Electrical Equipment and Machines: Finite Element Analysis

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Lecture 01 - Course Outline and Introduction

Good morning and welcome to this course, Electrical Equipment and Machines: FE Analysis. This is an NPTEL MOOC course exclusively devoted to finite element analysis and its application to electrical machines, both static and rotating machines as well as some other equipment like high voltage devices.

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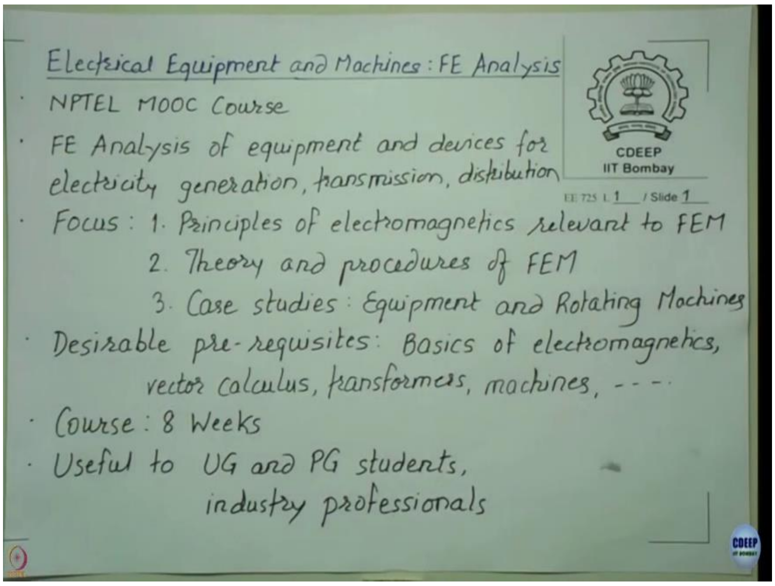

Now, all these devices that we are going to analyze by using FE analysis in this course, they are used in generation, transmission and distribution of electrical energy. Now, what are we going to study in this course? The focus will be on principles of electromagnetics relevant to finite element method, electromagnetics is a vast subject and in this course, we are going to focus only on low-frequency electromagnetics. And to that extent, we will cover some basics of electromagnetics which are relevant to FEM analysis of low-frequency apparatus.

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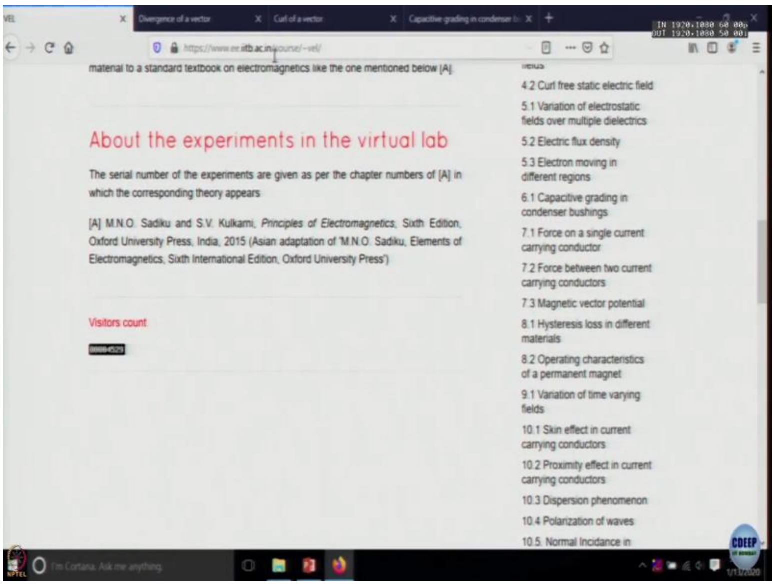

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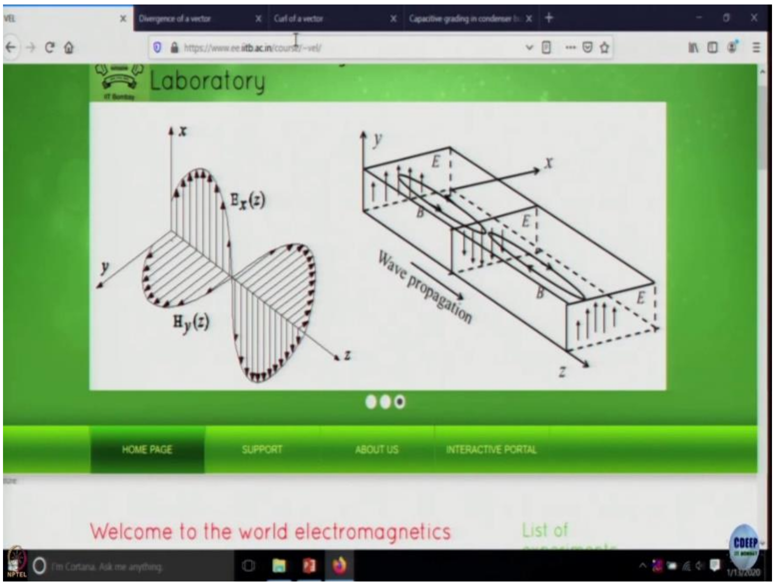

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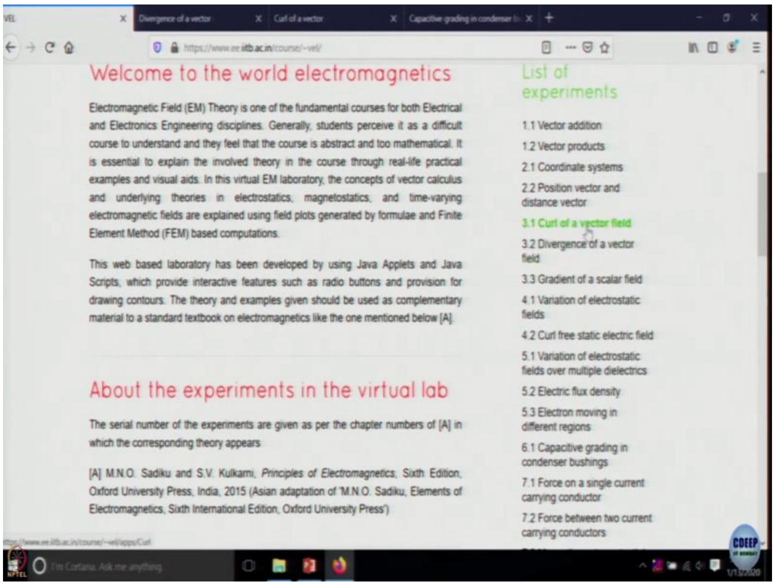

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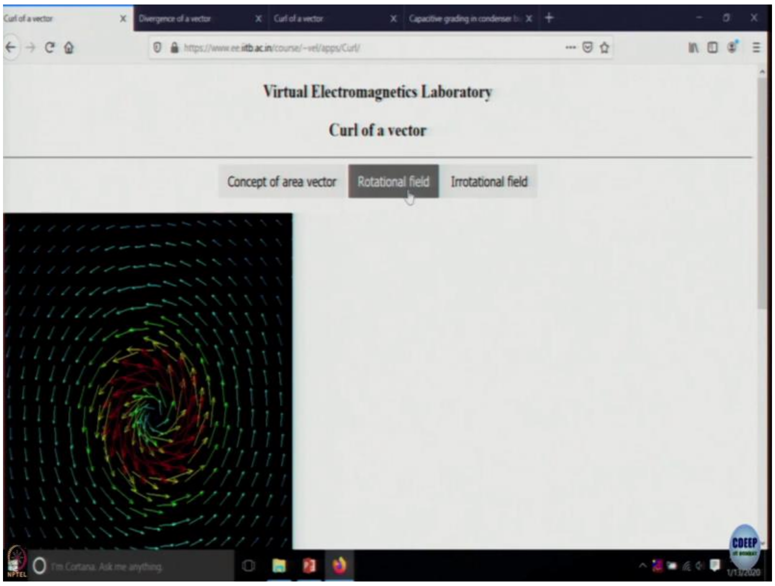

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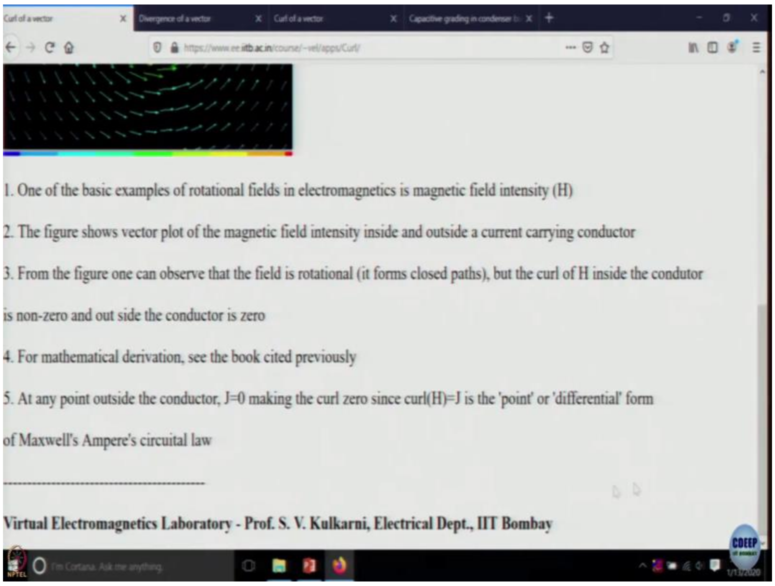

I will also suggest to those who are new to electromagnetics, they can quickly see this website at leisure time which is a virtual electromagnetics lab. The address is https://www.ee.iitb.ac.in/course/~vel/, if you Google VEL IIT Bombay, you will get this link and then you can see many software experiments and related theory mentioned in each of these experiments with interactive mode. Like, for example, if you click these buttons, you will get the field plots with the relevant explanations below.

So, those who are not so well in basics of electromagnetics, they can either read any basic book on electromagnetics or refer any such web-based material like virtual lab and upgrade themselves, but they need not worry too much because I am going to cover in about six half an hour lectures all the basics of electromagnetics, which are required for this course. So that will bring all of us on the same platform and that will be good I think.

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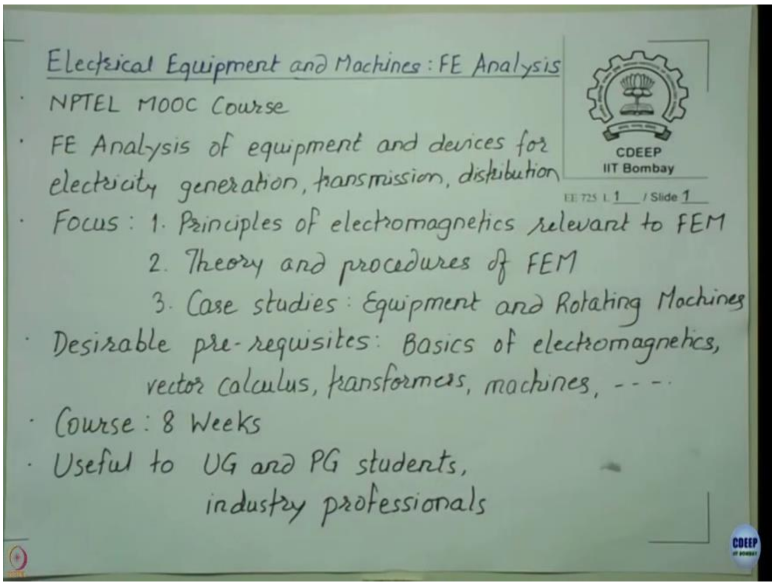

Then the second focus will be on the development of the theory of finite element method and the corresponding procedures. Now procedures that we are going to see are basically for one-dimensional and two-dimensional problems. Three-dimensional problems can also be solved by developing our own codes, but the amount of computational efforts in terms of coding and not from the point of electromagnetics are quite high.

So, we are not actually going to develop 3D codes as part of this course. For that many commercial software are available and they are best suited to solve your practical 3D problems. The idea of this course is when researchers and practicing engineers are using commercial software, they should know what they are doing and understand the results that they are getting from the commercial software. So, once you understand the FEM procedure, then you will be a better researcher or a practicing engineer to exploit various features of commercial FE software.

The third focus is going to be on solving some practical problems related to static and rotating machines. And we will solve various problems such as static, transient, time-harmonic, coupled problems and thus in the increasing order of difficulty and computational efforts. As I mentioned, it will be desirable if you refresh yourself with basics of electromagnetics, vector calculus and of course machines. I am sure most of you are exposed to principles of electrical machines, but in case you are not, you may want to refresh or if there are some doubts, of course, they can be addressed as part of this course during the interactive sessions.

The course is for eight weeks and there will be introductory lectures on the basics of electromagnetics and then we will get onto the FEM theory. First, we will see 1D, 2D, then from static calculations we will go to time-harmonic then transient, coupled and so on.

This course as I said earlier would be useful to practicing professionals who are actually solving industry problems as well as to undergraduate and postgraduate students. To undergraduate students, they will understand the potential of this finite element method and if suppose they go on further to do research or take the research career or join industry, they would be in a position to use this method effectively. Postgraduate students, many PhD students who are dealing with electrical machines and apparatus, need to design, optimize, improve performance of these equipment and for such reasons, at some point of time they will come across finite element method and I am sure this course would be useful to them.

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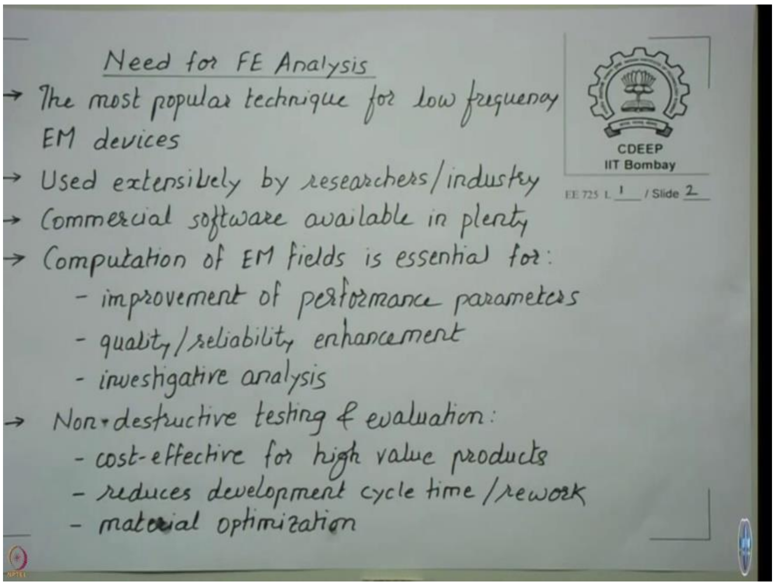

Now, what is the need for FE analysis? Finite element method amongst all numerical techniques is one of the most popular techniques particularly for low frequency. For high-frequency electromagnetic analysis, for example, when you are analyzing antennas and waveguides particularly antennas, where you have open boundary problems, there integral equation methods like method of moments are more useful. But here since our focus is on electrical machines and we have bounded structures, typically you have finite element method, finite difference method, but among these methods, finite element method has emerged as most popular and we will concentrate in this course only on the finite element method.

As I said, this is being used extensively by researchers and industry. Many commercial FE softwares are available. And why finally computation of electromagnetic fields is essential? Initially, when computational tools were not advanced, the designers of electrical machines used to have analytical formulae, thumb rules or curves derived based on experimental data and then they used to design machines, but there used to be always some kind of factor of ignorance and that factor of ignorance can be minimized by using numerical techniques like finite element method.

Using the finite element method, you can exactly know the field distribution and the stress levels. When I mean stress, it could be electromagnetic stress, thermal stress, structural stress, or any other stress related to engineering field. And although we are going to discuss here only electromagnetics and coupled systems as you are aware. Finite element method is equally applicable to other domains of engineering. And in fact, it was first well developed and initiated for structural engineering. And then it got adapted for electrical engineering and electronics engineering.

So, computation of EM fields is essential for the improvement in performance parameters, like calculation of reactance, calculation of losses, calculation of temperature rise, calculation of forces, torques, and whatnot. It can be also used for enhancing quality and reliability. I will give some examples in next slide. It can be also used for investigative analysis, that is failure analysis. Some equipment, suppose it fails at the test-bed or at the site, then how do we investigate and come to a root cause for such failures? That can be also done by using finite element method.

So, finite element method is basically a non-destructive testing and evaluation method. That means we are not actually physically stressing the machine, we are actually simulating or emulating a given device in a finite element software and then actually subjecting that machine to stresses and in that sense, it is non-destructive testing and evaluation and this has obvious advantages because if it is a very costly device like a large generator or a large transformer costing few crores or millions of dollars, then it is not possible to completely design, build, test that equipment and then find out, oh, there is some mistake and then do rework. That rework would be very costly or you know in today’s world where there is a cutthroat global competition, you need to optimize the material cost and again you have this FEM coming to your rescue.

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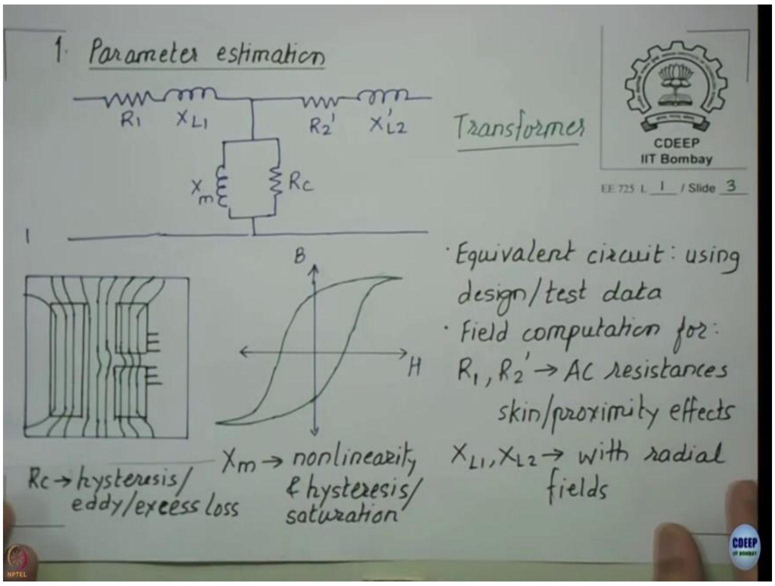
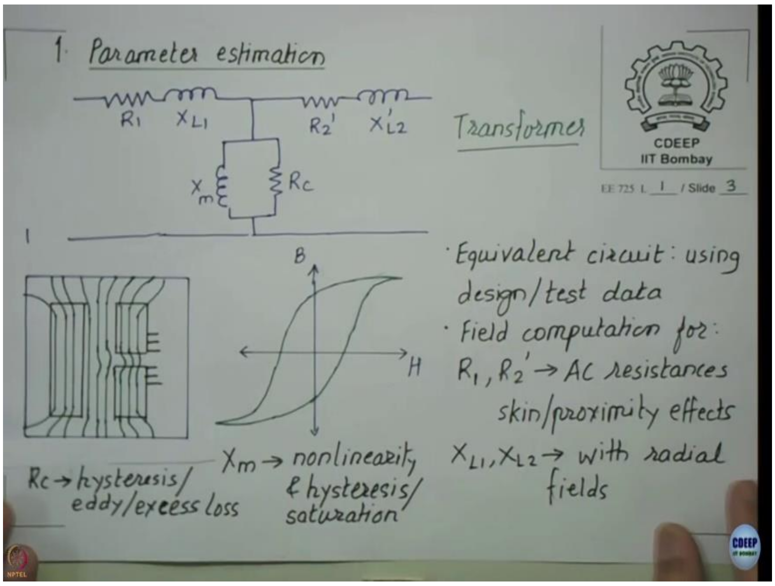


One of the first applications of FE analysis (mentioned earlier) is parameter estimation of any device that you are simulating. Now, here is the case of a transformer which all of us know and this is the equivalent circuit of the transformer. Now, this equivalent circuit has many parameters, and these parameters generally we have studied in our basic course on electrical engineering. Based on the theory of transformers we evolve this equivalent circuit, but to a practical designer, this equivalent circuit is a result of design and test. That means this equivalent circuit is of practically no use to a practicing designer who wants to design a transformer.

This equivalent circuit can be derived based on test and design data. So, what is required for a designer or a person who is trying to optimize a product like a transformer, he/she needs to understand each of these circuit parameters in depth. Now, when we are actually writing these reactances and resistances, we are already doing some approximations like when we are calculating reactance using some simple analytical formula, we are approximating that the flux is entirely axial, there are no leakages at the end or there are no ampere turn per mm imbalances and whatnot.

So, we basically tend to assume things which make the application of analytical formula possible. Similarly, when it comes to these resistances R_1 and R_2', as we know these are AC resistances. So, they are basically DC resistance of a winding plus skin and proximity effects or they lead to what is known as the AC component of the resistance.

And believe me to understand and compute this AC resistance in a practical device, it requires thorough knowledge of Maxwell's equations, theory of eddy currents, etc., which we are going to see in this course. Similarly, if you see this shunt branch of this equivalent circuit, which shows magnetizing reactance X_m and core loss resistance R_c. Now, these two parameters are extremely demanding in terms of understanding field behaviors and governing electromagnetic fields. As we know the ferromagnetic material that is used as core material of static and rotating machines, exhibits hysteresis characteristics, so there is not only a non-linearity but there is remanence and hysteretic behavior. So, in order to address this behavior and be able to take into account in a numerical method, it requires a lot of understanding of basics of electromagnetic fields, material science, and governing physics.



As I mentioned, here this is a typical leakage field plot of a transformer. This is a transformer window, core window and I am showing only one set of windings that means there is the other set of windings on the other side. So, this is the low voltage winding and the high voltage winding is in two parts with taps. Now because of these taps and because of this gap, which happens because some turns may be out of the circuit, you can see here the leakage field is basically turning here in this gap and there is a corresponding radial component of field in this zone. That makes the calculation of reactance as well as the eddy current losses in the windings difficult by using standard analytical formulae. And here again, that is why you need to use a numerical technique like finite element method.

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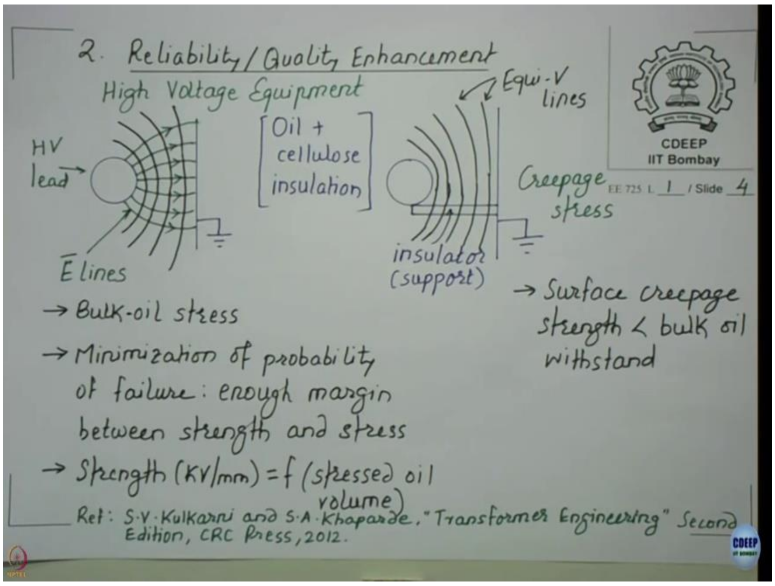

So the second focus of finite element analysis is typically reliability or quality enhancement. So, here I am showing a typical high voltage lead to ground arrangement in a typical high voltage equipment. So, this is a high voltage lead, this is a ground plane, these are equipotential contours, and these are electric field contours. We will see background theory of this phenomenon and the corresponding basics in next few lectures. Typically a high voltage equipment like a transformer or a condenser bushing has oil plus cellulose insulation.

And as we are aware, that insulation breakdown phenomena is highly statistical or stochastic in nature, it is a function of not only design parameters, but also a function of how the equipment is manufactured, whether the clearances that are designed are actually obtained or are there some impurities in the insulation which got introduced during the manufacturing, so all those aspects make the insulation breakdown phenomena highly statistical and unpredictable. So, that is why you need to have sufficient margin between the strength of the insulation and the corresponding maximum stress.

Now that difference between strength and stress is what decides the probability of failure. So, probability of failure will be high if the margin between the strength and the stress is smaller. So, by using finite element method, since we are actually going to get exact values of stresses and the corresponding stress distribution at various points, we will be able to find out exact margins that are available at various points within the high voltage equipment and be able to find out the margins between the strength and the stress.

And, a good insulation design is the one wherein throughout your electrical equipment if the margins between the strength and stress are more or less equal, that means you should not have a case wherein somewhere you are unnecessarily stressing the insulation very high and at some other places, we are actually under utilizing the insulation, which means it is not a good insulation design.

So, finite element analysis like the one that we are going to see in this course, will be able to tell you the stress distribution and then you will be able to find out the corresponding margins that are available at various points in the insulation structure and then you can optimize or improve the insulation design. In case of such typical high voltage equipment, you have oil and cellulose insulations. As shown here, there are two cases. One is the bulk oil stress, wherein the oil between the high voltage lead and the ground is getting stressed and then you have to find out the maximum stress which occurs at this point at the surface of the lead. And then you can actually minimize the probability of failure as mentioned by finding out the maximum stress by using FE analysis. And the strength, you can find out by various means maybe experimental curves that you may have or maybe using some theory like stressed oil volume, which we will see later in one of the tutorials.

There is another phenomena what is called as surface creepage. Now, the same high voltage lead is basically supported by an insulating structure here, on the surface of this insulating structure, you have these equipotential contours crossing, so along this surface you have potential difference and the corresponding creepage. So, this creepage phenomena is very important and it is well known that the creepage strength is less than the bulk oil withstand and that makes the creepage phenomena important to analyze. So, such things can be analyzed using finite element method.

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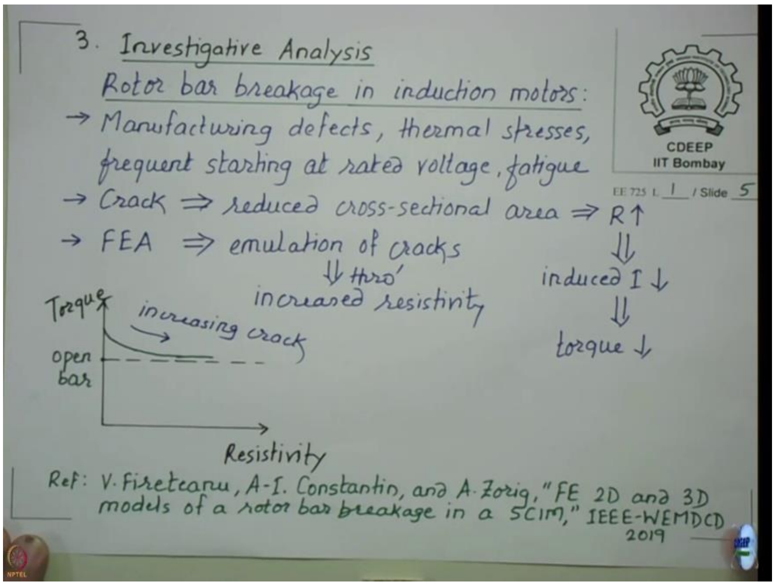

Similarly, you can do investigative analysis, for example, here we see how to do analysis of rotor bar breakage in case of squirrel cage induction motor. As you can see, this is a latest paper published in 2019. And researchers are exploiting finite element method's capability to help investigate the problems that are commonly observed in rotating machines. So, basically, you can have rotor breakage because of manufacturing defects or thermal stress or due to frequent starting at the rated voltage or maybe due to fatigue. A crack that gets developed due to such irregularities and stresses basically reduces cross-sectional area and increases the resistance, that increase in the resistance leads to lower induced currents and lower torque.

Now, what one can do is by a series of FE simulations wherein you can emulate the increasing crack by increasing resistivity, you can get a reference curve of torque versus resistivity and wherein this dashed line is representing the torque value of a open bar that is open circuited bar. So, once you get this kind of curve and when you have test results of a machine having such suspected problem, you can basically verify this with a reference curve and be able to predict the level of problem in case of the analyzed machine.

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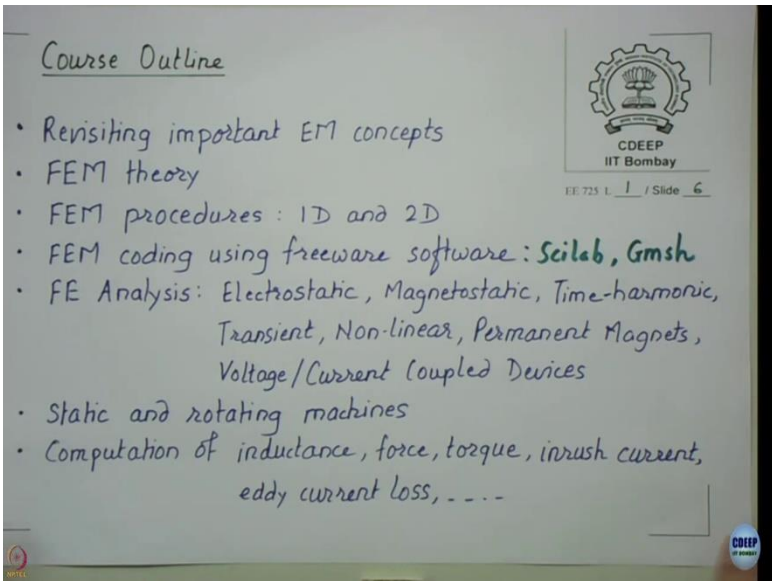

So, with this introduction we will see briefly the course outline. We will revisit some important concepts in electromagnetics, we will study finite element theory and the corresponding procedures for 1D and 2D problems.

Then FEM coding using freeware software will be covered. So, now what are the freeware software that we are going to use, so one of course is going to be Scilab, which is equivalent of MATLAB, Those who have registered for this course if they have MATLAB or any other commercial software, they are free to use that. But those who are not having such commercial softwares, for them we are also giving the option of using Scilab as part of this course, then there is something called as Gmsh, which is a meshing software that also we will see how to use that in conjunction with Scilab to develop your own 1D or 2D codes.

Then we will cover FE Analysis for electrostatic, magnetostatic, time—harmonic, transient, non—linear problems as well as for machines with permanent magnets, voltage and current coupled devices and so on. And then as I said, we will also see tutorials and case studies involving computation of inductance, force, torque, inrush current, eddy current losses and so on.

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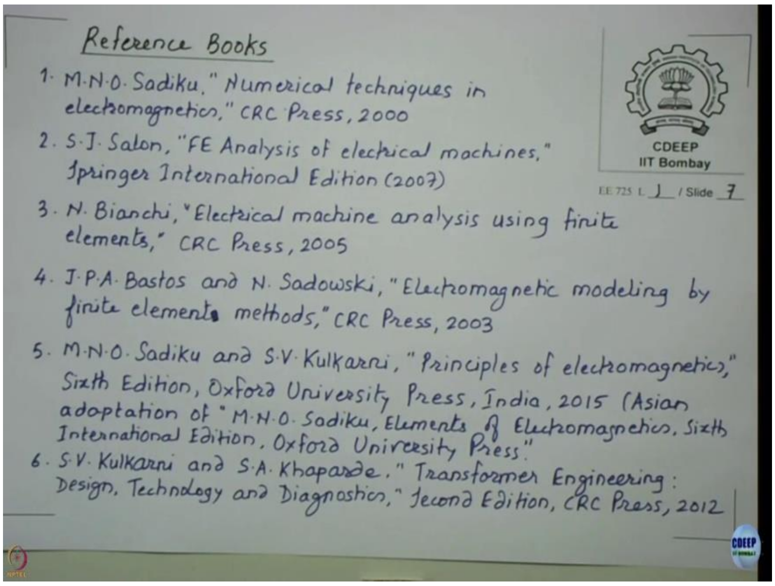

These are the reference books for this course, there are many books available, but during my academic and research career, I have mostly used these books. So the first book by Professor Sadiku is on various numerical techniques, particularly useful for low frequency electromagnetics. So, in books also you will find two distinct sets of books. One set of books are devoted to low frequency electromagnetic FE Analysis and other set you can say is devoted to high frequency electromagnetic FE Analysis.

So, these books that are listed these are mostly for low frequency electromagnetic analysis. So, the first book basically covers the various techniques that are available for low frequency electromagnetic analysis. The second and third books are quite good for analysis of rotating machines by using finite element method. The fourth book is good for understanding FE procedures. The fifth book is good for understanding basics of electromagnetics and theory related to finite element method at the introductory level and chapter 15 of this book is particularly good for finite element method.

The sixth book is exclusively dealing with transformer engineering and in this you have, the fourth and fifth chapters devoted to analysis of eddy currents and chapter 12 on basics of electromagnetic fields and finite element method, including coupled analysis. So, this book also will be a very good reference book for this course. And of course, there are so many other books exclusively devoted to finite element analysis of rotating machines. Like one is this S. J. Salon, second one and there are so many other books. So those also can be referred. And this is just a representative reference book on one of the products that is transformers. Thank you.

L1: Review Question

By preforming literature survey, study one or two examples (other than the examples explained in the lecture) for the following applications of Finite Element Method to any electrical equipment/ machine

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1. Parameter estimation
2. Reliability/ quality enhancement
3. Investigative analysis

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