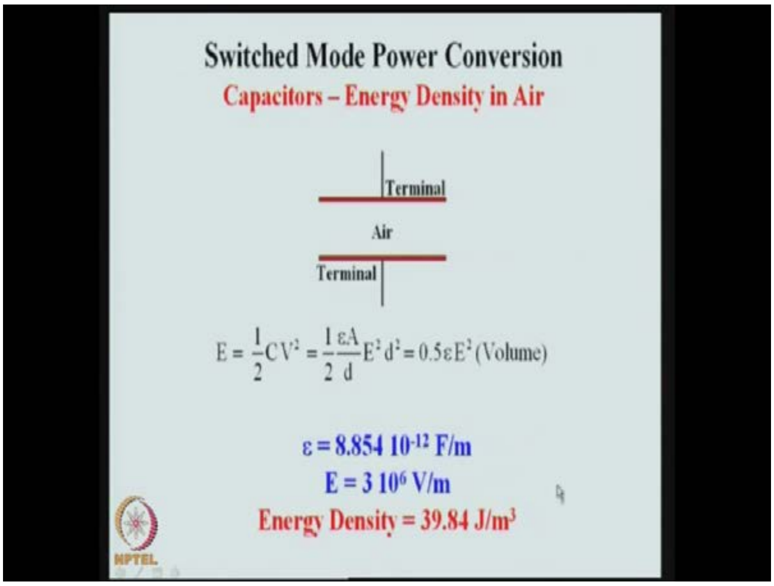

In the case of air, if we wish to store energy in air, it is possible to set up a capacitor where, air is a dielectric material. The dielectric material air has permittivity which is the same as free space permittivity 8.854 10 power minus 12 farad per meter. And air can with stand a voltage of field intensity as high as 3 mega volt per meter or 3 kilovolt per millimeter. So, from this it is possible to see that in air it is possible to store energy with the specific energy density of about 40 joules per meter cube, if you work out this number. 40 joule per meter cube is a very very small number, if you convert into calories about 4 joule is 1 calorie. So, this equivalent about 10 calorie per meter cube. 10 calorie is just the energy required to raise 10 gram of water through 1 degree centigrade or 1 gram through 10 degree centigrade and you can imagine that it is not a lot of energy. So, very small amount of energy. So, in air, the maximum amount of energy one can store is not very high.

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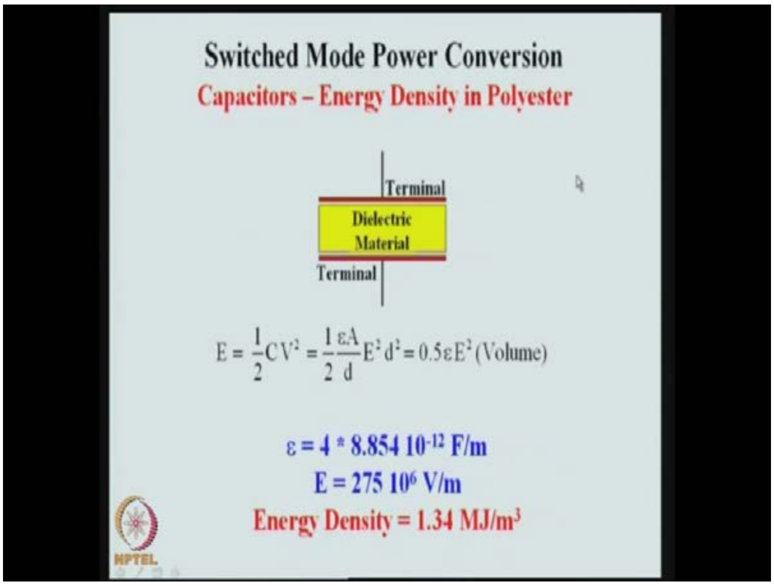

On the other hand, if we use dielectric materials which are special materials; for example, polyester is one of the widely used dielectric materials and in this particular material the energy density can go as high as 1.34 mega joule per meter cube. This is almost 10 to power 6 times higher than what can be stored in the air. This is because, the field intensity that you can set up is almost 200, 300 times more and the permittivity is about 3 to 4 times more. The relative permittivity of polyester sheet is about 3 or 4, I have taken 4 here. So, if we plug in these numbers the energy density that you can get from capacitors is of the of the order of 1.3 mega joule per meter cube.

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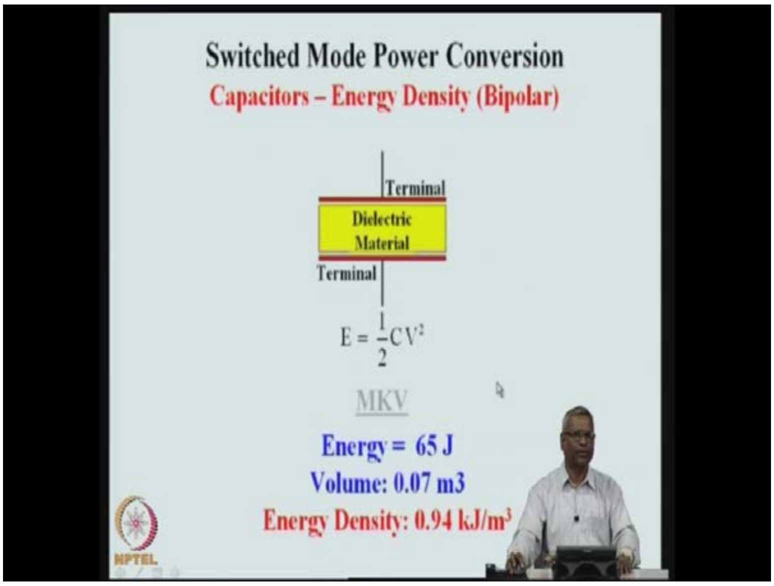

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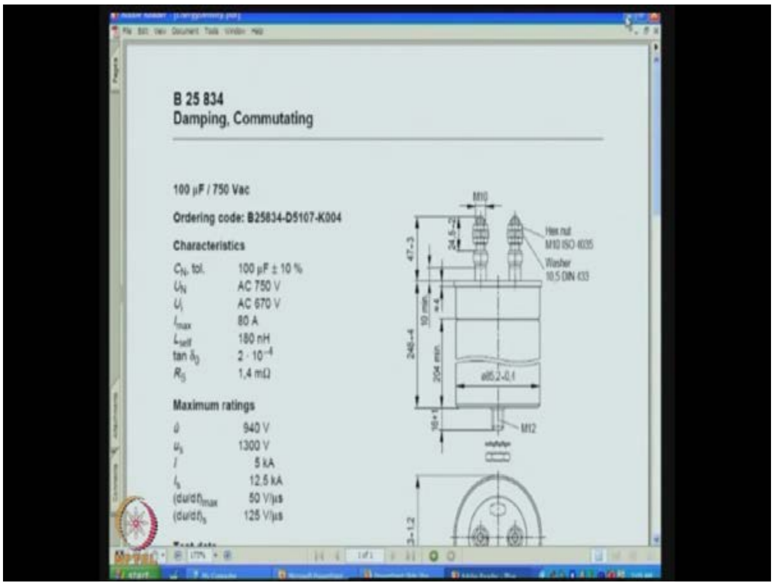

And this is from a data sheet of a particular capacitor; it is possible to find out the dimensions here. For example, we see that the height of this is about 248 millimeter and the diameter is about 85 millimeter and if we find out what is this volume. And for this capacitor, if we calculate C V square. We know the voltage rating and also the capacitance value and this capacitor is capable of storing about 65 joules and it has a volume of 07 meter cube or the energy density is of the order of what point 94 per 1 kilo joule per meter cube. So, commercially available capacitors invariably will have power densities of this order about 1 kilo joule even though, theoretically the maximum possible will be of the order of mega joule per meter cube, commercially available capacitors are almost 1000 times less; this is because one is required to handle the heat produced inside and then, the volume is not fully efficiently utilized and so on. So, roughly you can remember easily, it is 1 kilo joule per meter cube is a typical energy density of many of the bipolar capacitors.

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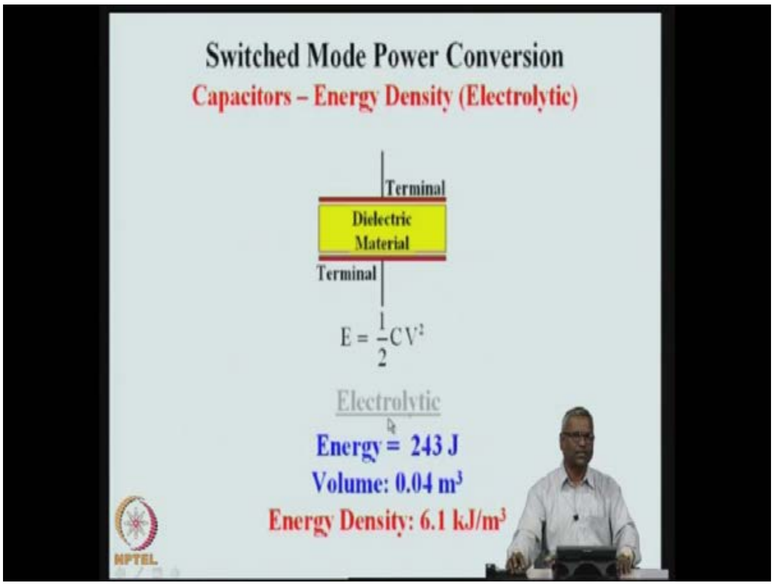

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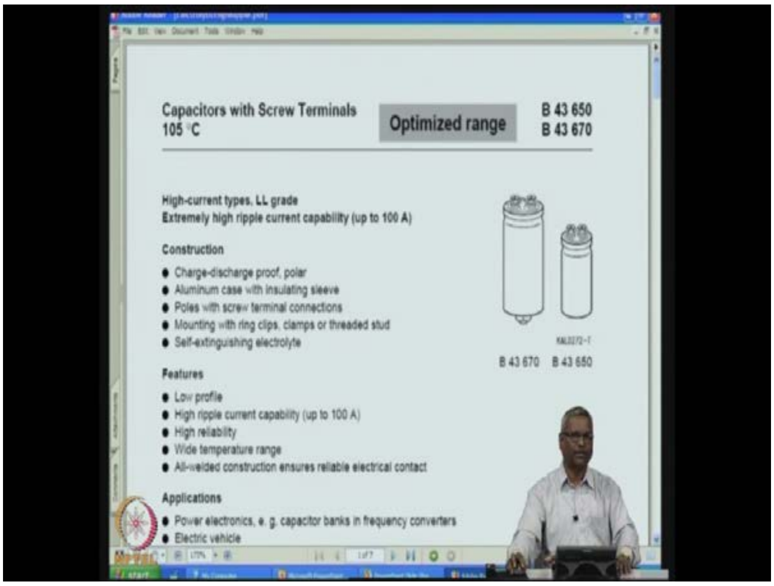

Against this we also have electrolytic capacitors which are unipolar. They can withstand only one polarity of voltage and such capacitors, what we see here is in the data sheet, these capacitors have the file terminals and an electrolyte in between and the some process which increases the effective area of cross section of the dielectric material which in effect gives rise to a power density of the order of about 6 kilo joule per meter cube or you can roughly take it is almost 10 times more than what can be obtained in a bipolar capacitors. Electrolytic capacitors typically may have about 10 kilo joule per meter cube and bipolar capacitors will have about 1 kilo joule per meter cube and theoretically possible energy densities are much higher than that easily, 1000 times higher than this.

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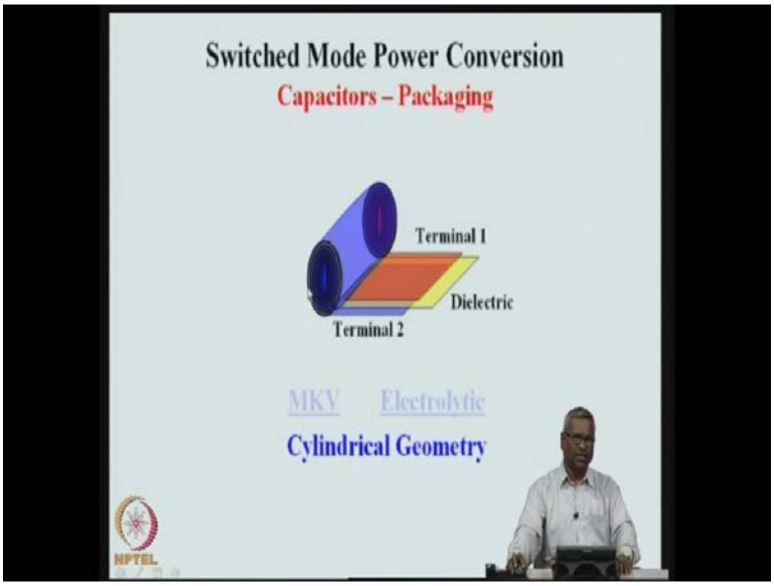

The construction of a capacitor or the packaging of a capacitor is in more or less in a geometry which is cylindrical.

We had seen both these capacitors which are bipolar and also the electrolytic capacitors which are unipolar have a cylindrical geometry. And the cylindrical geometries obtained by winding 2 terminals in the form of a cylinder with a dielectric material which is in between and this is rolled and obtained in the form of a cylindrical geometry. And with this cylindrical geometry it is packaged inside appropriate canes with insulations and so on. This is the preferred or the prevailing geometry which is used for capacitors which are used in most power electronic applications.

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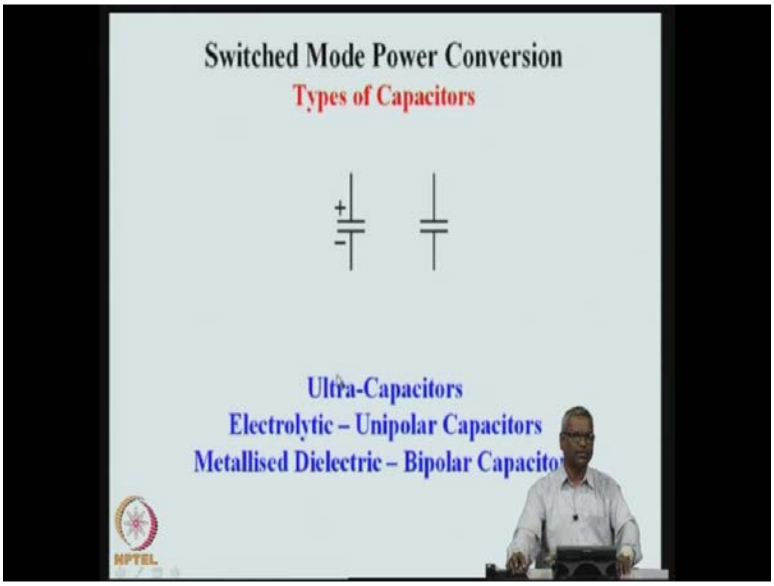

There are several types of capacitors in the market; the simplest classification is between DC and AC, bipolar and unipolar, electrolytic and non electrolytic. There are also some modern capacitors which are going by the name of ultra capacitors or super capacitors. They follow a different mechanism of storing energy that is not in the scope of what we are going seen now but, it is good to remember that we have emerging capacitors which are called ultra capacitors which store energies, which have energy densities which are easily orders of magnitude more than the electrolytic capacitors. Electrolytic capacitors have an energy density more than the metallic metalized dielectric capacitors. The ultra capacitors have even better than electrolytic capacitors.

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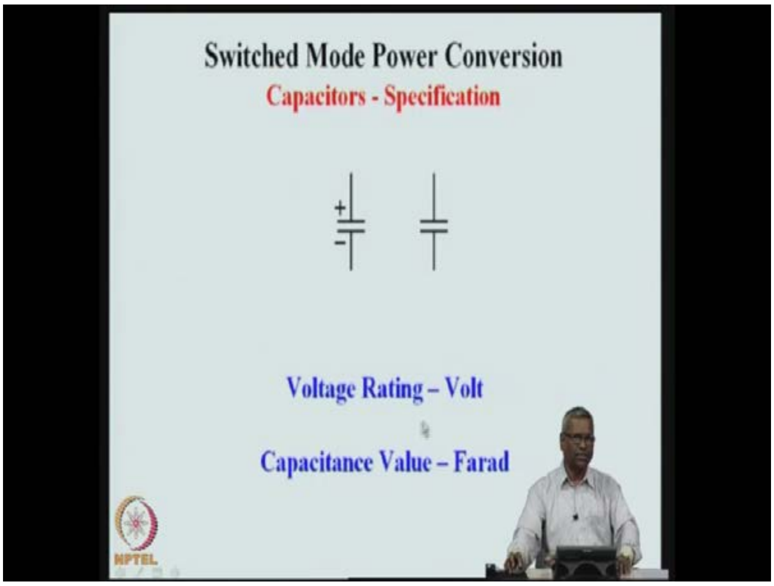

The capacitors are specified by their voltage rating and the farad value. The capacitor unit for capacitance is farad, when one coulomb of charge gives rise to a voltage difference between the terminals of 1 volt, that capacitance is defined as having a value of 1 farad; Q is C into V. Charge is the product of C into V or C is Q by V charge per volt. The 2 quantities which defines, which specify the capacitors of the voltage rating and the farad rating.

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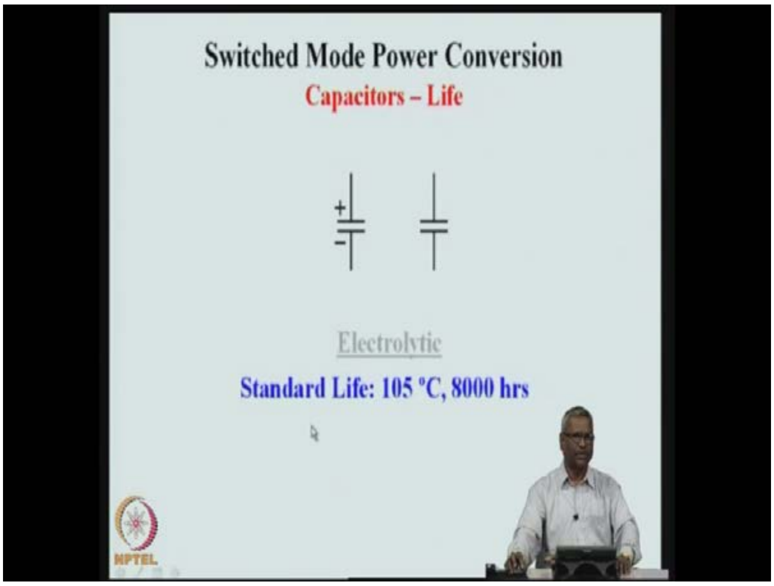

And unlike inductors are many other electronic elements, the capacitors many times suffer from limited life; specially, electrolytic capacitors have limited life typically, it could be about 8000 hours at 105 degrees and if the temperature is reduced, it is possible to have more number of hours of life.

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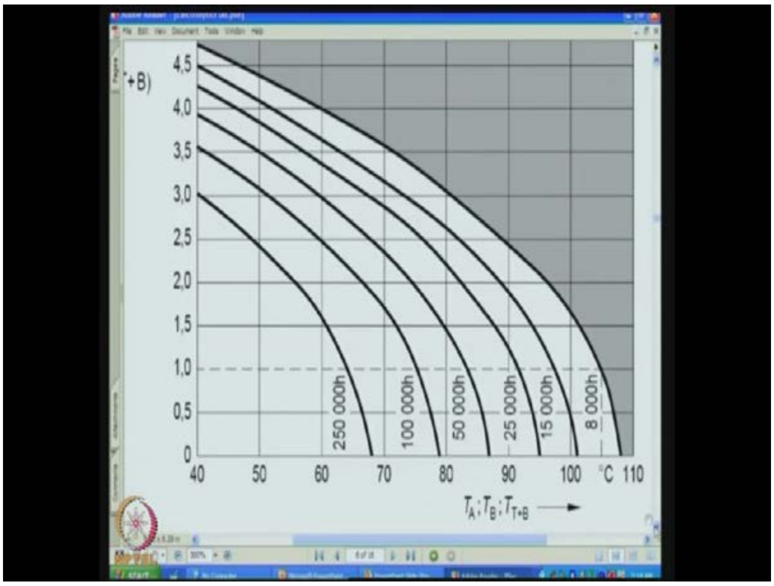

For example, here is a data sheet for capacitors and you can see that, what you see here is the life characteristics, when the specifications are as given in the data sheet. One is 1.0 normalized specification at a temperature of 105 degrees gives a life of 8000 hours. So, typical 8000 hours is about 1 year of continuous operation, 1 year of life and that is a satisfactory number and if you operate at 60 degrees or 40 degrees it is possible to get higher life's 100 thousand or 200 thousand so on.

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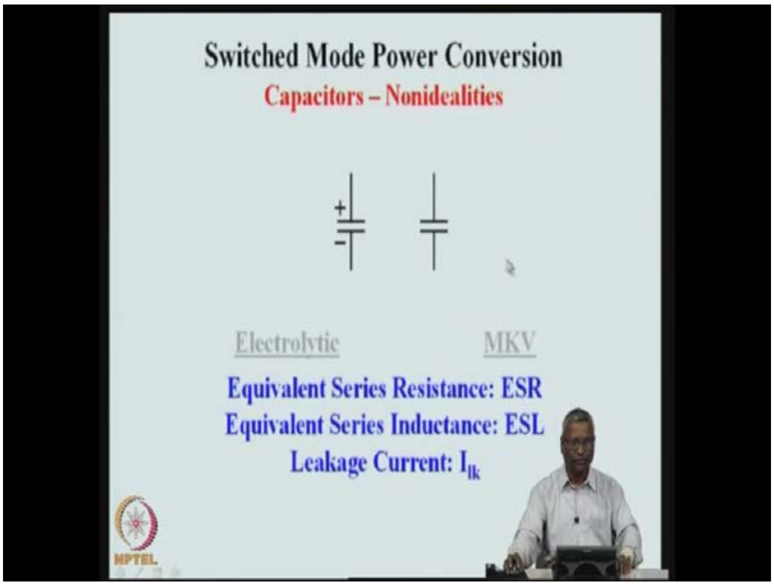

In a real capacitor other than the voltage rating and the capacitance ferrites. There are number of other the non ideal quantities that are involved. And what I have shown here are 3 non idealities associated with capacitors. One of them is called the equivalent series resistance ESR, another one is called the equivalent series inductance ESL and the third one is a leakage current high leakage. In a capacitor under DC excitation there should be ideally no current flowing from the positive to the negative terminal. The current through a capacitor for DC has to be 0. But, in a real capacitor on account of the ohmic leakage paths between the electrodes through the dielectric or through the surface of the dielectric, there is some small leakage current flowing and that is one of the non idealities in the capacitor, a small leakage current.

Another non ideality is that because the current is passing through conductor and lead to the terminals and similarly, from the terminal taken to the other plate of the capacitor taken to the terminal. It is necessary to establish a current path from the terminals into the capacitor. And we know that every current path has an associated magnetic field and on account of that every current path will also have an associated equivalent inductance. This series inductance which is known as ESL is associated with the conducting path of that. And in the same way, every conducting path when current is flowing will result in a voltage drop proportional to the current and that part of the non ideality we call it has equivalent series resistance.

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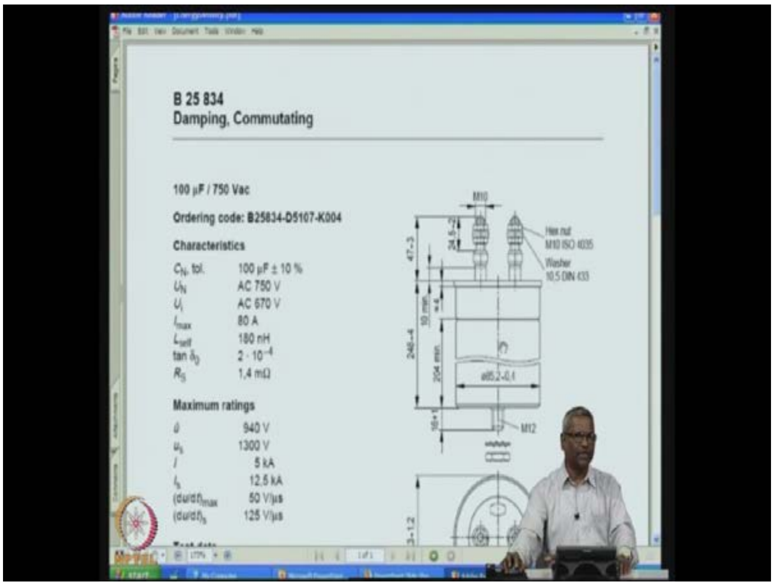

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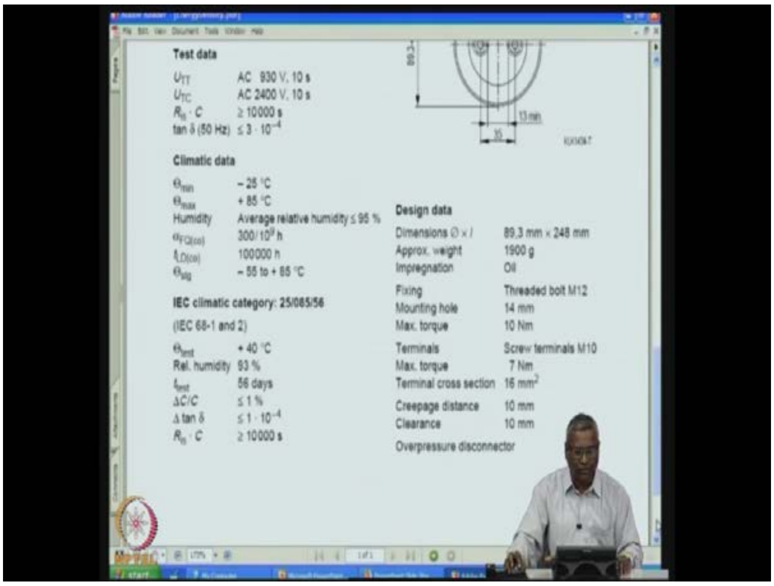

For example, if you take the capacitor specification of this one, you can see that there is a self inductance which is a same as LESL 180 nano henry and it has a series resistance R S shown here as 1.4 milli ohm. So, this ESL and ESR are the series resistance and the self inductance or the non idealities that is associated with every with every capacitor.

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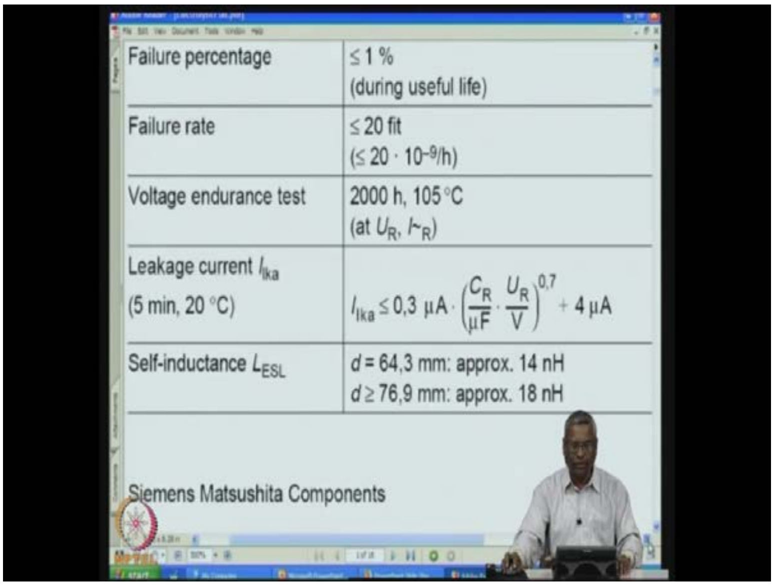

If we look at the data sheet of the electrolytic capacitor it is possible to see that as, at 20 degree centigrade there is a leakage current associated with the capacitor which is not very high but, it is there it is about micro amperes. 4 microamperes multiplied by a variable quantity which is proportional to the capacitance value. And the ESL is also given for this self inductance LESL for different packages: 14 nanohenry or 18 nanohenry.

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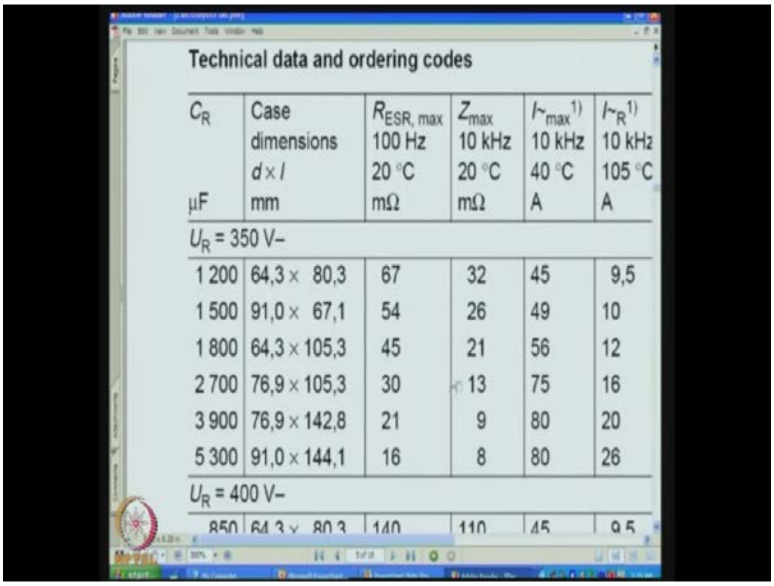

And in the same way you will see that there is an associated ESR also at 100 hertz, at 20 degrees. Most of these capacitors have certain milliohms what you see here in this column 5300 micro farad capacitor which is rated for 350 volt DC, has an equivalent series resistance at 20 degrees centigrade which is 16 milliohms. These are small resistance but, certainly they are there and associated with that there will be losses also.

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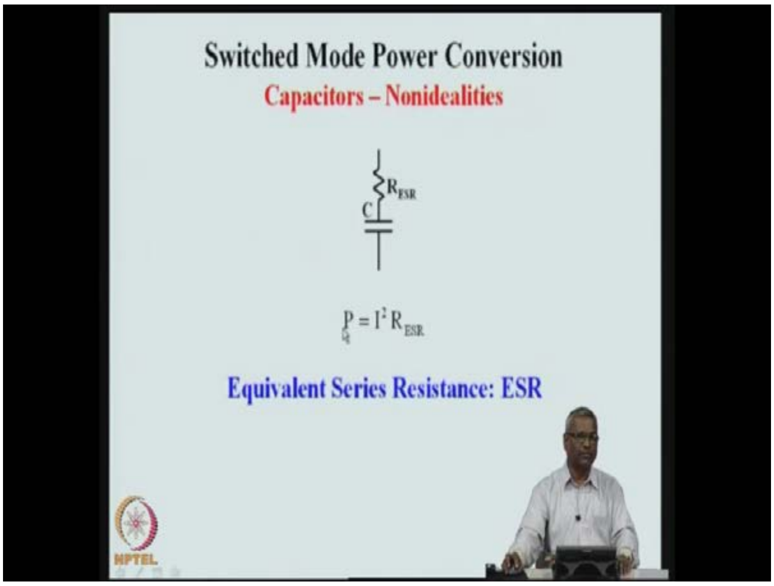

The consequence of this ESR is the loss in the capacitor on account of the current that is flowing. The AC current or the ripple current that flows into the capacitor and this ESR produce a power loss which is I square into ESR resistance.

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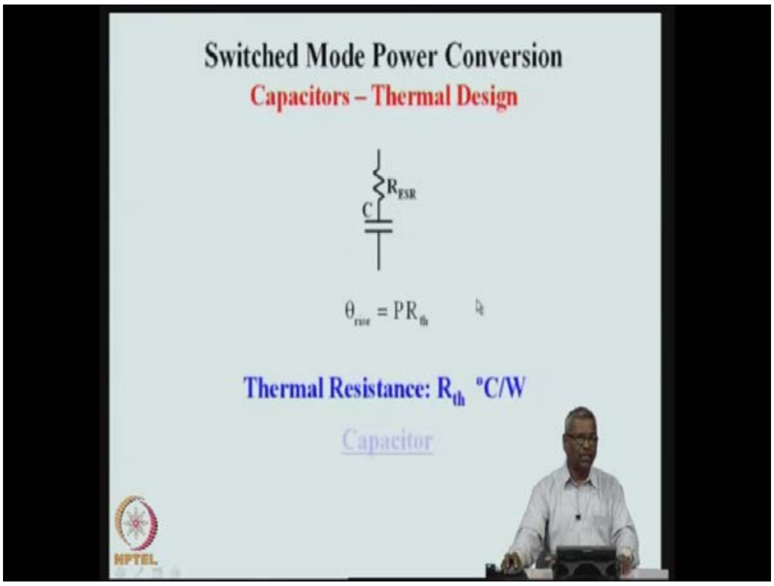

This loss is also going to result in temperature wise inside the capacitor. If the capacitor has certain thermal resistance which is in degree centigrade per watt and depending on how much power is dissipated on account of this ESR, the power dissipation multiplied by the thermal resistance will result in the temperature rise of the dielectric material inside the capacitor. And if this temperature rise is to highly then, the capacitor will fail. So, it is necessary therefore, to make sure that we do not dissipate more power then what is safe for that. Let us see in this data sheet, probably we will see the power dissipation limits.

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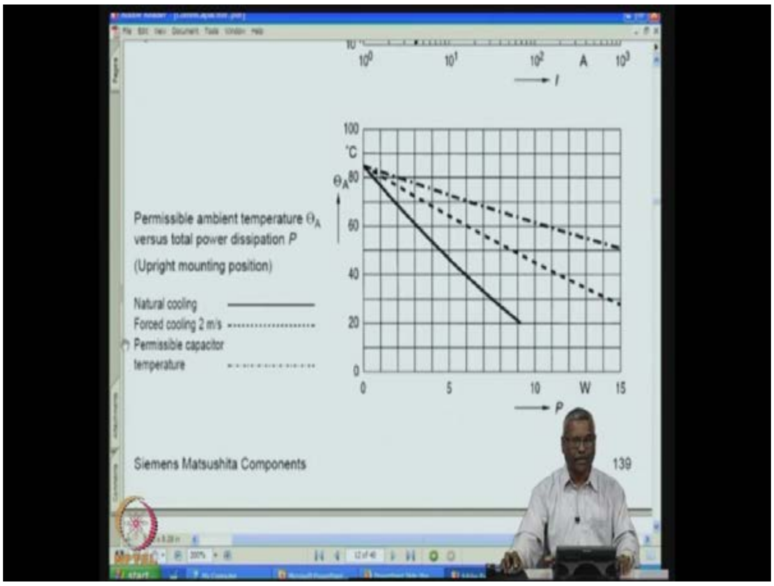

So, you can see here in this particular data sheet; the ambient temperature on one side and the power dissipation on the other side. So, this capacitor it is possible to dissipate about 9 watts, 9 watts of power at an ambient temperature of 20 degree centigrade. And at an ambient of 45 degrees, the power dissipation can be only 5 watts. And at an ambient of 85 degrees, you cannot dissipate any power at all. So, this line is the power dissipation characteristics for natural cooling. So, what you see here on this site is for natural cooling and if you use fans for forced cooling, it is possible to dissipate more power in the capacitor. And the kind of relationship is what we had seen that, the temperature rise is a related to the thermal resistance multiplied by the power dissipation in the capacitor.

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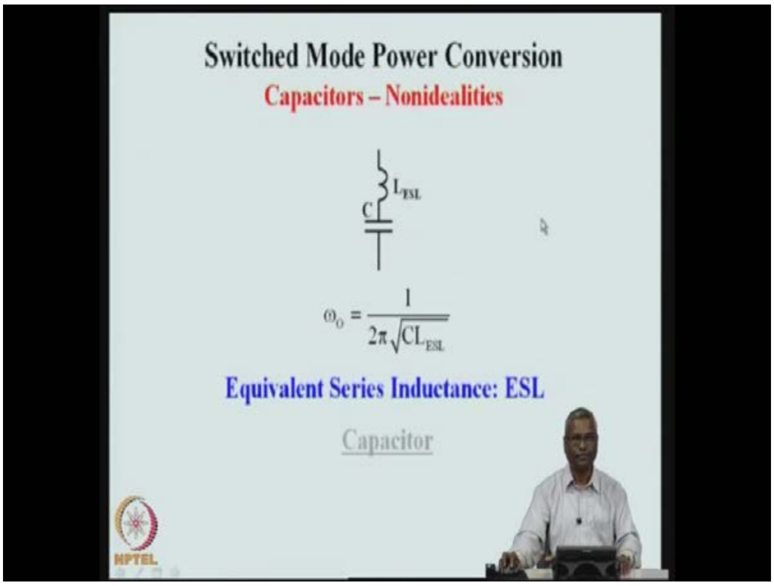

The ESL has a different consequence in the capacitor on account of the self inductance, the capacitor and the self inductance can form a resonant circuit and this resonant frequency is 1 by 2 pie root C into L, this product. So, on account of this inductance you will find that as you go to higher and higher frequencies, there is a resonance in the circuit which can give rise to damage to the capacitor or if you go beyond the resonant frequency the complete element will behave only like an inductance and these are also bad things if you try to use a capacitance at too higher frequency, the ESL will not allow that capacitor to function purely as a capacitance and it will have a number of side effects which are not very advantages.

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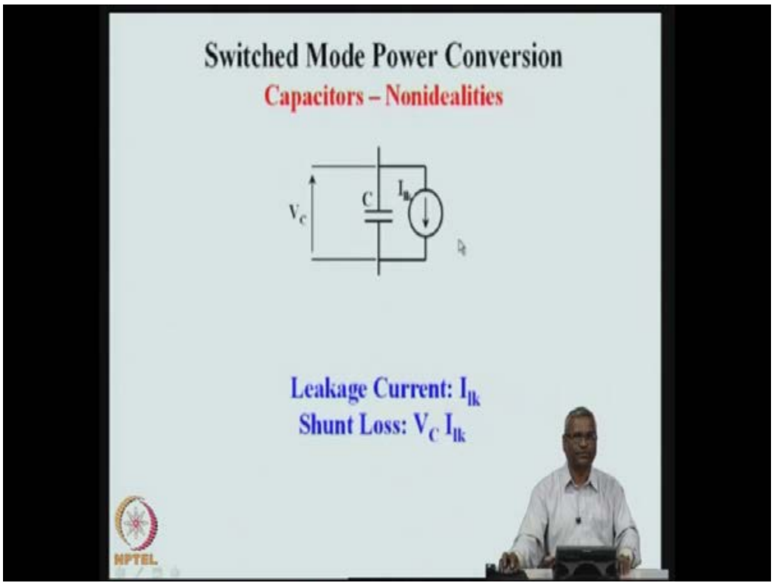

The leakage current can be shown as a shunt loss. Normally, the loss is not very heavy. We will see later, what is a more major consequence of this leakage current. So, these are the 3 major non idealities equivalent series resistance, equivalent series inductance and the leakage current.

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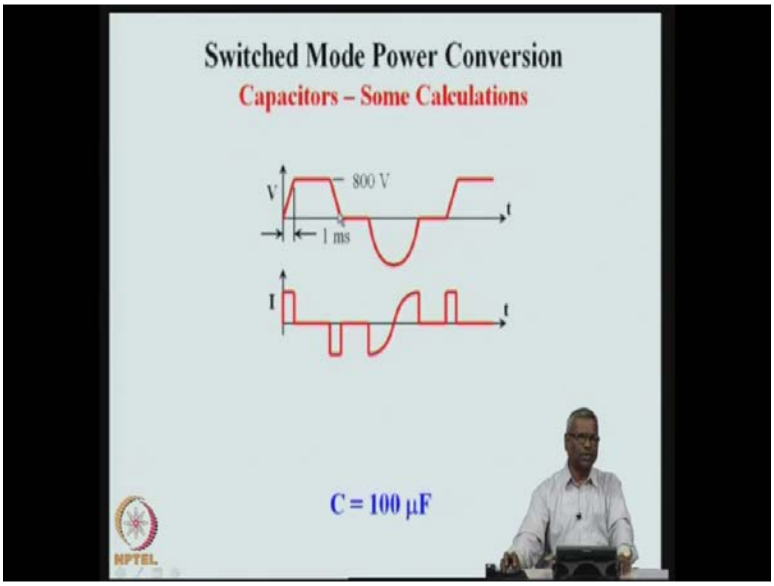

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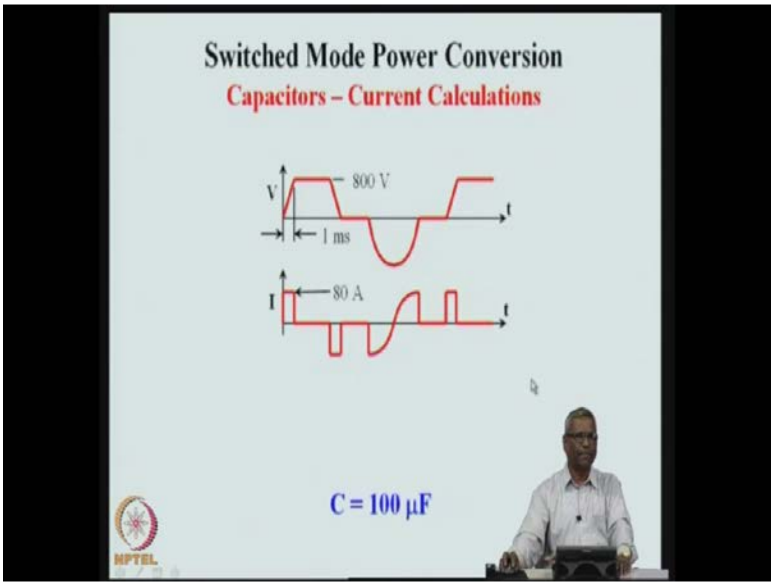

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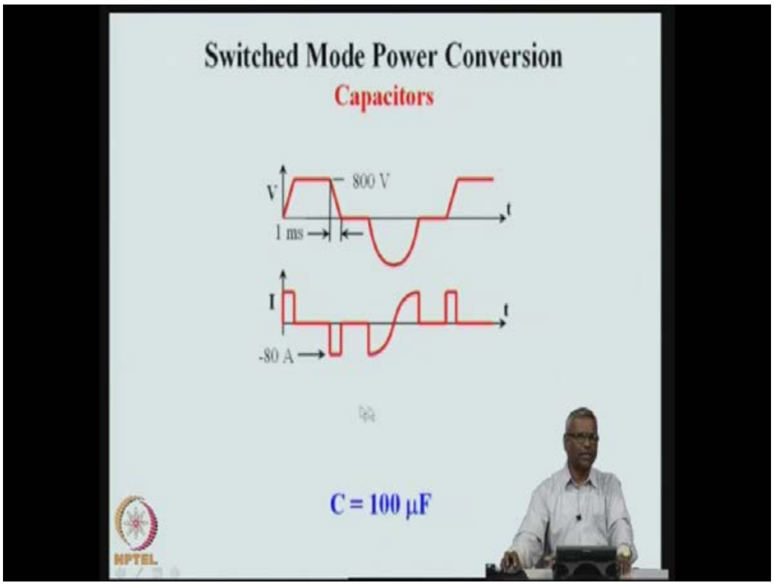

We come back to the same kind of wave form. It is possible to work out the numbers convert this voltage wave form into the appropriate current. If the capacitance is 100 microfarad a 800 volt rise in a time of 1 millisecond will give rise to a current here at this point which will be C into d v by d t, d v by d t is 800 volt per millisecond multiplied by 100 microfarad will give us a current which is about 80 amperes positive. And during the time here, the current is 0 and similarly, during the fall time the current is minus 80 amperes because a current is falling down.

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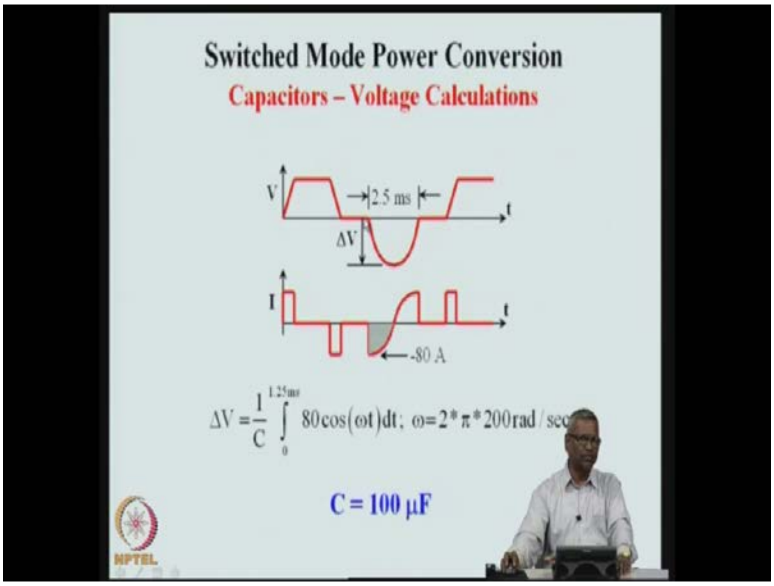

And if you come to the next section where, the current is sinusoidally changing, the voltage is sinusoidally changing; the current is now a cosine. The peak I have taken as minus 80 amperes. So, we can work backwards to find out what will be this maximum voltage. We see that that voltage is the maximum voltage accumulated on the capacitor is nothing but the charge that is accumulated on the capacitor from instant, from this instant to this instant which is 1 half of this sine time, which is about 1.25 milli seconds. So, in a time 0 to 1.25 millisecond, how much is the charge which is the area of this figure, that area can be mathematical calculated? 80 cos omega t d t integrate from 0 to 1.25 millisecond and divided by the capacitance value and this number is 637 volts.

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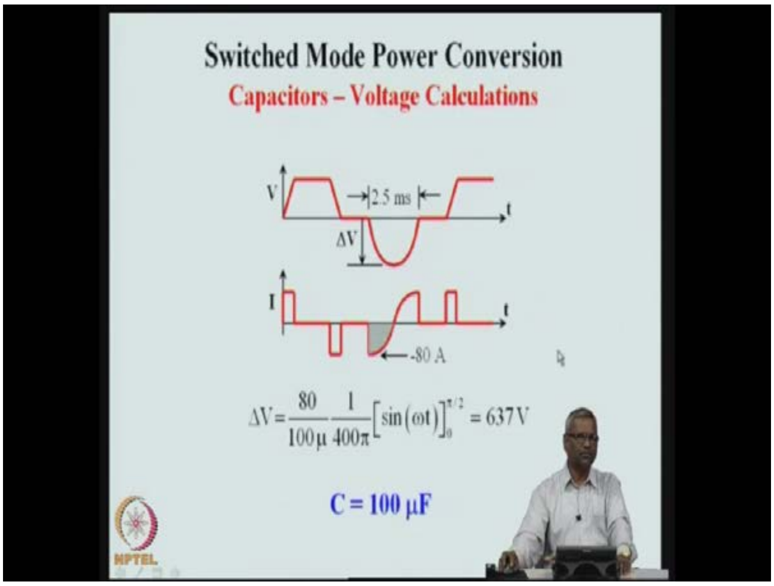

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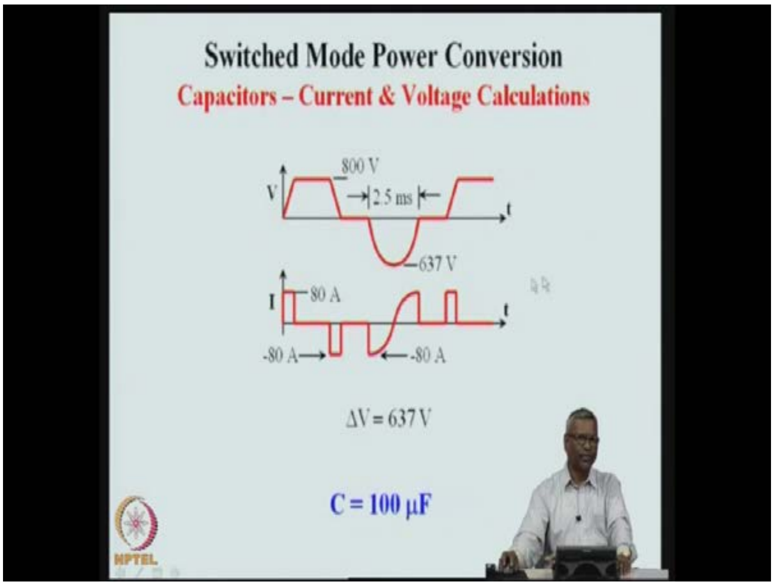

So, what we see is that the voltage accumulated in the capacitor for this current is 637. And then, during the next portion the current reverses and this 637 is lost and the voltage across the capacitor comes back to 0 and continues till the end of the cycle, after that the cycle repeats.

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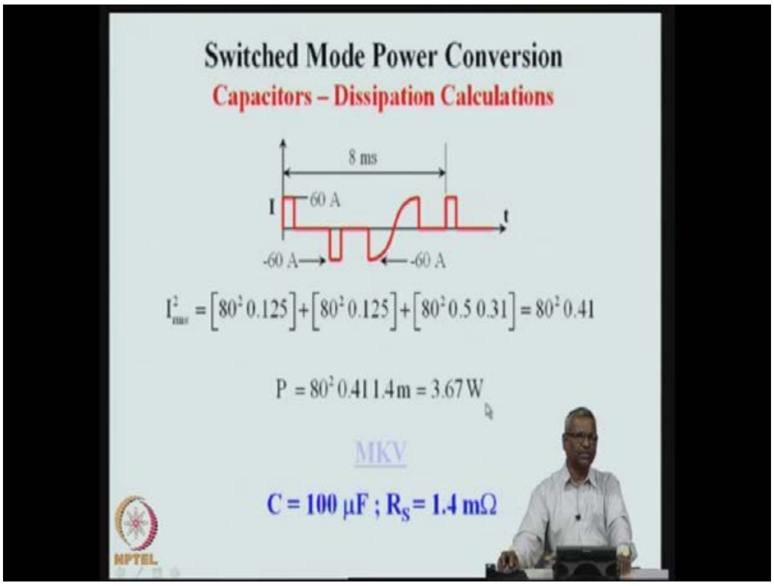

So, in this particular situation we can find out, what is the dissipation in the capacitor by finding out all the RMS currents and multiplying it by the ESR. ESR of this capacitor is 1.4 milliohms and that has to be multiplied by the RMS over one cycle, over 80 millisecond cycle we find out RMS contribution on account of the current. Here, this must be 80 amperes; 80 and minus 80. 80 square into 0.125, 1 eighth of the cycle. 80 square into 1 eighth of the cycle then, this sinusoidal 1. If it is a pure cosine or sine it will be 80 square into 0.5 will be the RMS square. But, this is only over a period of 2.5 millisecond which is 0.31 times 8 millisecond. So, this quantity now turns out to be 80 square into 0.41 that is the, I square RMS that multiplied by the equal and series resistance gives a power dissipation of about 3.67 watts.

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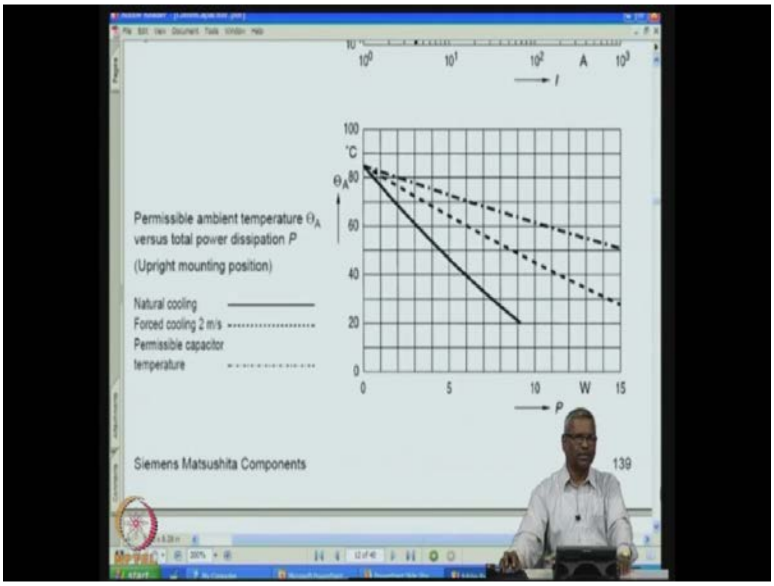

So, for this particular capacitor the power dissipation can be as high as 9 watts on 20 degrees or about 5 watts at 45 degrees. And the dissipation that we see here in this example is about 3.67 watts and that is not a very bad thing. We are well within the limits of the dissipation of this particular capacitor. And this is the way one goes about finding out how much power dissipation takes place in a capacitor.

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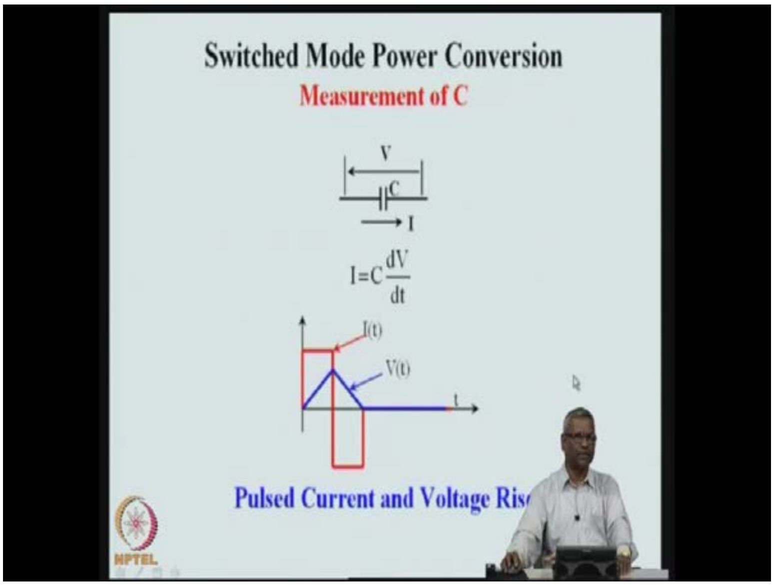

How do we measure a capacitor? The measurement of a capacitor can be done following the same kind of relationship, current is C d V by d t. So, if we apply a current to charge the capacitor and discharge the capacitor, a constant current will give rise to a charge in the capacitor which linearly increases, which is some peak and a negative current will discharge the capacitor back all the way to 0. So, if it is possible to set up a circuit in order to charge a capacitor with known amount of current for a known duration and measure the voltage across the capacitor then, using this relationship of I is C into d V by d t it is possible to measure the capacitance. So, many times this will be very necessary to measure the value of the capacitance. The reason is the value of capacitance as given in the circuit. Let us go back and see some of the data sheets and we will see that. So, we see that this is one simple way of evaluating the capacitance by supplying some current and finding out in a known time how much voltage has been picked up.

A typical capacitance values change by as much as plus minus 30 percent. If you buy a 1000 microfarad capacitor, it could be anywhere between 700 microfarad to 1300 microfarad. Because, the manufacturing processes are not very well controlled or stable. The typical tolerance on the value of capacitance can be plus or minus 20 percent. And so, it may be necessary that in many cases even though you know the value given on the label, it is better to cross check and see, what is the value of the capacitance. And a circuit of this nature can help us to measure the value of the capacitance.

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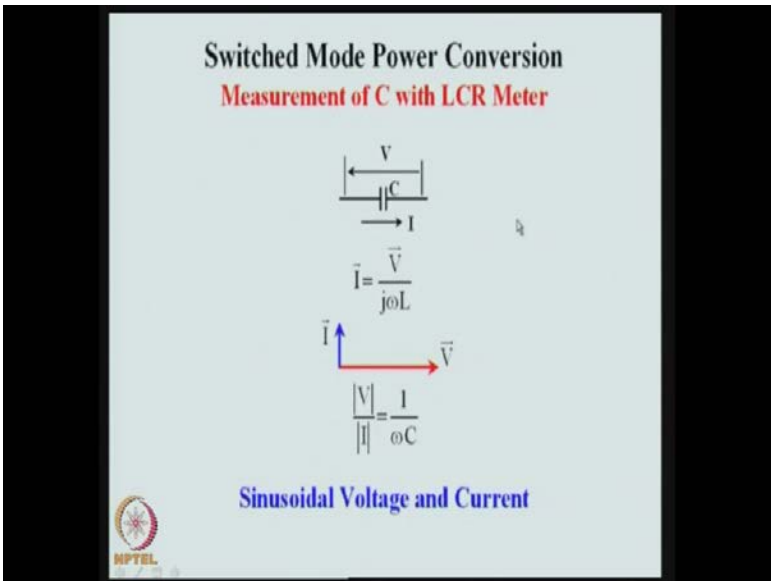

There is also another way of measuring the capacitance which is the measurement through LCR meter. Just like the inductors which are used for which are measured with

LCR meters, capacitor measurement using LCR meter uses the principle of sinusoidal excitation supply a certain high frequency voltage to the capacitor and measure the current flowing through that which is at 90 degrees. Now, this process of measurement normally will work with some small amount of current and at different frequency. In many cases the frequency can be different from the frequency at which we use the circuit and so on.

So, the measurement of C with an LCR meter, even though it is useful it is not a very dependable number. It will give a number which is the small signal capacitance or not the kind of charge by V at the operating conditions. So, it will be better to make the measurements following this method when you are in doubt. The LCR meter is one method of a making the measurements.

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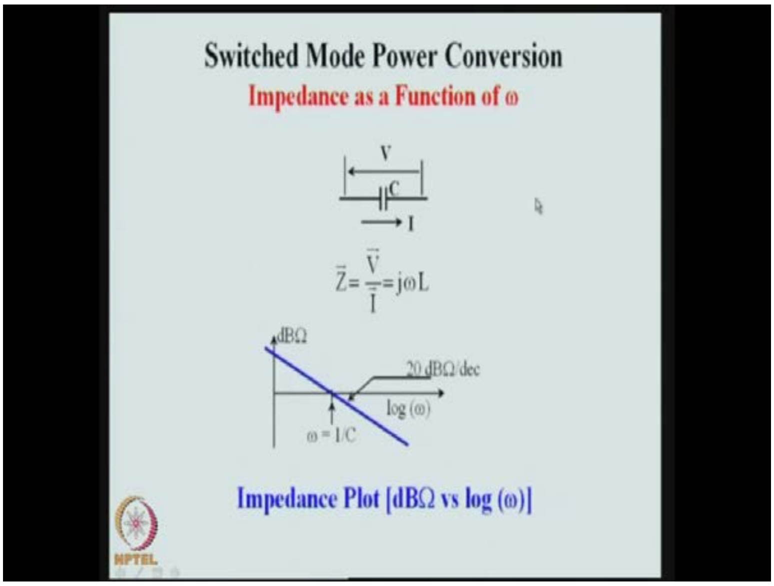

Just in the case of inductance, a capacitance also can be seen as an impedance and we see that the capacitive impedance V by I, it must be 1 by J omega C. It is not j omega L; it must be J omega C. And as a function of frequency the capacitance keeps dropping. If it is capacitance, the impedance is 1 by J omega C and it keeps dropping with frequency with the slope of 20 dB per decade, drop is minus 20 dB per decade. And the frequency at which the impedance is 1 ohm will be omega equal to 1 by C. This is the impedance plot dB ohm versus log omega; we had seen a similar kind of curve for the inductance. This would be the ideal impedance curve for a capacitance. When we have a netwok analyzer, it is possible to measure the impedance is a function of omega and then, also find out the value of capacitance.

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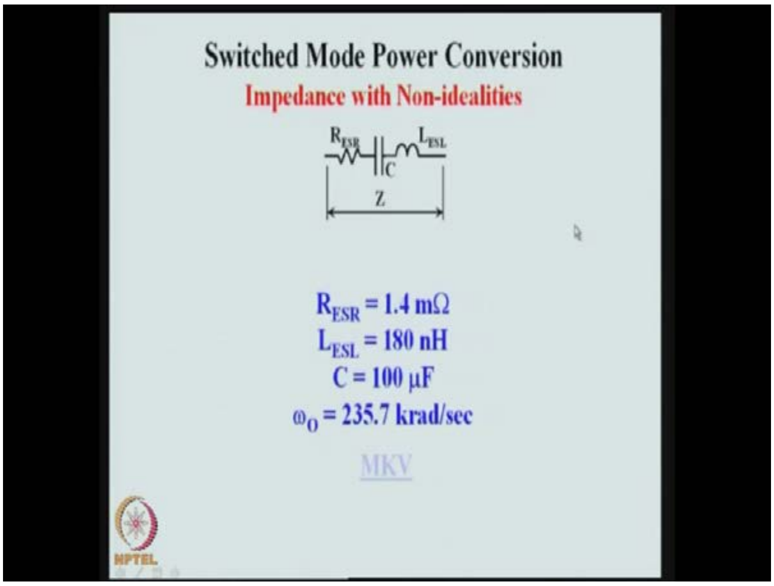

Let us look at a typical capacitance that we had seen here, we saw the data sheet of this capacitor. It has 118 nanohenry is the self inductance, 1.4 milliohm as the resistance and 100 microfarad as the capacitance. And those are the numbers that we see here, R ESR is 1.4 milliohm; L ESL is 180 nanohenry; the capacitance is 100 microfarad and if you calculate the natural frequency with these values of L and C it is about 235 kilo radiant per second, 1 by 2 pie root of L and C that frequency is 235.7 and the unit for that is kilo radiant per second.

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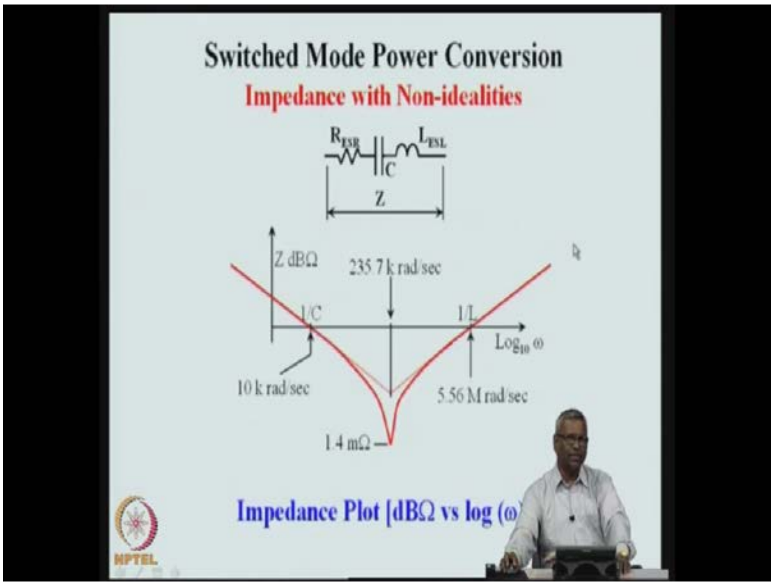

Now, if we plot this is a function of frequency, you can see that at very low frequencies this is open circuit because, the capacitance is open circuit at low frequency and so you will find as you go to lower frequency the impedance goes to infinity. But, at the lower current this behaves like a capacitance. So, with increasing in frequency impedance keeps falling and this fall is with minus 20 dB per decade, the slope of this. And where this goes through 1 dB ohm that is 0 dB ohm which is equal to 1 ohm is when omega is 1 by C. And in this particular case C is 100 microfarad. So, 1 by C is 10 kilo radiant per second. So, at an angular frequency of 10 kilo radiant per second this capacitance has a impedance of 1 ohm. And on the other hand when you go to very high frequency this behaves like an inductance and this capacitance being a short and this R ESL being a very small 1.4 milliohm this behaves like an inductor and you see that the high frequency impedance is increasing, increasing with frequency with plus 20 degree per decade. And again, there is 1 ohm impedance on this part of the characteristics is when 1 by L is the impedance. L is 180 nanohenry in this particular example. 1 by 180 nanohenry is 5.56 mega radiant per second.

So, at that frequency also the impedance is 1 ohm, at 10 kilo radiant per second also it is 1 ohm, at this frequency the capacitance is contributing to the impedance and the inductance is practically short circuit. And at this frequency, the inductance is contributing to the impedance and the capacitors is a short circuit and in between 1 by root L C which is the natural frequency 235.7 kilo radiant per second which is resonant frequency of this capacitance, that is when the circuit resonates and the impedance becomes minimum. The inductive reactance and the capacitive reactance cancel each other and terminal impedance is just R ESR which is 1.4 milliohm. So, if you know plot the terminal impedance of this device which consists of a resistance, a capacitance and inductance; it will be following linearly at minus 20 dB per decade, passing through 1 ohm at 10 kilo radiant per second and then, reaching a resonance or the minimum frequency at 235.7 kilo radiant per second, having a value 1.4 milliohm and as you go to still higher frequencies impedance keeps increasing because of these impedance inductance and at 5.56 mega radiant per second this reaches is again 1 ohm and then, it keeps increasing. Now, if you see this curve is very easy to see that at the low frequency the impedance behaves like a capacitance; at high frequency the impedance behaves like an inductance and there is resonance in between, there is a resonance at this natural frequency.

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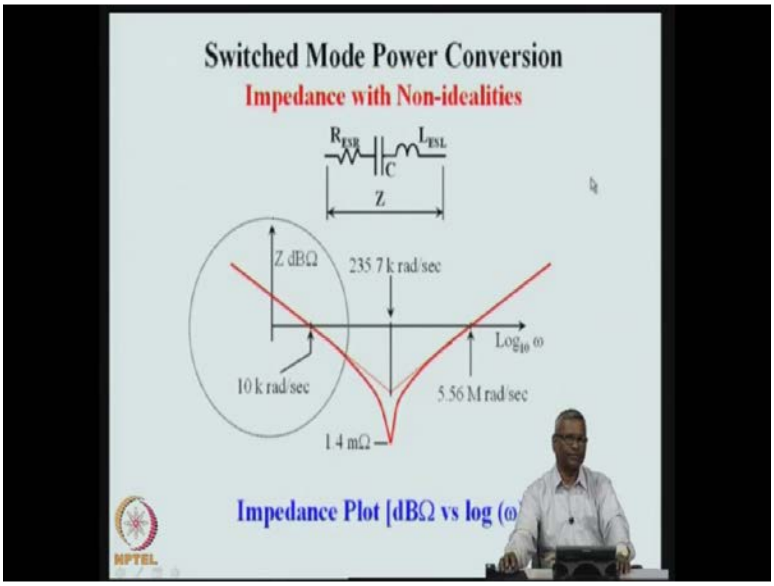

Now, it is possible to now identify a region where the capacitive impedance as calculated by 1 by omega C and as seen from this composite element is very nearly equal at any other point. See, ideal capacitor will have a capacitance which is falling linearly all the way down. But, you can see that the impedance of this what we see here and the ideal 100 microfarad capacitor are very nearly the same with respect to each other, only in this frequency range. I have marked circle here. So, probably up to a frequency of somewhere between 10 kilo radiant and 235 kilo radiant we might probably take it is somewhere around 100 kilo radiant. Only in that range this is a satisfactory capacitor beyond that range the non idealities become dominant and they do not allow you to use these capacitors successfully. So, this impedance curve is a very very powerful method of finding out, what is a useful range of a capacitive, useful range of operation.

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Now, there are few safety features one has to worry when using capacitors because the capacitors hold charge and the charge holding can be forever. Because the leakage current being so small this discharge time constant of a typical capacitance is about 10,000 seconds is almost 3 hours. So, even after you have removed capacitor from the circuit, even 3 hours after have remove the capacitor, you might still have about 30 percent of the charge left on the capacitor. And if without meaning to unintentionally if you short circuit the terminals it can give rise to a big spark and a fire accident.

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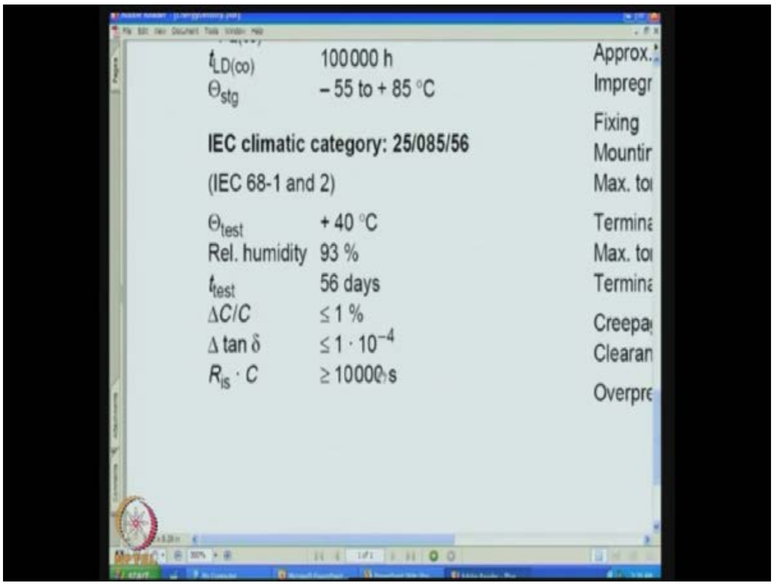

So, you can see that this MKV capacitor has a time constant which is of the order of R S into C is greater than 10,000 seconds. What you see the bottom most line; yeah, this is the bottom most line that it has a time constant of 10,000 seconds which is what is equal to about 3 hours. So, it is very necessary that one has to be very safe while working with capacitors, even when the circuit is not connected it is possible that capacitors may be carrying charge because of what they had taken will they were previously energized. So, it is necessary to wait for sufficiently long times are have appropriate circuits to discharge the energy in the capacitor. This is a very very important safety precaution while you are working with capacitors.

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Many times you may buy capacitors from the market and you are voltage rating may not match with what you want and it may be necessary to operate this capacitors in series in order to obtain higher voltage ratings. You can easily obtain higher voltage rating by connecting the capacitors in series. All that one has to take care is that the voltage sharing between the capacitors is proper. Now, for that purpose it is necessary to use resistors across the capacitors known as bleeder resistors.

Normally, we will use a bleeder resister which will draw a current through them which will be a enough few times more than the internal leakage resistance so that, the voltage division is now decided more by the bleeder resistor and not by the internal leakage resistance. And this is one way of ensuring that the capacitors share the voltage properly. And this is an additional loss in the circuit on account of that builder bleeder resistor you will have additional losses. A typically electrolytic capacitor we had seen had; let me see the current, how much was the leakage current.

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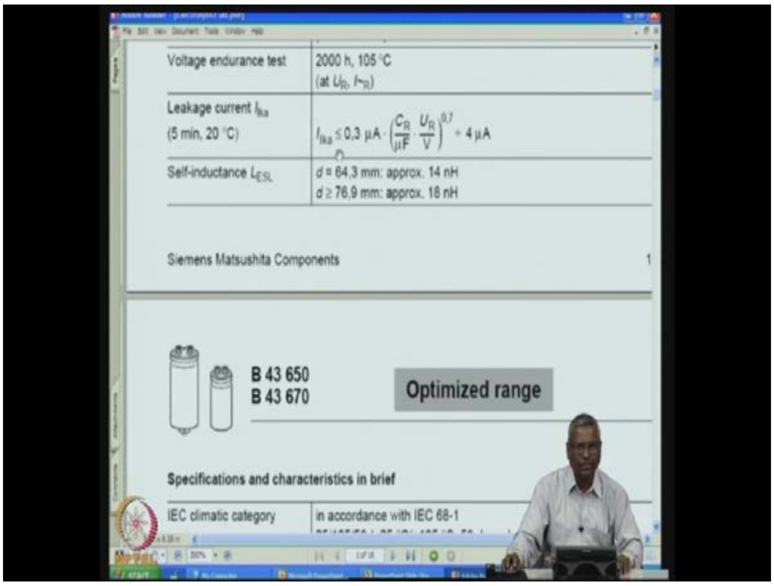

We saw that leakage current of the order of 4 microampere plus some number. So, invariably this 4 microampere is a more dominant quantity when the capacitor value and its microfarad rated voltage and the operating voltage all these are fitted. Probably leakage current will be very close to 4 microamperes or maybe a little more than that.

This is a small current because it is a very small current this can give rise to large unbalance in the voltage that is shared when they are using in series. So, on account of that it is necessary to use what are known as bleeder resistors across the capacitors. Make sure that voltage sharing is proper.

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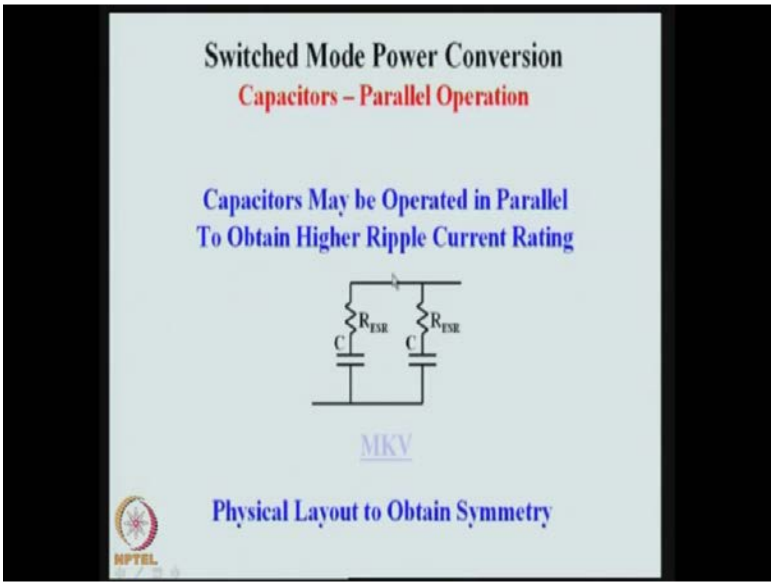

In the same way if you are using capacitors for large current applications, it is necessary to connect several of them in parallel. A single capacitor may be capable of taking only about 40 or 50 amperes of RMS current and if our application demands of 500 amperes of RMS current, we may how to connect several of them in parallel in order to reach the requirement. When capacitors are connected in parallel one more precaution essential is that the high frequency currents are now going to be decided by the ESR values. So, the ESR values as per the catalog may be equal but, if your connection has non-ideal contact resistances or the conductor resistances, it is necessary to make sure that those paths are also identical.

For example, if you connect an external connection coming from here to the capacitor back here and then, next capacitors is connected from here to here, you will find that for the external current that is coming from the left hand side, the first capacitor R ESR is only what is given in the data sheet. But, for the second capacitor it is a capacitor resistance plus the track resistance here, plus the track resistance here. This can give rise to problems. So, that is the reason when you connect them in parallel it is necessary that the physical layout has to be done so that the symmetry is not lost. For example, we will feed in from this point and feed out from this point so, this parasitic resistance and this parasitic resistance, one will come in series with this capacitive, one will come in series with this capacitor so that both of them are equal.

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Yeah, we have seen most of what is needed for capacitors and with this we have seen the devices that are essential for power converters. And from here, we will move on and then, in the next few lectures try to cover some problem sets covering all these materials. And I am going on to circuits which use the devices in order to do the carry out the function of power conversion.

Thank you very much.