Electrical Machines
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Lecture 01
Introduction to Electrical Machines

We are starting on electrical machines. We are going to look at both motors and generators in this particular course. But it definitely requires some amount of recalling of what was already done, so let me give you roughly what is the course plan initially and then I will go over whatever is the recalling that needs to be done.

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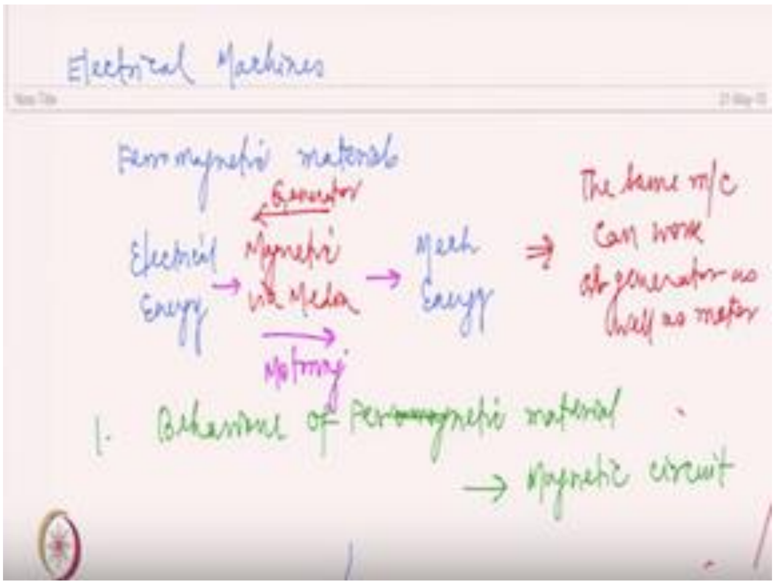

So if you look at any of the electrical machine normally they are going to be made up of ferromagnetic materials, because if you look at electromechanical energy conversion it is always through a magnetic via media. So I am going to have a magnetic via media and I am going to have on one side let us say electrical energy and I am going to have on the other side mechanical energy. So it is converting from electrical energy to mechanical energy through magnetic via media. So when this is being done if electrical energy is converted into mechanical energy it is going to be motoring operation on one side whereas if I am going to do from mechanical energy to electrical energy this is known as generator operation.

So I can have either motoring operation or generating operation, the same machine can work as both generator as well as motor. So all I need to do is I have to do the controlling such a way or if I give mechanical energy it will convert that into electrical energy and it can work as a generator or vice versa. So I can in general say the construction wise and functionality wise both are almost similar. So the same machine can work as generator as well as motor. But because we are using ferromagnetic material it is very essential to know about the behavior of ferromagnetic materials; so, which we call as basically magnetic circuit.

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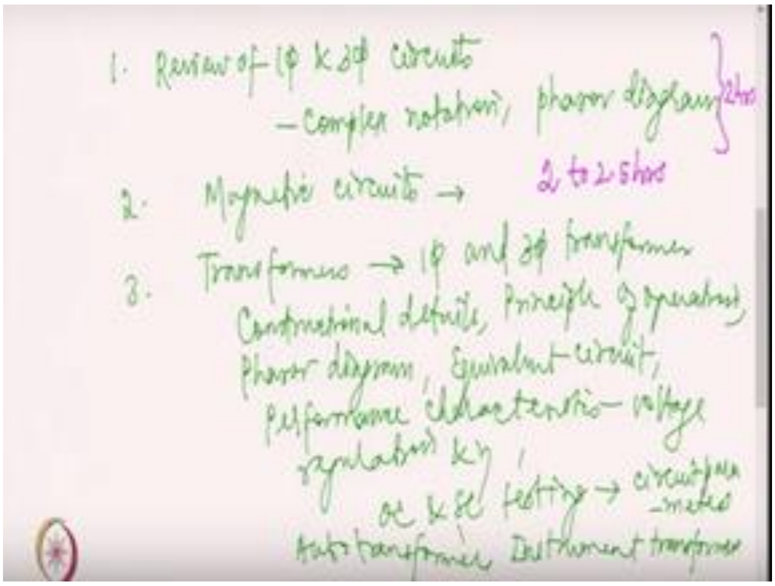

So we call this whatever is the behavior we try to analyze it by the help of magnetic circuit concepts. So we will be starting off with this first then we are going to look at, so if I actually start the flow of the course, the first and foremost thing we will be doing is review of single phase and three phase circuit. You must have studied this already you must have seen what complex notation is, what phasor diagram is, and how the power is measured and so on. So we will be revisiting these things to some extent first, the second topic is going to be the magnetic circuits, so we will be looking at magnetic circuits, as the second topic where we will be talking about the behavior of ferromagnetic material around that if I wind a wire how it is going to function that is what we are going to look at.

The third topic after this we are going to look at, basically transformers, so in transformers we will be actually looking at both single phase and three phase transformers. We will of course start with constructional details how the transformer is constructed then after doing that we would be looking at what is the principle of operation and then we will be actually looking at the phasor diagram of the transformer; how the voltages and currents are displaced from each other, then we will be looking at equivalent circuit of the transformer.

Once we have the equivalent circuit derived we should be able to really talk about the performance characteristics of the transformers like voltage regulation and efficiency, these two we will be talking about and after that we will be looking at actually open circuit and short circuit test or testing of transformers from which actually we derive the equivalent circuit parameters. Then after looking at these things we will be actually looking at the auto transformer, and instrument transformers that is instruments transformer are generally meant for instrumentation that is measurements, so we may use potential transformer and current transformer.

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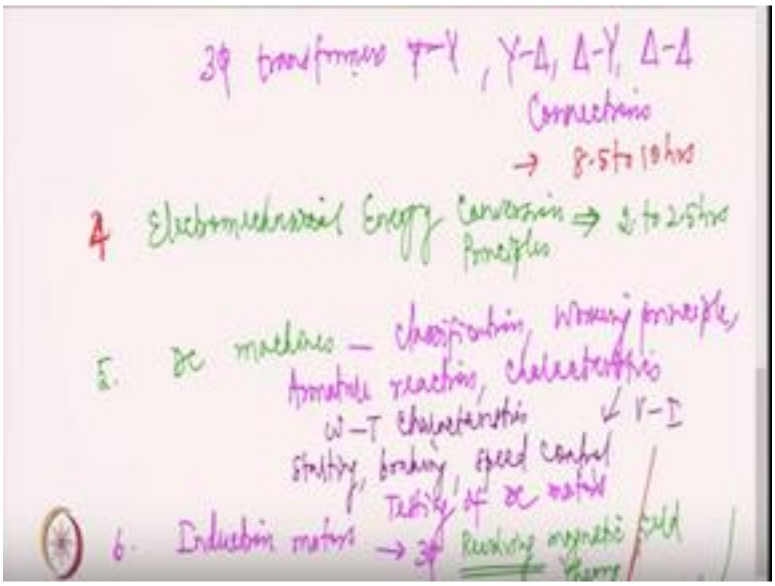

After looking at all these single phase transformer principles then we will be going over to three phase transformers, in three phase transformers we will be looking at star-star, start-delta, delta star and delta-delta connection and any other special connections.

I forgot to tell you the number of hours roughly I will be dwelling on each of these topics, review of the single phase and three phase circuits might take about maximum of 1 to 2 hours, so I am giving myself maximum two hours inclusive of introduction. Magnetic circuit again should take anywhere between two to 2.5 hours, nothing more than that, transformers is a vast topic, so inclusive of three phase transformer I may be requiring in about 8.5 to 10 hours, the entire thing.

Then the next topic that I am going to have which is actually the third topic, fourth topic I suppose, the fourth topic actually is going to be the electromechanical energy conversion principle, until now what we had seen in the topic was only static machines, they are not having any moving parts but if mechanical to electrical energy conversion or electrical to mechanical energy conversion has to take place through a magnetic via media we have to have definitely looking at energy conversion principles themselves. So this is just giving an introduction to how electromechanical energy conversion takes place. This will take anywhere between about 2 to 2.5 hours.

After this we will be looking at DC machines because this is one of the simpler machines in terms of operation I would not say constructional principle, definitely in operation. So we will be looking at first of all basic construction after that we look at the classification of DC machine, working principle, then after that we will be looking at something called armature reaction, what happens when the armature is also creating some flux along with the field so this is known as armature reaction.

Then we will be looking at characteristics of the DC machine, so if I am talking about motor I have to talk about speed torque characteristics if I am talking about the generator I should talk about voltage versus current characteristic. So this we will be looking at then, then when we are talking about motor we will be actually concentrating on starting, how we start a DC motor, then we will be looking at breaking very briefly and we will also be looking at speed control, how to control the speed of a DC motor.

These are the different things we will be looking at, of course I have left out testing of DC machine we should actually look at the testing of DC machines as well. Depending upon of course time, availability of time, then after completing DC machines we will be actually taking up induction machines, which is one of the most important AC machines, if you look at the industries 80 percent of the electrical energy actually in factories or industries is consumed by induction motors, three phase induction motors.

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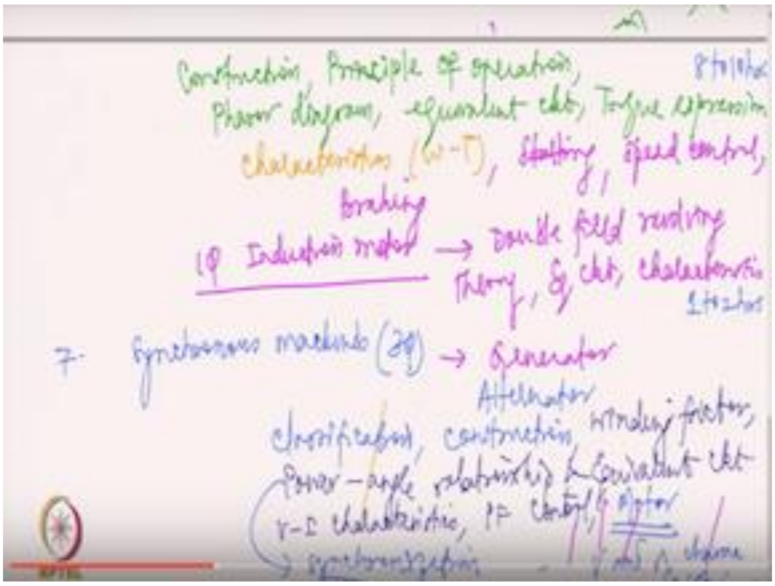

So we will be first looking at three phase induction motor in three phase induction motor we will be looking at construction but even before that we should look at revolving magnetic field theory. How we are going to have when three phase voltages are applied to three phase time displaced, space displaced winding how a revolving magnetic field is created, this is how we will start the three phase induction motor, then in the three phase induction motor itself we will talk about construction, two types of construction, that is squirrel-cage and wound rotor, then we will talk about principle of operation.

After looking at the principle of operation then we will be looking at phasor diagram and equivalent circuit, after looking at the equivalent circuit we will be able to derive the torque expression, torque slip or torque speed characteristics, then we will be clearly looking at how the characteristics are dependent upon these expressions. So we will be talking about the speed torque characteristics mainly.

Then after that, we will be looking at starting what are all the different starting methods, and then we can look at speed control and very little bit about breaking. So these are the topics that will be covered under induction motor then if time permits we will also look at single phase induction motor.

Let's see how it goes, so single phase induction motor we will be looking at basically double field revolving theory and then we will be looking at again equivalent circuit characteristics, etc. So these are going to be different topics in single phase induction motor. I would not like to call this as a separate topic because this will be pretty small.

So for three-phase induction motor I might take anywhere between again in 8 to 10 hours minimum, this might take about 1 to 2 hours, because we are just going to touch upon this, nothing more than that, then the next topic that we would be looking at will be synchronous machines. This is also a three phase machine but we will be concentrating on this as a generator.

So we call a three phase synchronous machine working as a generator as an alternator so we will be looking at alternator and its working, basically in this particular topic, the synchronous machines generally we will start with classification then we will look at construction after looking at construction here we will be concentrating more on the winding arrangement, so we will talk about something called winding factor and how we influences the voltage generation in a synchronous machine.

After that we will looking at power angle relationship and equivalent circuit and because it is working as a generator it is very important to look at VI characteristics of the generator whether it will be able to maintain a constant voltage in case of disturbance how do we handle it, these things will be talked about.

After this, we will be talking about power factor control which is one of the most important aspects of the synchronous machine. Then we will be talking about the same machine functioning as a motor, very briefly that is synchronous motor under which we will be talking about V and inverted V characteristics. One more thing I have forgotten we also need to look at the generator as how it can be synchronized, how the synchronization can be done with the three phase grid. So this is an important thing we need to do when we want to feed power from the synchronous generator into the three phase grid, so we will be talking about the synchronization as well.

In my opinion this should not take as long as what it has taken for induction machine, so it may be anywhere between 6 to 7 hours. So I think on the whole if we actually compute the total number of hours we will be spending about 6 plus 2, 8, 8 plus 8, 16 and we are having a electromechanical energy conversion principle plus transformers maybe about 10-12.5 hours, so 16+12=28, have we left to DC machine, I have not given any time here that has to be again about 8 to 10 hours, so about 38 hours of 36 hours gone here, then introduction and review everything together about 2+2=4 hours, so I think it comes to about 40 to 42 hours. So that is the way the entire lecture is going to be planned.

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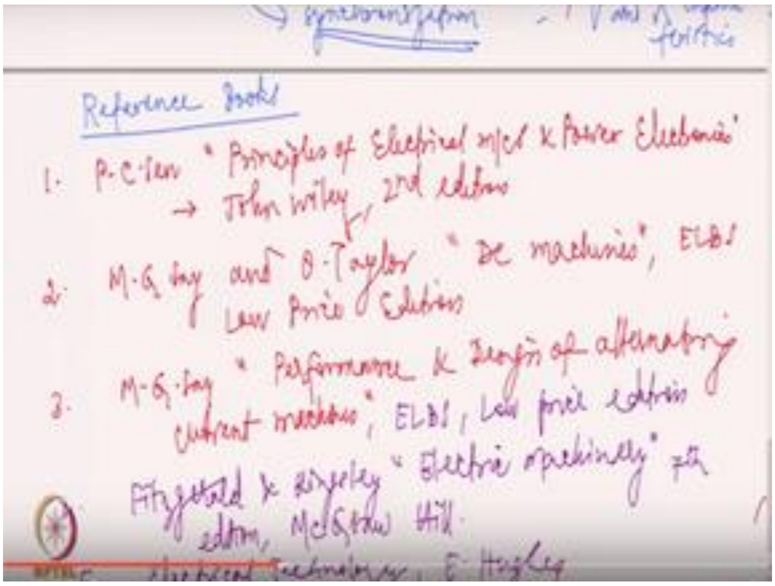

We have some reference books for this electrical machines course. I would like to start with simplest of books, basically for electrical machines, although some of the topics I mentioned may not be covered very well in this book, nevertheless for a beginner it is very easy to read that book so I would rather recommend that book, this book is written by P.C. Sen and this is called Principles of Electrical Machines and Power Electronics, of course we will not be going into power electronics portion, no doubt but this covers electrical machines from a fundamental principle, it starts with magnetic circuits and so on there are appendices given on a three phase circuits and single phase circuits . So I think it almost gives you a very good introduction to entire machines course.

This is from John Wiley and second edition is available as far as I remember, if you ask me the year I don’t remember, the second book I would rather recommend very strongly is that there is one book on DC machines, let me probably erase this, let me write this same order as I have done, so M.G. Say and O. Taylor, there is a book on DC machine by these two people, it is a vast book that is why I would not give this as a principle reference book but it is written extremely well and this is from probably ELBS, it used to come from ELBS, English language books society, low price edition, I don't know whether Pearson has taken it already.

Similarly, the counter part in the AC side is again by M. G. Say, this is actually a Performance and Design of Alternating Current Machines, this is again a very vast book but the explanations are extremely good and this is also from ELBS, this is a low price edition, then I would say one more book which is really worthy of reading that is by Fitzgerald and Kingsley, of course there is a third author Umans, I have left him out. So this is actually Electric Machinery. I think seventh edition or something has come now as far as I remember and this is from McGraw-Hill, there are definitely other books that are available as well from Pearson, for example there is Electrical Technology by Edward Hughes, this is a very good book.

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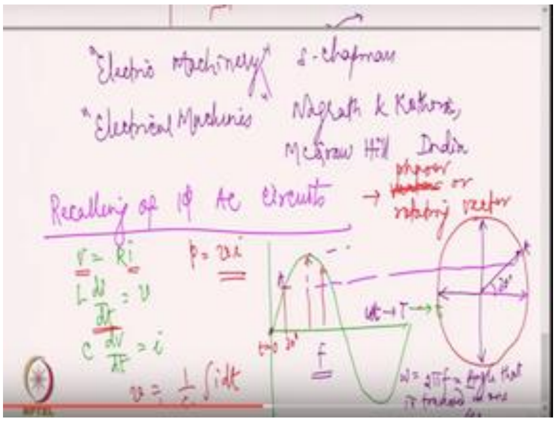

There is one more which is actually Electric Machinery by Chapman-Stephens, these are from Pearson, and one more Indian author book, probably Electric Machinery by or by Electrical Machine by Nagrath and Kothari. I think this is from Tata McGraw-Hill, it used to be from Tata McGraw-Hill so this is now McGraw-Hill India. So these are some of the reference books that we might like to refer to whenever we have some confusion in any of the topics.

So let me start with actually the recalling of single phase AC circuits. So I am starting with recalling single phase AC circuits, all of you guys know that generally when we talk about single phase AC circuit we are going to have sinusoidal excitation basically. So we are going to give basically a sinusoidal excitation, what we mean by excitation is a voltage, we are going to give a sinusoidal voltage.

So whenever we have a sinusoidal voltage rather than using that as a sign quantity, let us say this is *t*, if I am writing this with respect to time I have to add and subtract sinusoidal quantities, I have to multiply, I have to differentiate, integrate, all of them needs to be done on this sinusoidal quantity because I am sure fundamental elements in an electric circuit you guys know so $v = Ri$, this is corresponding to resistance. I can write $L\frac{di}{dt} = v$, this is with reference to inductance, $C\frac{dv}{dt} = i$, this is with reference to capacitance.

So you can very well see that I have *v* and *i* without being differentiated or integrated here and ultimately if I want power I should say $v \times i$. Instantaneous power. So I will have to multiply some of the sinusoidal quantities, I have to differentiate some of the sinusoidal quantities, I have to integrate if I want actually $v = \frac{1}{C}\int i\,dt$. So I have to integrate these quantities.

The major advantage of using a sinusoidal is that whether you differentiate, whether you integrate, whether you multiply, whether you divide, you are going to get ultimately sinusoidal quantity itself, and in nature most of these wave forms that are available are sinusoidal in nature, so that is the reason why and it does not have any abrupt rise or fall and in nature nothing grows abruptly, nothing really you know, may be death is the only thing which occurs abruptly but other than that everything is not abrupt, that is the reason why we are using sinusoidal quantities in all our electricity and magnets.

Now, if I have to actually refer to this quantity in the form of a vector or rotating vector, actually rotating vector is generally known as phasor. So if I want to refer to this as a phasor then what I can do is I can try to look at the projection along this axis and try to plot it, for example I am looking at time $t = 0$, at that point I am having 0 value, if I look at corresponding to say 30^o, this is 30^o, I am going to have half the value of the peak, so I can actually project this as though a vector is rotating continuously with respect to time, so when I had time $t = 0$ if I actually specify this vector somewhat like this.

If I look at the vertical projection or projection along the vertical axis the magnitude is 0 which corresponds to the sinusoidal quantity also at time $t = 0$, when I look at 30^o I can just take it a long, may be it would have rotated exactly by 30^o here and this is actually 30^o and if I call this point as A this point is going to correspond to A.

So if I try to look at the vertical projection it will exactly have this value. So similarly I should be able to draw basically this corresponds to 90^o, this corresponds to 180^o, and this corresponds to 270^o, and this corresponds to 360^o again. So if I say that this is actually oscillating at a frequency of f in one second I am going to see f such oscillations. So if I am traversing $0^o - 360^o$ completely, or if I go from small that is 0 to T here, then I would have traversed this by 2π rad or 360^o.

So if I am saying that f times it is going to oscillate in 1 second I will have $2\pi f$ as the radiance that is traversed within 1 second. So this is the angle that is traversed in 1 second. So we call this as angular velocity, which is omega. So we are going to say this as omega equal to $\omega = 2\pi f$. So then we are plotting with respect of angle, we can write this as omega t rather than t because I can say $2\pi f$ is the angular velocity so $2\pi ft$ will be the angle that is traversed, so every time when we draw actually the wave form of voltage or current we will always write the angle write the x axis as ωt rather than *t*, this is what we are going to do.

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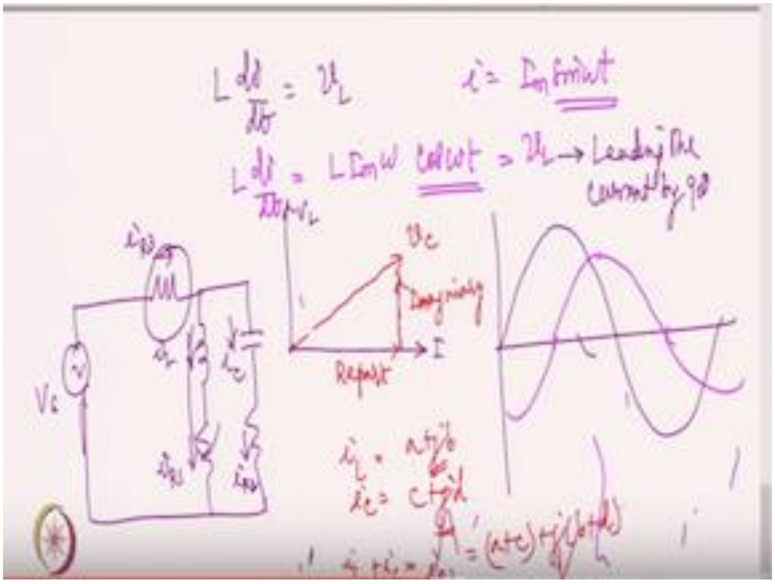

Now, if I am having 1 inductance probably let us say $L\frac{di}{dt} = v_L$, voltage across the inductance, let's say I am going to have i equal to some $i = I_m \sin \omega t$. So if I do that I am going to have $\frac{di}{dt} = I_m \omega \cos \omega t$. So this is multiplied by *L*, and this is going to be my V_L, and because of which cosine wave always leads the sin wave by 90^o.

So I am going to have this voltage leading the current by 90^o, it is going to lead by 90^o, so if I draw the two quantities here I should probably show the voltage like this and I have to show the current as though it is 90^o lagging behind like this, this is how it will be. So if I try to plot both of these in the form of phasor at any instant if I say this is what the current is, then I am going to have the voltage leading by 90^{o}. So this is what we call as the phasor diagram when we draw two of the quantities which are alternating in nature, we say at any instant of time how they are displaced from each other.

So we call this as the phasor quantity. So if I have a circuit for example that I am going to have an alternating voltage then may be a resistance may be an inductance, another resistance may be a capacitance and another resistance. It is not going to be very easy for me to draw for each of them, let us say I call this as i_L, I call this as i_{R1}, and I call this as i_{R2}, let me call this as may be *i* through C and let me call this is i_{R3} and when I add these that is these two currents I will be able to get what is i_{R3} and when I add the voltage drops across these two elements and this element I will be able to get what is the voltage source, but it's not going to be easy for me to draw all these phases and add them.

So people wanted to find out what is the easier way out, because you are mentioning voltages and currents, maybe another voltage. I may mention the voltage like this. Why can't I mention this in the form of complex numbers, that is the thought that came into people's mind. So that is the reason why if I say this is some v_C or something it can have a horizontal component, it can have a vertical component, the horizontal component we call as the real part of the complex number and the vertical component we call as the imaginary part of the complex number, imaginary part of the complex number.

So we are essentially now diversifying from mentioning a sinusoidal quantity as a phasor to indicating that as a complex number. So the complex notation mainly gives us the major advantages if I say for example i_L is going to be some $a+jb$ and let us say I am going to have i_C as some $c+jd$. Please note I am not using *i* here, normally in complex number we use $a+ib$ and $c+id$ but *i* we use normally for current, so I am using *j*.

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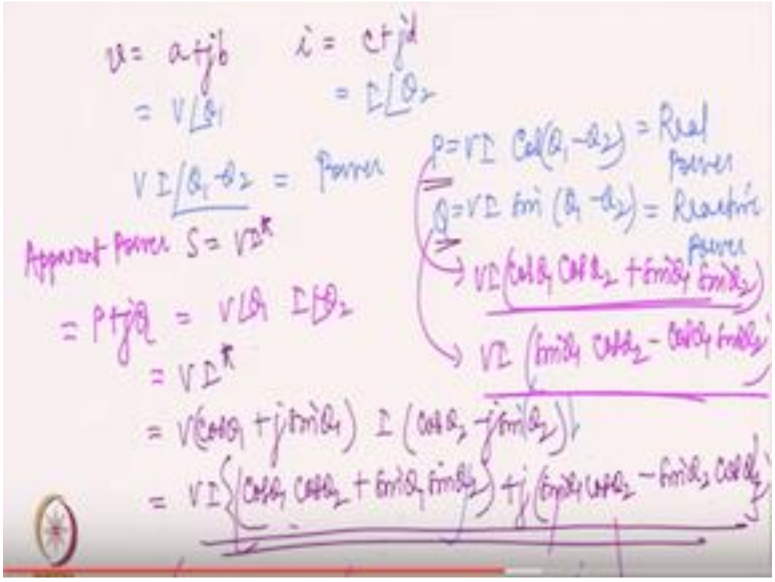

So $a+jb$ and $c+jd$, so I can say i_L+i_C will give me what is i_{R3}, it will be very easy for me to add it. I can say $(a+c)+j(b+d)$, very easy to add, so whenever we have a complex notation, the algebraic operation become much simpler that is the reason why we have chosen to have the complex number notation.

So once we have the complex number notation let us say I have $v=a+jb$ and let us say I have $i=c+jd$. I may be able to mention this as $V\angle\theta_1$, and I may be able to mention this $I\angle\theta_2$.

All of you know basically when we look at the power we generally say $VI\angle(\theta_1-\theta_2)$, this is what happens to be normally the power. This is what we normally write as the power. What I mean is $VI\cos(\theta_1-\theta_2)$ will be real power. This is what you must have learned in circuits, AC circuits. Similarly $VI\sin(\theta_1-\theta_2)$ will be the reactive power.

So if want actually how to calculate this power in the complex form let me call this as P, let me call this as Q and ultimately what I want is $P+jQ$, this is what I want. So if I have to write this, I have to write this as $VI(\cos\theta_1\cos\theta_2+\sin\theta_1\sin\theta_2)$.

And similarly Q will be $VI(\sin\theta_1\cos\theta_2-\cos\theta_1\sin\theta_2)$, so finally when I get the power which is actually we call that as apparent power, so we want to get the apparent power in the format of $P + jQ$. So if I actually try to do it as $V\angle\theta_1 \times I\angle\theta_2$, it's not going to work properly, so I have to take the conjugate of this particular *I*.

If you try to calculate backwards you will see that you are getting this expression for *P* and this expression for *Q*, so you are going to have basically in this particular case, if I write this as VI^* which means I am going to have, $V\left(\cos\theta_1 + j\sin\theta_1\right)I\left(\cos\theta_2 - j\sin\theta_2\right)$.

So when you multiply you are going to get VI commonly $\left(\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\right)$, *j* multiplied by *j* $j^2 = -1$, so I will get $\left(+\sin\theta_1\sin\theta_2\right)$, so this becomes my real part which is corresponding to the real power and I am going to have the imaginary part, which is going to have j , so, $j\left(\sin\theta_1\cos\theta_2 - \sin\theta_2\cos\theta_1\right)$.

So you can see very clearly that these two are matching each other, if I look at *P* and *Q* expressions that I have got, they are exactly matching with this. So normally we write the apparent power expression *S* as either $V \times I^*$, IV^* and so on. So we have one of them conjugate; that is what is important. So complex notation gives us a very easy way for calculating power, calculating summation of currents or multiplication of currents, multiplication of voltages and so on.

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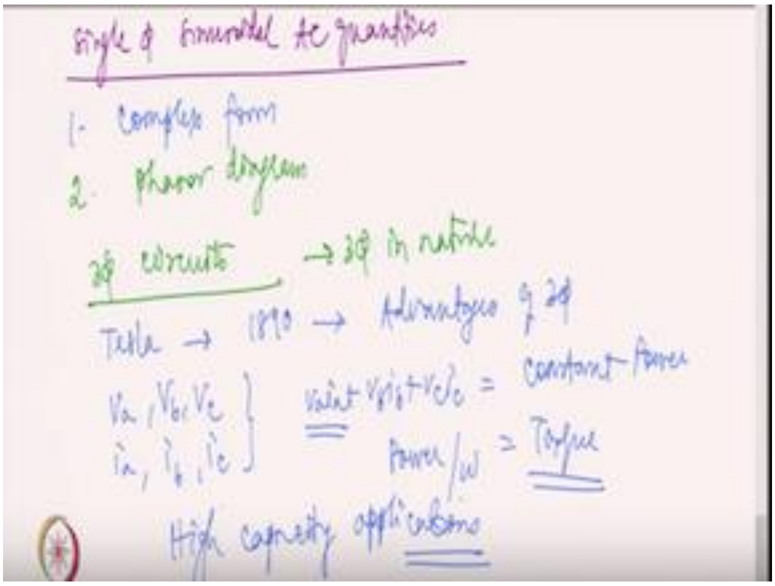

All those things are done quite easily when we have complex notation. So in general single phase quantities when we look at single phase AC quantity or single phase sinusoidal AC quantities, they are represented mainly in two forms, one is in complex form and the complex form indicated is also indirectly translating into phasor diagram.

So we will be repeatedly using in these form getting our power or phasor diagram equivalence circuit, all of them in transformers, AC machines and so on. So this is really important to know. Now let us recall some of the principles corresponding to three phase circuits. So if you look at many of the electrical machines that are available in the market, AC machines, they are all three phase in nature.

This was initially actually the three phase configuration was initially introduced by Tesla, it was invented by Tesla and he had made the induction motor sometime in 1890's or something, so induction motor design had not changed until day, it is almost remaining the same ever since 1890. So if you actually look at the three phase the major advantages, if I look at the advantages of three phase because I have in three phase I am going to have v_a, v_b, v_c and in all the three circuits I am going to have i_a, i_b, i_c and the overall power is going to be $v_a i_a + v_b i_b + v_c i_c$, this is going to be the power.

So if one of them is low, the other one may be high, so all of them balance with each other and ultimately you get a constant power, or constant torque, ultimately. So if I say constant power, power divided by ω is going to be torque, $\frac{P}{\omega} = T$ in any rotating machine, so the torque also becomes a constant quantity roughly, because you have the power and torque to be constant it is very suitable for high capacity applications, what is mean is MW level application or even 100 of KW level applications, you do not want the torque to change continuously, if the torque changes continuously you are going to have vibrations in the shaft, which cannot be tolerated especially at high capacity applications.

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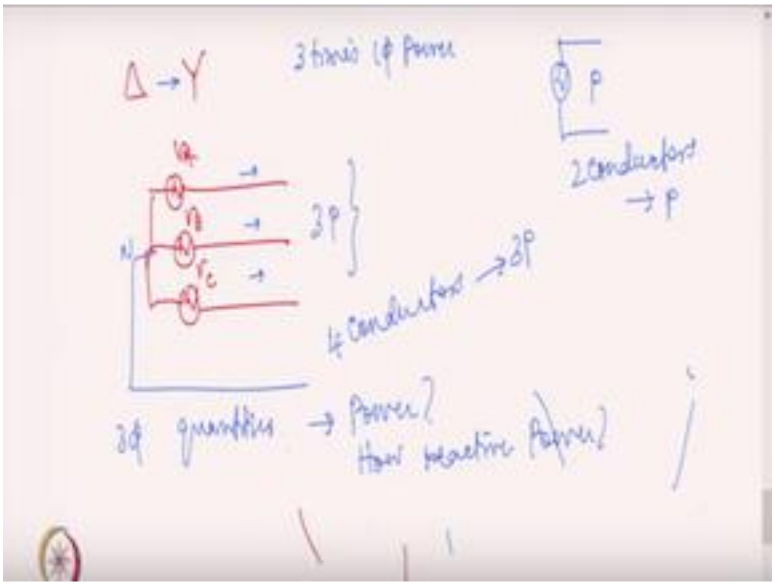

So three phase is really good for high capacity applications, and one more thing is that I am sure you guys know that three phase can be connected either in star or delta, so if I have v_a, v_b, v_c all the three phase voltages they can be applied to either star connected circuit or delta connected circuit. So throughout if I look at the transmission lines that are going I can just have three transmission lines, that's it.

And I will be able to disseminate power which is three times single phase power where as if I am disseminating the whole thing in the form of single phase power I am essentially going to require two conductor for disseminating just P whereas here I am disseminating 3 P for which I require only 3 conductor, so the cost what is involved in copper conductors that comes down drastically when you go from single phase to three phase, of course in most of the cases we will be having a neutral conductor also, if you look at most of the transmission lines we will be having a neutral conductor.

So even then four conductors are able to transmit 3 P whereas here two conductors, two conductors are transmitting only P, so obviously we are saving on the cost of copper. So three phase is very commonly used for generation transmission and as well as distribution except for domestic application, only for domestic application we are going to use single phase. So it's very important to learn about three phases quantities, how we measure power, and how we are going to actually justify measuring the power and reactive power, so how we are going to measure these things that is what we are going to see next.

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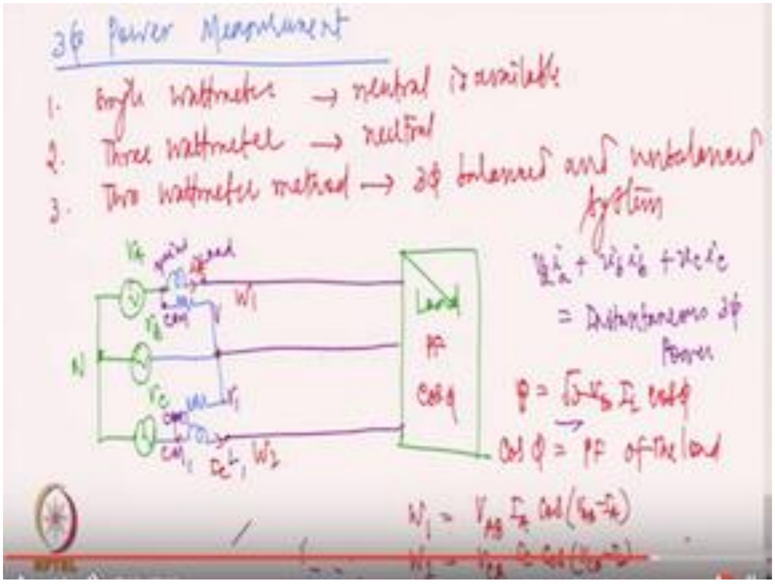

So, we are going to look at three phase power measurement if it is balanced load, I am not going to take the case of unbalanced load condition because most of the electrical machines normally are balanced so there is no need to really talk about t unbalanced. There are different power measurement methods, it can be with single watt meter, but this can work only when neutral is available, most of the times neutral may not be available so we may not be using it.

Similarly, three watt meter method which will also be used only if the neutral is available, otherwise it’s not going to be easy if it is delta connected we can still think of using this probably, three watt meter but two watt meter method is a very common method which is used for using, used for measuring power in a three phases balanced as well as unbalanced system. In both the case it will work quite well.

So what is this method all about that is what we are going to see now, so let me draw the circuit diagram corresponding to the two wattmeter method. Let us say I have a three phase supply here, so let me call this as v_A, this as v_B and this as v_C and this is the neutral. Now I am going to have probably a load here, the load can be delta connected or star connected, so I am showing the load just like a black box.

So I have only 2 watt meters with me so I am going to connect one of the watt meter current coil here another watt meter current coil here and I am going to connect the voltage coil or the pressure coil like this and the pressure coil is connected between the phase the current coils are connected and the other phase which is not having any current coil, then this is connected directly to the load.

I am sure you guys have seen already the watt meters so there will be the current coil which will be actually connected between M and L normally this stands for load and M stands for the mains and similarly I am going to have here also M and L, let me call this as M_1 and L_1. So this is the current coil 1 and I am going to have the pressure coil connected between the common point, which is common between the current coil and pressure coil and this is going to be the V.

So similarly, here also I am going to have COM_1 and v_1, so this is the connection that we are going to have in the three phase two watt meter method. Let me first of all try to justify that this will give me three phase power. So normally if you look at the three phase power you are going to have $v_1 i_1$ or $v_A i_A + v_B i_B + v_C i_C$. This is the instantaneous three phase power. But if I try to look at what is the actual value of power normally, we write, we write this as P equal to root $3 v_L i_L \cos\phi$.

where $\cos\phi$ is the power factor of the load.

So load power factor I am calling as cos phi in this particular case, this is going to be the power factor. So let us try to see what is it that I am going to get in watt meter one and watt meter two respectively. So in watt meter one I have here voltage of *A*-phase and here voltage of *B*-phase so I am going to get v_{AB} as the voltage across the pressure coil of this particular watt meter and a current through this is going to be i_A.

So I have to write this as i_A, please note, I am writing RMS quantity so all of them are RMS quantities so this is $v_{AB} \times i_A$, and between v_{AB} and i_A whatever is the angle that is present I should say cos of the angle between v_{AB} and i_A. This is going to be the reading of W_1. Similarly W_2 is going to have the reading to be this is voltage of *C* and this is *B* so I am going to have v_{CB} and the current that is flowing here is i_C so this is going to be i_C cos of v_{CB} and i_C. This is going to be W_2.

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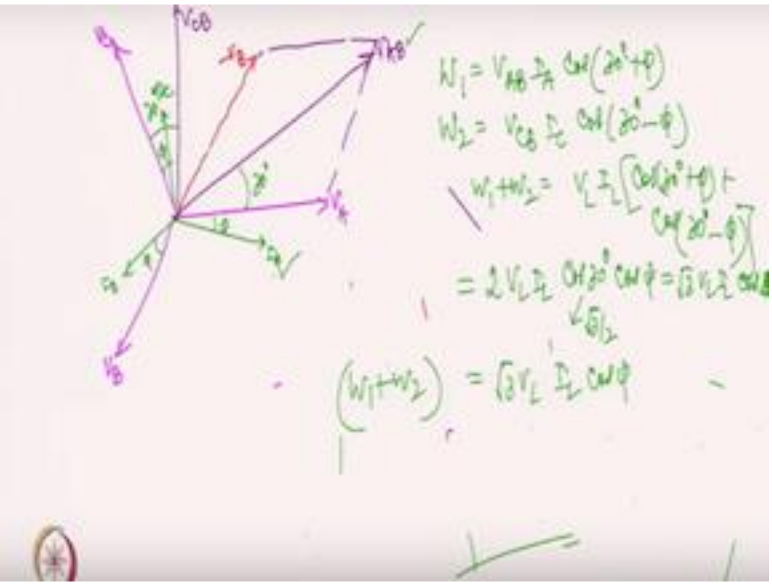

So let us try to take a look at exactly how this looks when we are having the phasor diagram completely drawn. So let us say this is v_A, this is going to be v_B and this is going to be v_C, these are the three phase voltages, they are phase shifted by each by 120^{o} each when I want v_{AB}, I can take v_B on the other side. So this is actually $-v_B$. So when I try to look at what is v_{AB} I have to just take the resultant of v_A and v_B added together, so I will have this as v_{AB}.

Similarly, I should be able to draw v_{AC} which should be mid, in between these two, I can't go beyond this, so this is will be v_{CB}. Now let us say I am going to have a lagging load, I am just arbitrary taking this as some at a power factor angle phi this is going to be i_A, and if I assume it as a balance load I am going to have i_B again at an angle of ϕ and i_C somewhere here which is also at an angle of ϕ.

Now, I have to look at what is the angle between v_{AB} and i_A if I want to get the power of W_1, so I am going to have $W_1 = v_{AB} \times i_A$, this is 30°. So this is going to be $\cos\left(30^{\circ} + \phi\right)$. Similarly, if I try to write what is W_2, W_2 is going to be $v_{CB} \times i_C$ but this angle is again 30°, so I am going to have $\cos\left(30^{\circ} - \phi\right)$. So I am going to have when I calculate W_1 plus W_2 it will be v_{AB} or v_{CB} I can call them as line voltage, V_L directly.

Similarly, I can say i_A or i_C, if it is a balance load condition and I can call that as I_L, I can say this is $\cos\left(30^{\circ} + \phi\right) + \cos\left(30^{\circ} - \phi\right)$. So this is going to be $V_L I_L \cos$, cos is actually going to be $\cos 30$ and $\cos\phi$. We are going to have $2\cos 30 \cos\phi$, so this is going to be root $3 V_L I_L \cos\theta$, because $\cos 30^{\circ} = \sqrt{3}/2$.

So we wrote the power expression earlier as root $3 V_L I_L \cos\phi$, we are having essentially the same thing, root $3 V_L I_L \cos\phi$ coming out as W_1 as W_2. So this is essentially the three phase power expression. So we able to measure the three phase power just by using two watt meters here and this is one of the most reliable methods as far as the three phase system is concerned.

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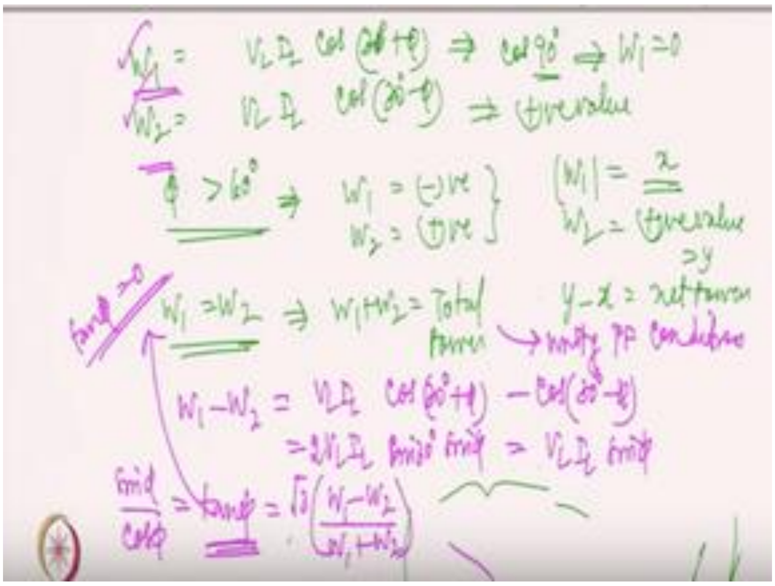

But we wrote $W_1 = V_L I_L \cos\left(30^{o} + \phi\right)$ and $W_2 = V_L I_L \cos\left(30^{o} - \phi\right)$, if the power factor angle happens to be greater than 60^{o}, very clearly I am going to have this to be $\cos 90^{\circ}$ or greater than $\cos 90^{\circ}$. So if the power factor angle happens to be 60°, I will have one of the watt meter reading to be 0 and the other watt meter reading will have a value which is positive because 30 minus whatever is the angle $\cos\theta = \cos\left(-\theta\right)$ so I will have a positive value.

Whereas if I am going to have the power factor angle to be greater than 60, W_1 will be negative and W_2 is going to be positive, that is why you will see that in some of the three phase experiments when you done of the watt meters might be kicking back, so in which case was either the voltage or the current you will be able to get a positive reading but that you have to treat as a negative value and subtract it, you cannot, in that case you have to say W_1 magnitude whatever you get the some value X, whereas W_2 is going to be a positive value, let us say Y, then you are going to say $Y - X$ is the net power in that particular case.

Similarly, if I get $W_1 = W_2$ by chance, That means I am going to have essentially W_1 plus W_2 as the total power, no doubt but I can also say from these expressions because

I am having $W_1 = V_L I_L \cos\left(30^\circ + \phi\right)$ and $W_2 = V_L I_L \cos\left(30^\circ - \phi\right)$. $W_1 - W_2$, I can write this as $V_L I_L \left(\cos\left(30^\circ + \phi\right) - \cos\left(30^\circ - \phi\right)\right)$ and I can write this as $V_L I_L \sin 30^\circ \sin\phi$.

$\sin 30^\circ = 0.5$, so I am going to get basically $V_L I_L \sin\phi$, so if I try to write what is $\sin\phi / \cos\phi = \tan\phi$. That will be $\frac{W_1 - W_2}{W_1 + W_2} = \frac{\sin\phi}{\sqrt{3}\cos\phi}$. This will give $\tan\phi$. So if $W_1 = W_2$ then $\tan\phi = 0$.

From here I can say tan phi is 0, which means it is going to be unity power factor condition. When W_1 equal to W_2 it will be unity power factor condition. So we would be able to deduce the power factor of the load if I have these two reading with me, W_1 and W_2, these two readings with me. So in general two watt meter method is a very advantageous method from various viewpoints you will be able to determine what the power factor of the load is. You will be able to get the accurate power whether it is balanced load condition or unbalanced load condition normally with the help of just two watt meters alone.