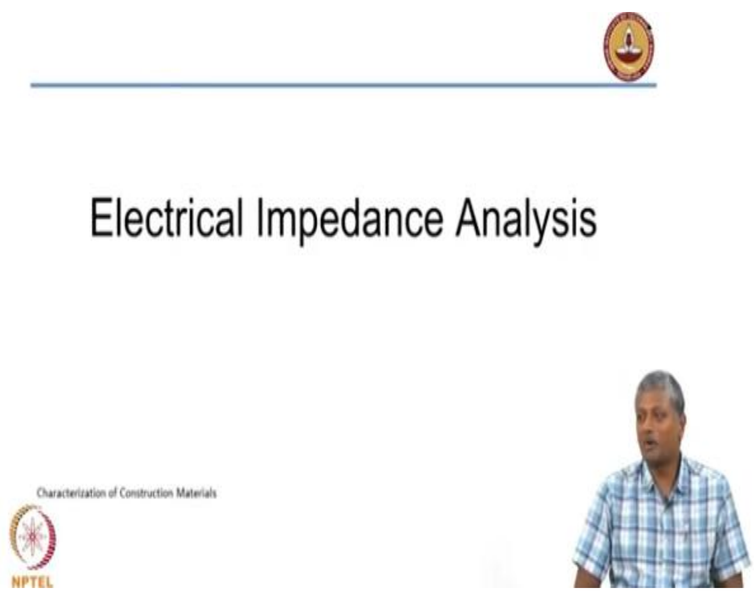
**Characterization of Construction Materials**
**Prof. Manu Santhanam**
**Department of Civil engineering**
**Indian Institute of Technology, Madras**

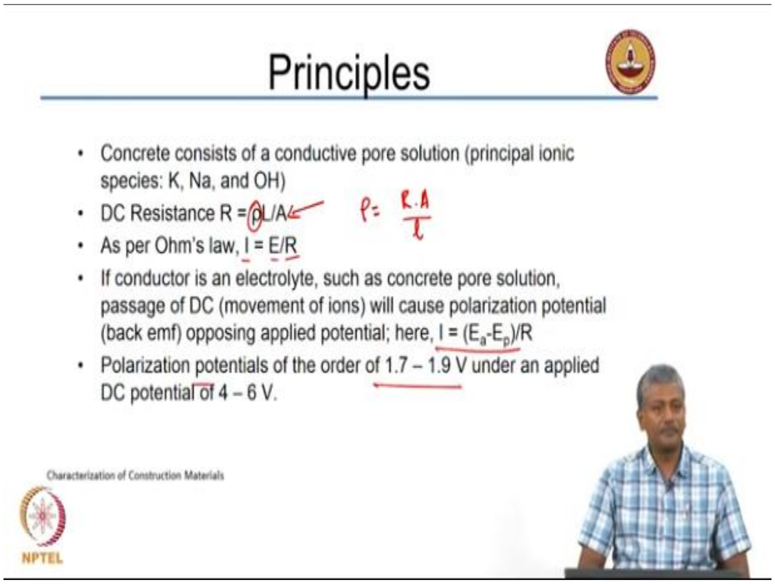
**Lecture -62**
**Principle and different methods - Part 1**

**(Refer Slide Time: 00:12)**




So welcome everyone today we will talk about Electrical Impedance Analysis which is the last technique that we will undertake in this course. Now electrical impedance is used in many different fields and very commonly in electrochemistry, especially with studies involving corrosion. With concrete you can go beyond just studying corrosion, you can also look at how the electrical properties of concrete are defining the pore structure and the pore connectivity on the concrete, and that remains a very useful information that you can actually get about the durability of the concrete itself. So let us look at these techniques on electrical impedance.

**(Refer Slide Time: 00:52)**




So just first let us look at some basic principles that you might have learned before in science. Now concrete itself consists of a conductive pore solution, you know that concrete has some porosity, many of these pores are connected and depending upon the degree of saturation, the pores inside concrete will mostly be filled with water, sometimes in dry conditions you do not really have water filling the porosity. But it is not just plain water that is filling the pores, it is a pore solution that is caused because of the dissolution of certain species from the cement and primarily these are alkaline species like sodium and potassium and to create a balance in the pore solution, you always have hydroxyl ions also in the pore solution.

So if you take a mature concrete and you are able to squeeze out the pore solution in the methodology that we discussed earlier, the only ionic species that you will find in any appreciable concentration would be sodium, potassium and hydroxyl. Now of course you have learned before that the presence of ions in a liquid will tend to increase the conductivity or charge carrying capacity of the liquid. So, if you study the electrical properties of concrete, it will give an indication first of the ionic strength in your pore solution. And secondly, on how connected your pore solution or pore network is, because concrete itself is an insulating material. The solid phase in concrete does not transmit charge it is only the pore structure, interconnected porosity that can transmit the charge. Of course, if it is dry concrete again it will not be able to transmit anything because water is not available to carry the charge. And the fact that you have ionic species dissolved in water allows the conductivity across a path within the concrete.

So what we generally tend to apply whenever there is electric charge transfer through a system involved, is a typical assessment of the resistance to flow. Resistance to flow is given by a material parameter which is we otherwise call as resistivity (ρ) which is a material parameter and of course you also define the path of flow and the area through which the flow is actually occurring by multiplying by the length (L) and dividing by the area (A). Or in other words the resistivity (ρ) is equal to:

$$\rho = \frac{RA}{L}$$

Where R is the resistance.

Now you know very well about Ohm's law which relates the current (I) to the potential difference (E) and the resistance (R).It is given by:

$$I = \frac{E}{R}$$

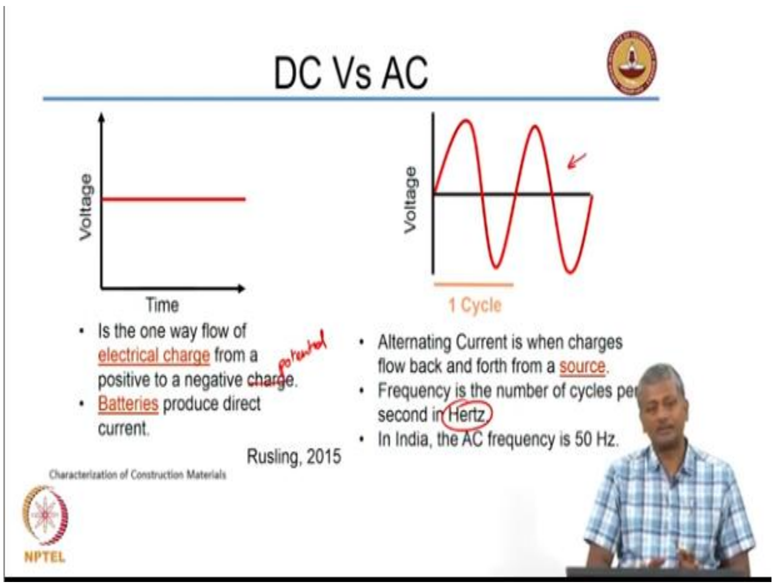
Now what happens is if the material that is conducting happens to be an electrolyte like the pore solution in concrete, you may actually have some sort of a polarization effect, that means you will have charges building up on either side and not really distributed evenly through the pore solution. So if you apply a direct current keeping one end at a positive potential and the other at a negative potential, what will happen is because of these ionic species inside there will be alignment of the negatively charged ions close to the positive potential and positively charged ions close to the negative potential. So in other words because of this effect of polarization what is actually happening is a reverse potential is actually created by your polarized material. So you have an applied electric potential ‘E’ (or $E_a$) and you have a reverse potential that is generated because of polarization it is also called the polarization potential ($E_p$). So here your current should be calculated as:

$$I = \frac{E_a - E_p}{R}$$

Of course this is only a very straightforward assessment of this entire situation, you will see later that it is a lot more complicated than just applying directly Ohm's law to this condition because you cannot take resistance as the only quantity which is impeding the flow of current. You need to actually start considering impedance when we talk about the use of alternating current to describe the structural property of the concrete.

Now, generally just to give an idea, the polarization potential can be as high as about 2 V for a DC potential that is applied of 4 - 6 V. So whenever you do a DC measurement, you have this error that is going to be built in into your system.

**(Refer Slide Time: 05:35)**

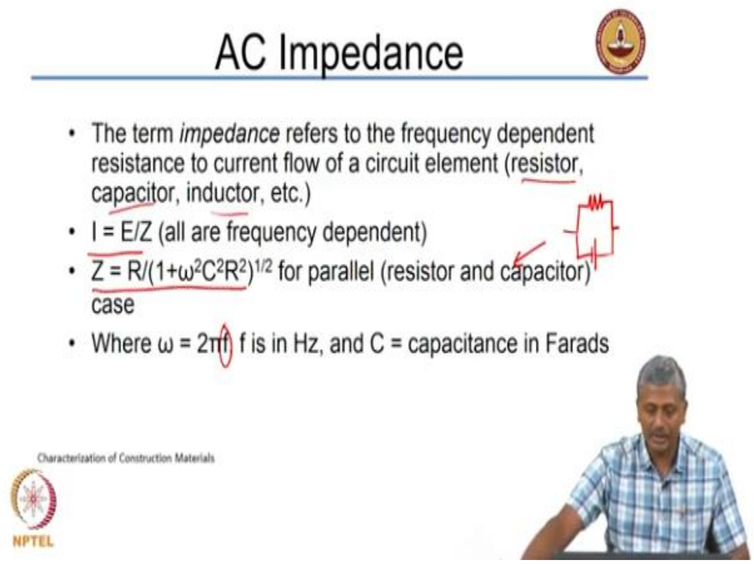



First of all how does DC differ from AC? Of course, you know this very well from your physics. DC involves only a one-way flow of electric charge from a positive to a negative potential (mistake in slide corrected from ‘charge’ to ‘potential’). So your direct current is produced in circuits which are done by your batteries for instance.

On the other hand what we commonly deal with in terms of the electricity that is supplied to households is AC or alternating current. So here you have the charge flow back and forth from a source, so since it is defined by a sinusoidal wave, you also have to look at the characteristic frequency of transmission of the alternating current and that frequency is typically measured in Hertz (Hz) just like any other frequency, so what we typically do is for an alternating current we need to specify the potential difference as well as the frequency of application of the AC.

So what is common as far as India is concerned with respect to your household electricity, how much voltage is typically given? 220 to 240 V and frequency of 50 to 60 Hz. If you go to the USA for instance, they may have a different voltage: 110 V systems are typically followed in the US and in Japan for instance. The frequency generally varies between 50 and 60 Hz in most countries. In India mostly it is 50 Hz.

**(Refer Slide Time: 07:14)**




So as I was saying earlier you cannot directly apply the use of resistance to study the impedance of the current through a system which has a solid phase and electrolyte phase you need to rely on a more useful characteristic that is called *impedance*. So impedance mainly refers to the frequency dependent resistance to the current flow within a circuit element. So current flow can happen through different types of circuit elements like resistors, capacitors and inductors - all of these as you have learnt in your basic physics have very different characteristics.

Now the simplified form or if you want to say the more complicated form of Ohm's law or a more generalized form of Ohm's law for an alternating current is written as:

$$I = \frac{E}{Z}$$

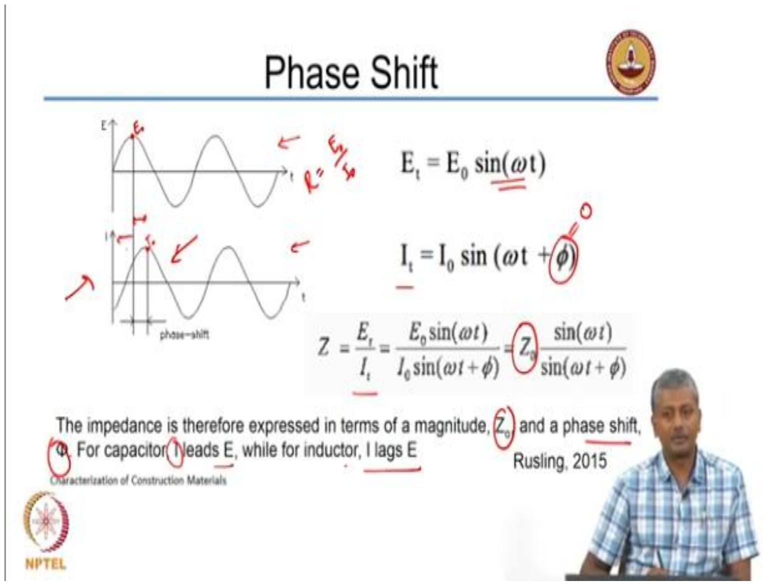
where Z is your impedance; and the calculation of Z will depend on the kind of electric circuit that you draw for your model. For example, for a parallel case of a resistor and a capacitor it is generally represented by:

$$Z = \frac{R}{(1 + \omega^2 C^2 R^2)^{1/2}}$$

Where C is the capacitance in Farads

ω is the angular frequency which is related to the frequency of the alternating current $f$ as ω = 2πf. But we will look more at these electrical circuits that can define the kind of systems that you are studying in just a few slides.

**(Refer Slide Time: 08:53)**




So first of all again one of the common aspects of understanding impedance is that the impedance is not always in phase with the current. You know very well about phase shift with respect to waves, you can have waves that are in phase or out of phase. So for the waves to be in phase you should have an exact difference of nλ between the wavelengths of the waves; any waves that are nλ apart will be in phase; if you have (nλ/2) they will be completely out of phase.

So exactly that is what is being shown here. This is the wave form that describes the potential with respect to time (E vs. t) and this is the wave form that defines the current with respect to time (I vs. t). So if you have to represent these wave forms in terms of sinusoidal functions your $E_t$ or potential at any given time is given as:

$$E_t = E_0 \sin(\omega t)$$

Where $E_0$ is the maximum potential; ω is the angular frequency.

Similarly the current ($I_t$) is given as:

$$I_t = I_0 \sin(\omega t + \phi)$$

where $\phi$ denotes the phase shift.

So, again impedance (Z) is given by:

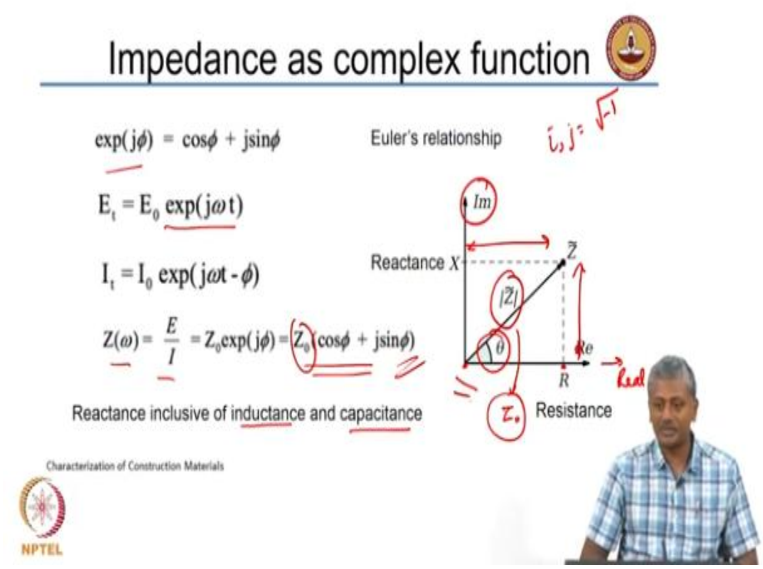
$$Z = \frac{E_t}{I_t} = \frac{E_0 \sin(\omega t)}{I_0 \sin(\omega t + \phi)} = Z_0 \frac{\sin(\omega t)}{\sin(\omega t + \phi)}$$

$Z_0$ is basically the magnitude of the impedance.

So the impedance is expressed in terms of a magnitude $Z_0$ and phase shift $\phi$. So you need two values to represent impedance $Z_0$ and $\phi$. Now if you have a plain resistor, your current and potential are perfectly in phase. For the case of a pure resistor, and that is why we say R= ($E_0/I_0$). In the case of a plain resistor you will have the current and your potential perfectly in phase because $\phi$ = 0 in that case. In the case of a capacitor your current will actually lead the potential, whereas for an inductor, current will lag the potential.

So if I have to draw this current diagram for a capacitor how will it be? I should start somewhere here (starting from above X-axis). In the case of an inductor - what is actually shown is for an inductor. So your current is lagging the potential - that means the $I_0$ will happen after the $E_0$ in the case of the inductor. And in the case of a capacitor, $I_0$ will happen before the $E_0$.

**(Refer Slide Time: 11:51)**




So impedance can also be represented on a complex plane by the use of these Euler relationships.

$$\exp(j\phi) = \cos\phi + j\sin\phi$$

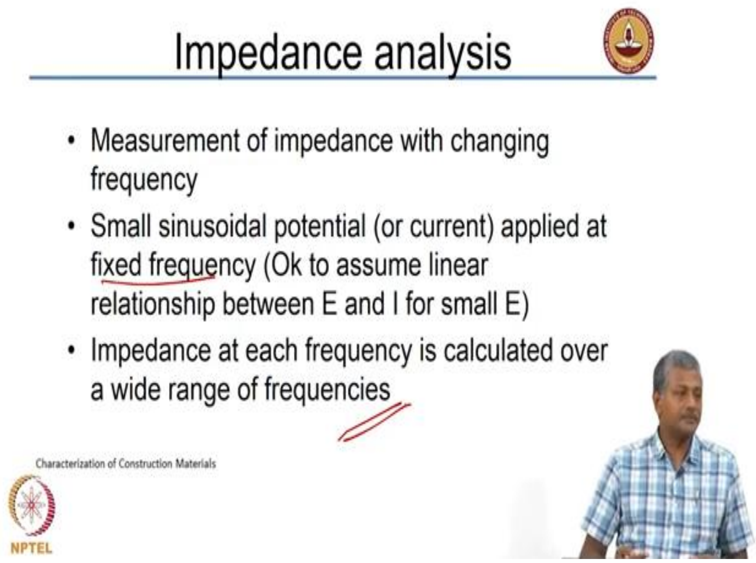
$j$ is also used interchangeably as $i$. i or j is nothing but $\sqrt{-1}$. That is the factor that we use for representing on the complex plane. So when you have this sort of a relationship we can also write this in terms of the impedance.

$$Z(\omega) = \frac{E}{I} = Z_0 \exp(j\phi) = Z_0(\cos\phi + j\sin\phi)$$

So you are basically representing the impedance on a complex plane here, where the real part of the impedance is on the X-axis and the imaginary part of the impedance is on the Y-axis. So if this is your origin, the impedance at any given point has two components: one is your Reactance component and the other is the Resistance component. So you know very well that reactance is composed of both inductance and capacitance. So the ordinate of this $\tilde{Z}$ point represents the reactance which is consisting both of inductance and capacitance, the abscissa is the resistance R. So here, the modulus $|\tilde{Z}|$ which is basically the length of the vector, the magnitude of the vector, is what has given as your $Z_0$. The length of this vector which is defined from the point of origin to Z prime ($\tilde{Z}$) that is given as $Z_0$.

So essentially what you are trying to do is representing the impedance by this value of $Z_0$ (by modulus) and this phase angle θ or $\phi$ (both are one and the same in this case). Of course you can see very well that I have taken the equation from a different reference and the diagram from a different reference that is why in one case you have $\phi$ the other case you have θ. Both are the same - just the phase shift.

**(Refer Slide Time: 14:15)**

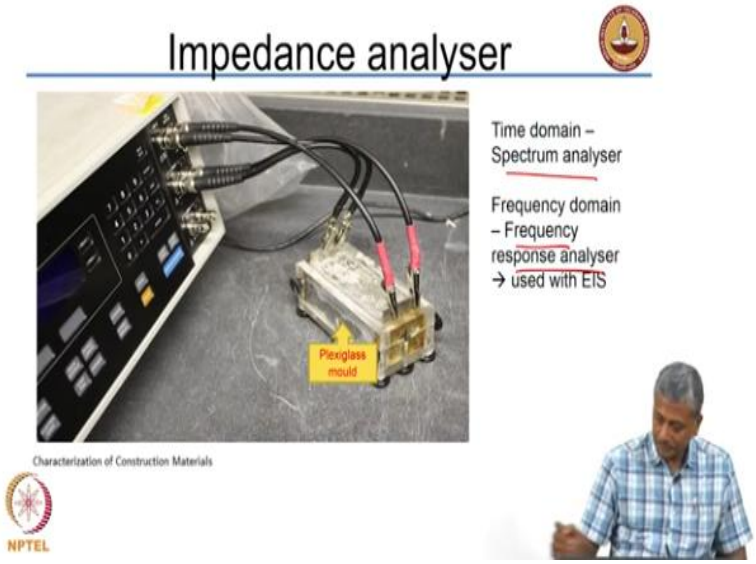



So what do we do in impedance analysis? What we do is essentially we measure the impedance of a system while we change the frequency of the alternating current that is applied in the system. Alternatively, what we can also do is fix the frequency and apply a sinusoidal potential or current and assess the opposite behavior. That means when you apply a potential you check the current behavior and when you apply a current, you check the voltage behavior at a fixed frequency that is the other way of using impedance analysis.

But for the most part what we simply do is we calculate the impedance at each frequency over a wide range of frequencies. That depends on the capability of your instrument - how wide a range that you can go in terms of the frequency.

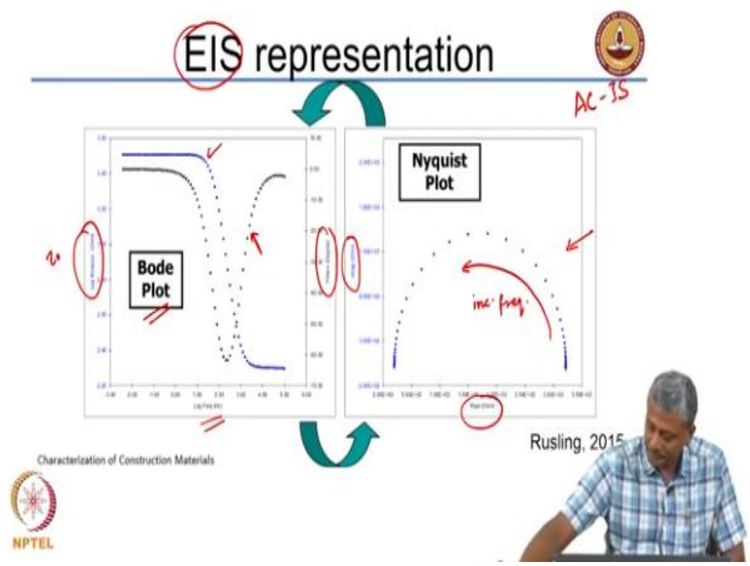
So what are we doing here is, we have a system which is either fully conductive or fully insulated or partially conductive which can be subjected to a potential difference which is given through an alternating current. And then what we are simply doing is changing the frequency of the alternating current and measuring the impedance value at each frequency.

**(Refer Slide Time: 15:27)**




This is your impedance analyzer which is typically used - this is the one from our lab. So in the impedance analyzers which are also known as spectrum analyzers when they do just a time domain analysis, whereas when you do a frequency domain analysis which you typically get with most modern EIS systems, you call it a frequency response analyzer.

**(Refer Slide Time: 15:55)**

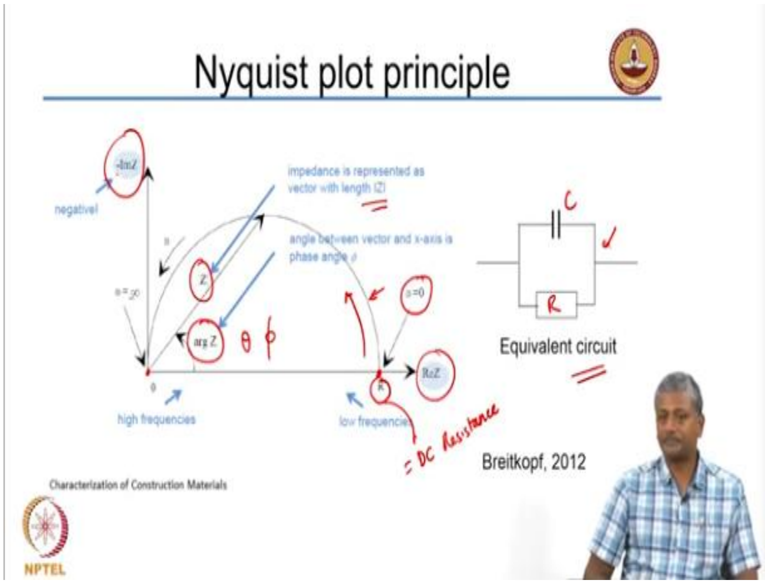



Let us look at what sort of representation is done with the data that you collect. So as I said you are simply changing the frequency of the AC current and determining the impedance value. So, one way of representing the response is simply the modulus, that means $Z_0$, as a function of the frequency (Hz). Typically it is on a log-log scale for what we call as a Bode plot. On the same graph, on the second Y-axis, you also represent the angle $\theta$ or $\phi$, which is basically the phase shift as a function of the log frequency. So you see here the blue curve defines the change in the log modulus with frequency, the black curve defines a change in phase angle with frequency. So this is one way of representing the data collected from impedance analysis.

The other way is to do the Nyquist plot. In Nyquist plot what is plotted is the imaginary value of the impedance on the Y-axis, the real value of the impedance on the X-axis and you are basically changing the frequencies in this direction. You are basically representing these points in the direction of increasing frequency towards the origin; as you go more and more towards the origin your frequency becomes more and more.

So a Nyquist plot or a Bode plot can be used to represent the data collected from your Electrochemical Impedance Analysis (EIS). Now again lot of names are used sometimes we might refer to it as EIS - electrochemical impedance analysis. Generally when you do corrosion studies you call it electrochemical impedance analysis. But if you are just doing conductance measurements of samples, you do not call it EIS, typically we just call it AC-IS, Alternating Current Impedance Spectroscopy. Now of course it is redundant to put the AC there, because you do not get impedance in DC you only get resistance, but we still call it AC Impedance Spectroscopy.

**(Refer Slide Time: 18:07)**




So just to explain Nyquist plot once again, so most of your data resembles this sort of an arc for an equivalent circuit that looks like this (as given on the right). Again this is a standard equivalent circuit where you have a resistor and a capacitor in parallel. So for an angular frequency (ω) = 0, this arc touches the real axis that is the X-axis and this resistance that you get from here is almost equal to your DC resistance. As you increase the frequencies, you go along this arc and theoretically for ω = ∞, you should have a zero impedance. You can calculate this based on the expressions that we have used for Z and I.

Now, as ω is increasing as you are going along this arc, you can represent the impedance in terms of your modulus (the vector with length equal to magnitude of $|Z|$), and arg Z is nothing but the phase angle θ or ϕ.

So this is essentially your representation of the Nyquist plot. Please note that in this imaginary part, you actually plot the negative above the 0 point. That is how you will be actually representing it. The negative of the imaginary Z (which is –ImZ) will be represented on the Y-axis whereas the positive of the real Z (ReZ) is on the X-axis. This is just the way that representation is done for this equivalent circuit which has a capacitor and resistor in parallel.