Fundamentals of Electric Vehicles
Technology and Economics
Professor L. Kannan
Indian Institute of Technology, Madras
Lecture 17
Future Frontiers

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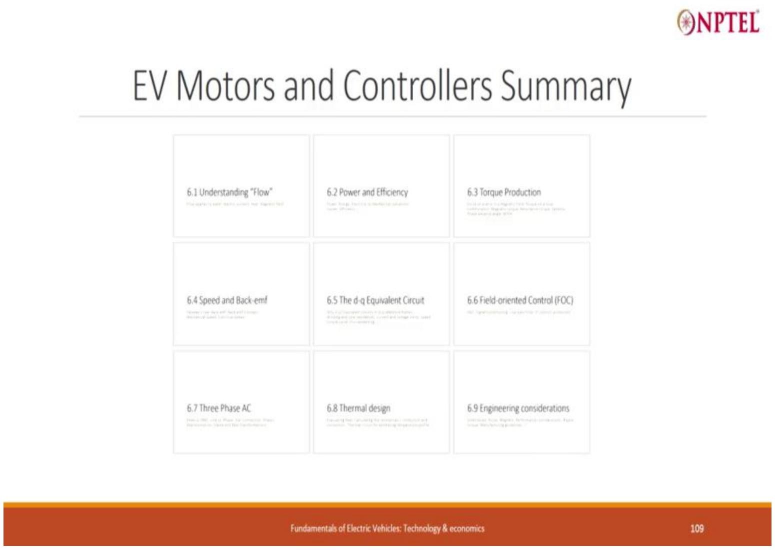

So, with this we come to the end of whatever we wanted to cover and discuss about in motors and before signing off I will quickly take you through a recap of whatever we learned.

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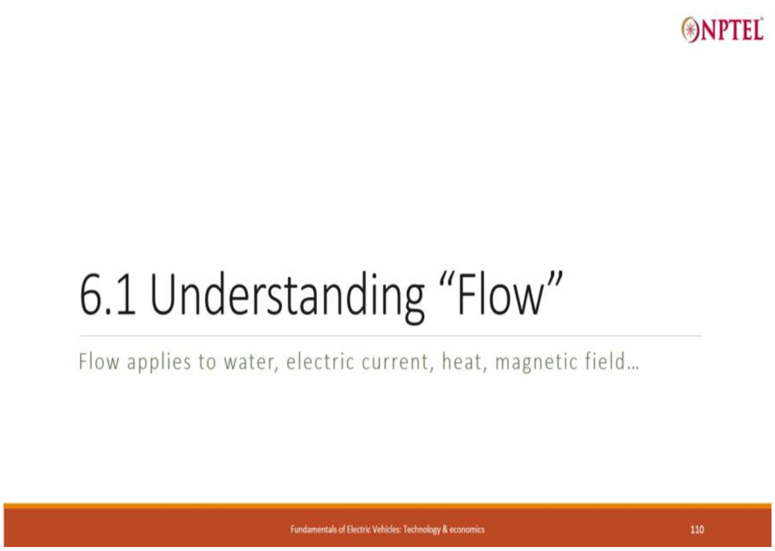

We started by looking at what is called Flow and flow has only 3 common phenomena associated with it. One is Ohm's law another is like conservation of mass which is called Kirchhoff's first law and the second phenomenon is conservation of energy which is called Kirchhoff's second law and if we understand these three things, we can pretty much describe all the flows that occur in nature and we discussed the 7 different flows that play out in a motor.

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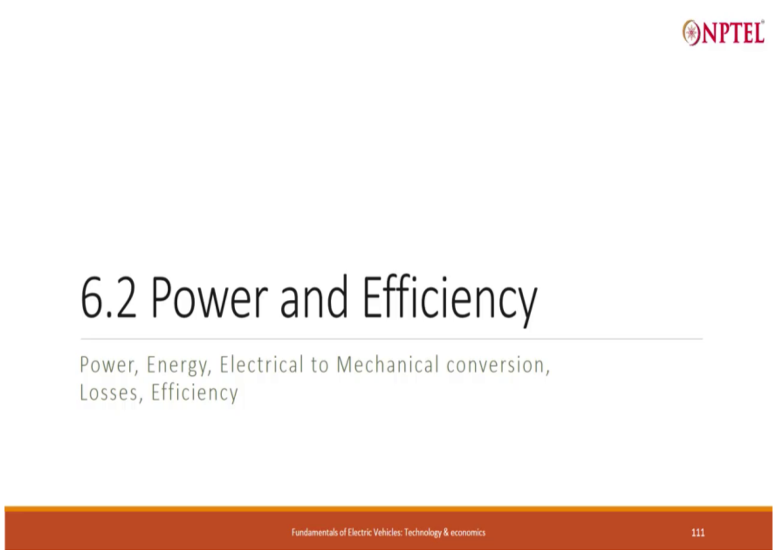

And the next thing that we looked at is about Power and Efficiency. How conversion of power from electrical to mechanical and happens in a motor and then the mechanical power from the motor is translated into translational mechanical power at the vehicle and along the way at every stage there are different kinds of losses and efficiency is a measure of how much useful output gets delivered compared to the input and efficiency will always be less than 100 percent.

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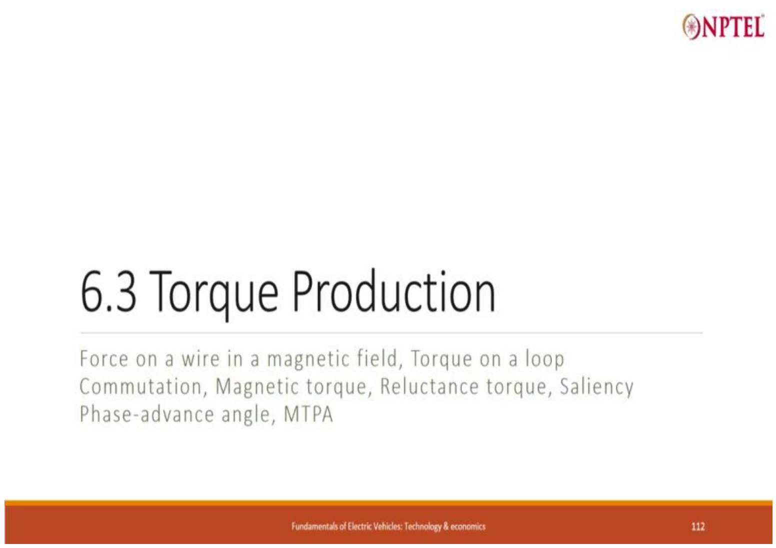

And then we went into some depth about torque production. Torque happens because electricity passing through a wire results in a force acting on the wire if the wire is in a magnetic field and this idea we extended by turning the wire into a loop and then we got torque and then we also explored very interesting phenomenon where merely the presence of steel in a magnetic field can cause what is called reluctance torque and we said we will go with IPMSM architecture for the motor because it gives us significant amount of magnetic torque and also a good deal of reluctance torque. So, the overall torque is very optimum in that and when we tried to optimize between magnetic reluctance torque, then we really optimizing something called the phase advance angle and that algorithm we called it as MTPA Maximum Torque Per Ampere.

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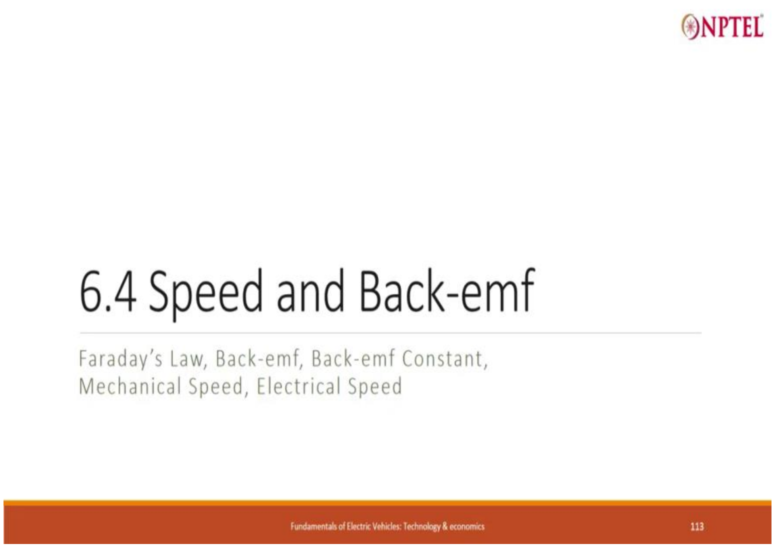

And just as torque is related to the current we found that the voltage is linked to the speed. If I increase the voltage the motor will run at higher speed, if the motor runs at higher speed it will demand a greater voltage and this comes because of what is called back EMF which is produced when the rotor is rotating and the reason for production of back emf is Faraday's law. And because of this back emf and the wave from associated with the back emf.

We also noted that there is something called electrical speed which is different from the magnetic field, magnetic speed the both are related but they are different and what relates them is that the electric field is P times the magnetic speed where P is the number of pole pairs mechanical I am sorry mechanical speed. So, omega E and omega M, E is the electrical speed and the mechanical speed that is we are writing. They are linked by the parameter P given by the pole pairs.

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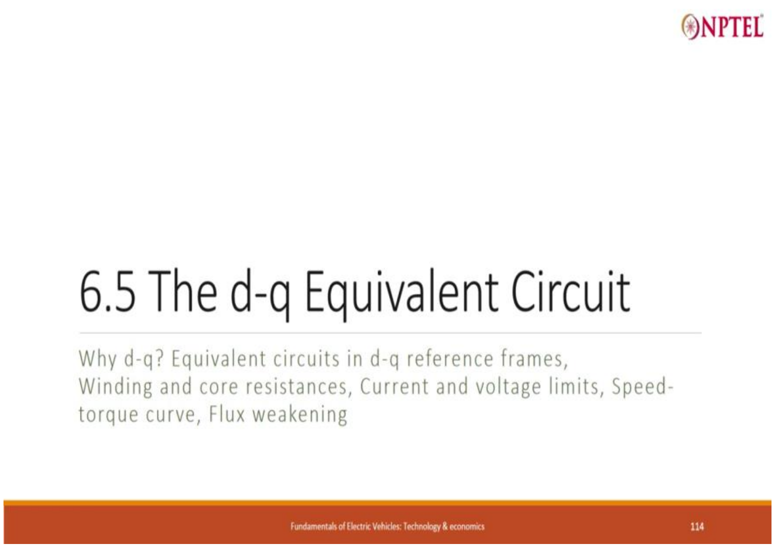

And then we look at what is called the d-q equivalent circuit which helped us to draw the motor as it were a pair of dc motors and dc is what we prefer because dc makes control easy and so we have one circuit diagram for the d axis another circuit diagram for the q axis and the vector sum of the voltages in the two. We developed a pair of voltages equations the vector sum of the pair of voltages is the actual physical ac voltage that is getting applied in this stator.

And based on this understanding using the d-q equivalent circuit we were able to define what is the current limit and therefore form it what is the rated torque. And then what is the speed limit defined by the voltage limit up to which we can get the rated torque. So, there is a certain rated speed up to which I can get the rated torque both of these are derived from the current limit and the voltage limit. And if we want to push the envelope of operation beyond the rated speed then there is this nifty technique called flux weakening by which I can push the operation and make it run at significantly higher speed for some loss of torque.

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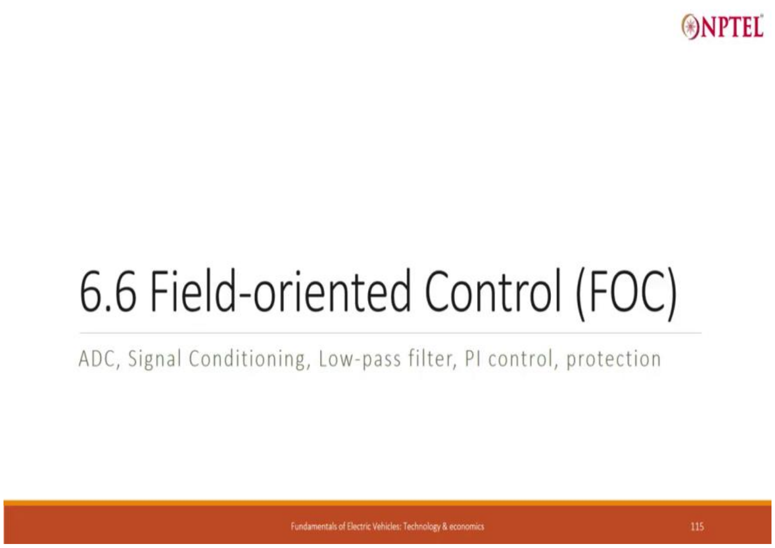

And with this knowledge we went into looking at how the controller works? The controller works in the control torque of the controller works in the dc domain because dc values are what can be control we talked about what is called PI control and the method of control is just nothing but MTPA on the one hand and flux weakening on the other. The combination of these two is all that is involved in the control but all of this is the dc domain. But then we have the to apply it on the motor which is an ac motor. We have to covert the values computed by the field oriented control algorithm. We have to take the dc values and convert them into ac values.

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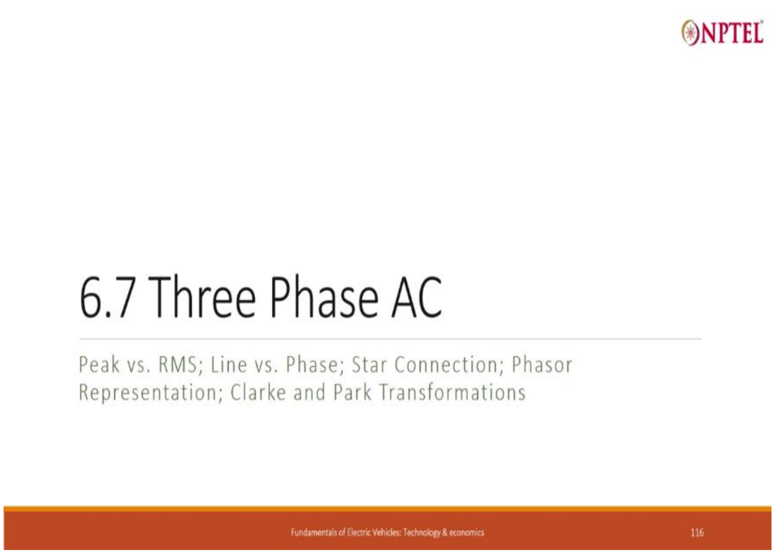

And for that we used what is called the Clarke and Park transform in the forward and the reverse directions to transit from dc to ac and then back to ac to dc

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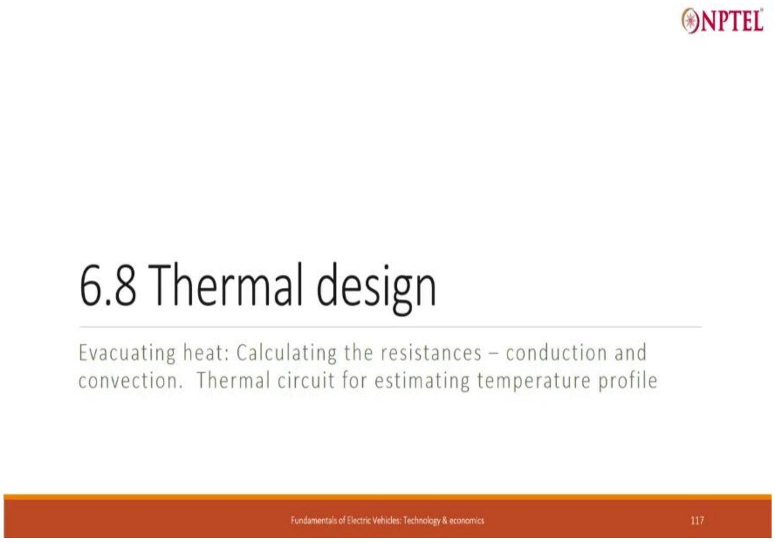

So, and then finally we looked at thermal design how the where heat is produced? How heat is evacuated? What can be done to improve it? How can we estimate the resistances along the way and from that how can we arrive at the temperature profile. And judge whether the peak temperature within acceptable limits or not.

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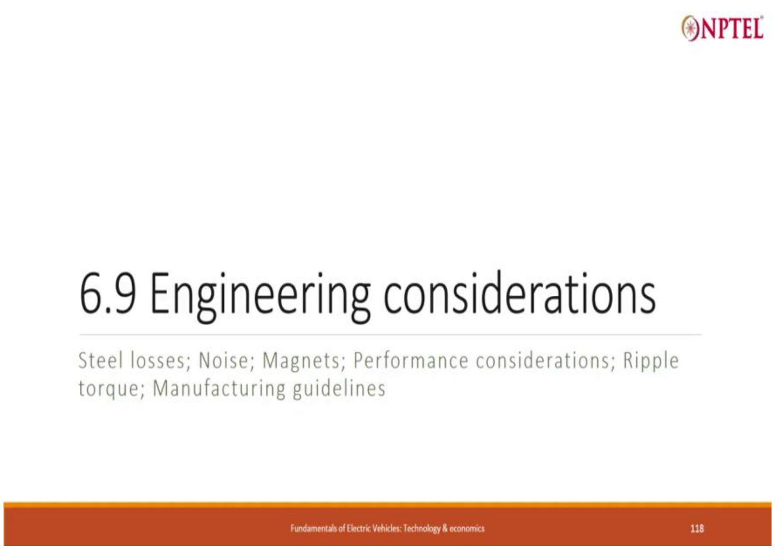

And lastly we looked at the number of engineering considerations about magnets, about selection of magnets, about noise, about balancing, ripple torque things that we have to be mindful of while manufacturing like shaft color, wavy version and other things.

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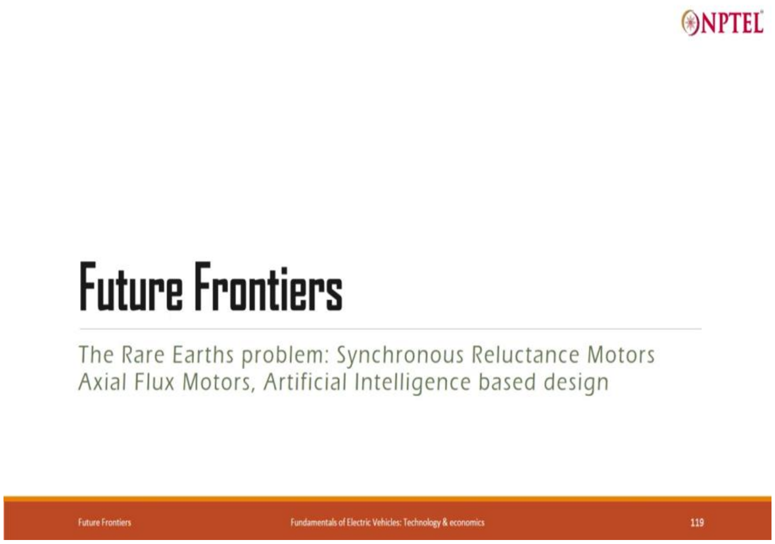

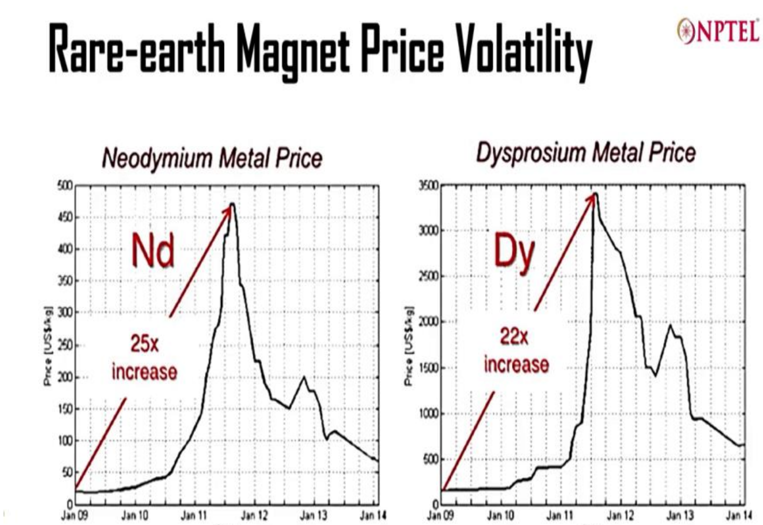

And so before I sign off I will just spend a couple of minutes in look highlighting some soft cutting edge areas which are been researched upon all over the world. This is the future frontier in motor design the first of this is about the problem with rare earth, rare earth are available very few places. India also has some deposits, there are some deposits in US, there are deposits in Australia, there are significant deposits in China.

But only China knows how to extract the metal from the ore, nobody else knows. So, part one of manufacturing of magnets is extraction of the metal part two is once the metal is extracted how do you magnetize? That is something that is reasonably more widely known that is also kind of difficult technology. But India can do it that is not the problem but the extraction of the metal is a very difficult thing and it is also very expensive thing.

It is very difficult to extract available in rare quantities which means the percentage concentration of the metal is very small. So, it is a very expensive set of materials that is why they are called rare earth. And in that context there is interest in something called synchronous reluctance motors. So, just to give you a picture of rare earth why we are so concerned. In a few years ago with a span of something like an year 20 to 25 fold increase in neodymium.

Which is the important metal for making the rare earth magnets happened and you can see that you know its price rouse up to almost 500 dollar's per kilo gram and even the rare earth metal which is about 10 times more expensive with the 8 times more expensive as neodymium is what gives it thermal stability. It is used in very small quantities compared to neodymium but it is also almost tens more expensive.

And if I do not add this dysprosium then the temperature stability of the rare earth magnet is very poor. So, this volatility in price in fact as I speak the volatility is again started because of tensions between US and China. And today if you approach your magnet manufacturer he will give you a quotation which is valid only for 2 days because it does not know what will be price after that the prices are just fluctuating up and down.

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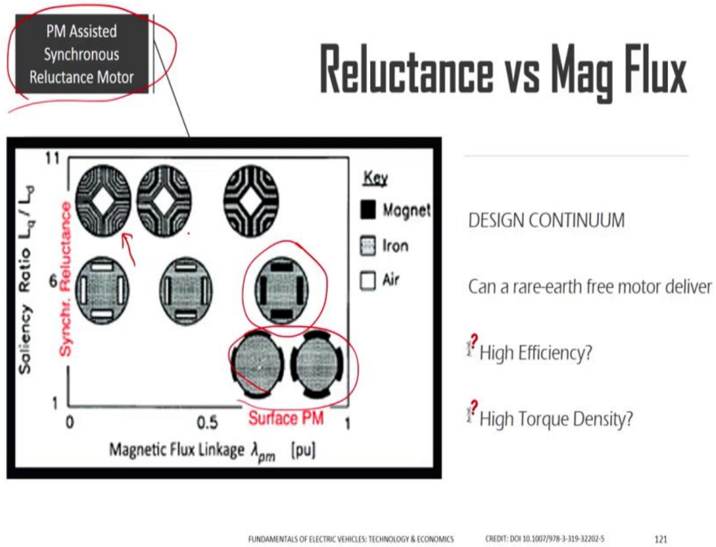

So, this brings a lot of uncertainty to the to people involved in electric vehicles and motors all over the world and in this context we discussed about reluctance torque and magnetic torque. Or reluctance torque is produce by the reluctance and magnetic is produced by the magnetic flux coming from the permanent magnets and we had said that we will not use surface permanent magnets because they do not produce any reluctance torque.

We instead operate what is called the IPM where a significant amount of surface permanent magnet torque is there and also reasonable amount of reluctance but if I look at the 2 coordinates the 1 coordinate being synchronous reluctance torque and the other coordinate being magnetic torque. I can actually design different kinds of motors at different places on this plane and something like this has very little magnet. And actually weak magnets you do not need rare earth.

And something like this has absolutely no magnet at all. So, that would be called a purely synchronous reluctance motor. Something in this region will be a permanent magnet assisted synchronous motor. But the assistance can be obtained from the normal ferrite magnets you do not require the rare earth. So, it is actually design continuum it is not like there is 1 category of permanent magnet and another without magnets.

You can have a transition and the most promising from sort of nearness of commercial viability will be one which ticks the help of some magnets but largely depended on reluctance torque. The challenge really is can rare earth free magnet deliver high efficiency and high density of torque and power not become very large in bulky.

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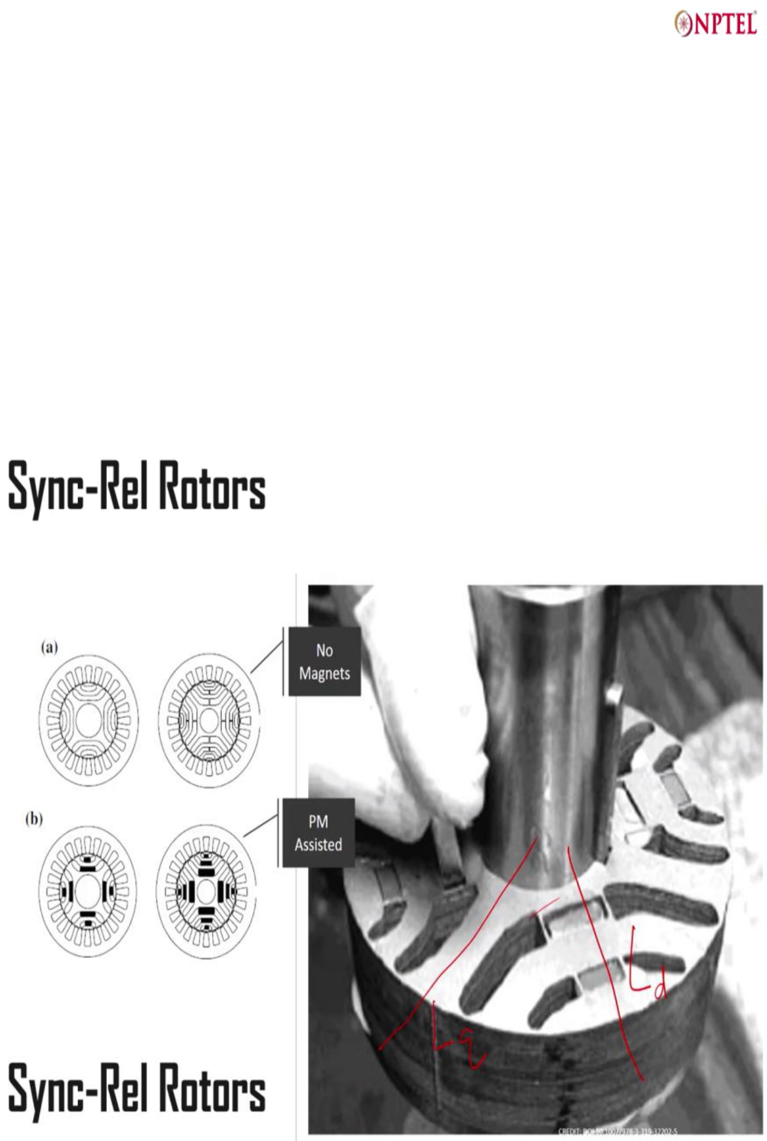

This an area of active research and so as I told you this will be the kind of rotor that have no magnets at all and these are rotor where there is a little bit of weak magnets. That is called the PM assisted magnet and this is how a PM assisted magnet would be assemble those little magnets are going into to the slots. What you can see here is that is the d axis and as you can see in the d axis there are large air pockets and magnets are as good as air. Or as bad as air in terms of reluctance.

So, this entire place has a very high reluctance which means very low permeance, n squared into permeance is the inductance so Ld is very low and here you have the q axis which is the very thick band of steel. And so Lq is very high and if Lq is much larger than the Ld then the saliency is very high that is what it means. So, Lq by Ld which is the saliency can be as high as 11 or ten in that range. Whereas in our normal IMP magnets the saliencies in the range of 2. That means Lq is 2 times Ld. So, we can bump up that ratio therefore generator large amount of reluctance torque.

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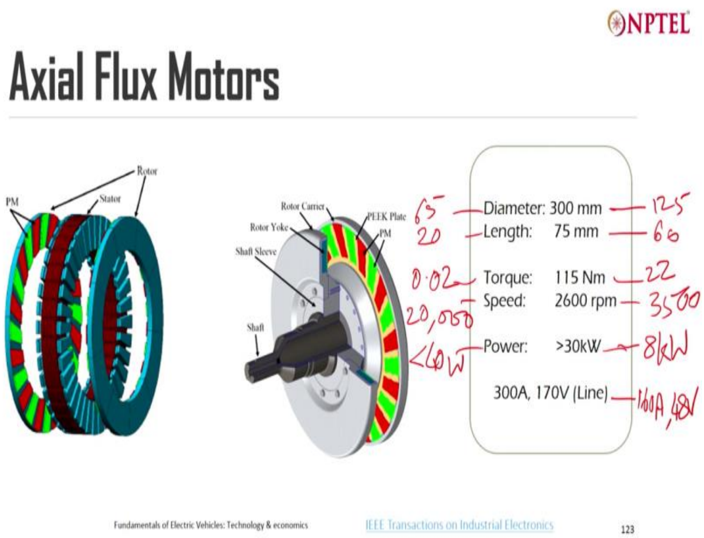

And another area which is interesting is what is called axial flux motors. Here the magnetic lines are parallel to the axis of rotation which is very funny. This is a rotor and this a rotor both the rotors they are like slices with magnetic poles facing each other and in between is sandwich the stator with the windings. And at the core of every winding in the conventional architecture we saw that the core is the teeth of this stator.

Here the teeth are also axially oriented parallel to axis and the lot of mechanical challenges because this static portion is in the center and around it the rotating portion is there. And you have to take the wires through a hole in the shaft and things like that. The interesting thing is that this picture is taken from a particular i tubbily paper with a 300 mm diameter the example that we looked at for the current limit which give a rated torque of 22 newton meter.

And speed rated speed of 3500 rpm the diameter was something like 125 mm and the length of the stack was 60 but the motor itself will be almost 150 mm long because there are OI hangs and then the housing and then cover in everything. So, the real motor length will be 150 mm but the stack is only 60 and the torque that we got there was 22 newton meter and the speed we got was 3500 and the power that we got rated power was 8 kilo watt.

22 newton meter into this I am just giving a comparison between the radial and the axial. Here you see the phenomenal torque is being obtained and interesting other example was of 160 amperes and 48 volts. but is here the voltage is about 33 and a half times more. So, we are getting a reasonably high speed of 2600 rpm because of voltage is high. If you we at only run it at 48 then we will probably get only one third of this speed say about 900.

So in every compact form factor it is like a sandwich slice we get a very high torque and that is advantage of an axial flux motor and at the moment we my team is building a axial flux motor. Which actually will do the opposite it will give a very low torque 0.2 newton meter but its speed is 20,000 rpm.

It is from industrial application not a EV application and its diameter is like 65 and its length is something like 20 mm and the power will be less than 40 watts. Not kilo watts so the axial flux apology is suited for very high torque and low speed application it can also be adapted to very high speed and low torque applications.

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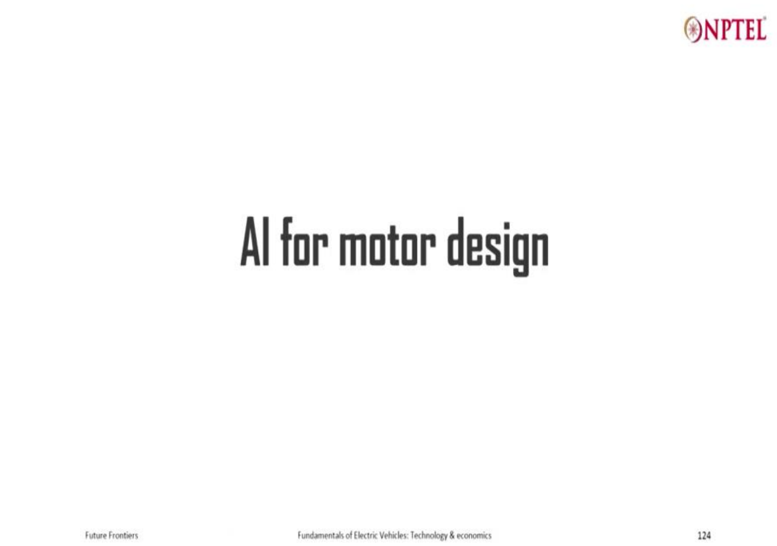

So this is another area and lastly I will just take you through another concept that our team is working on how to apply artificial intelligence in the design of motors.

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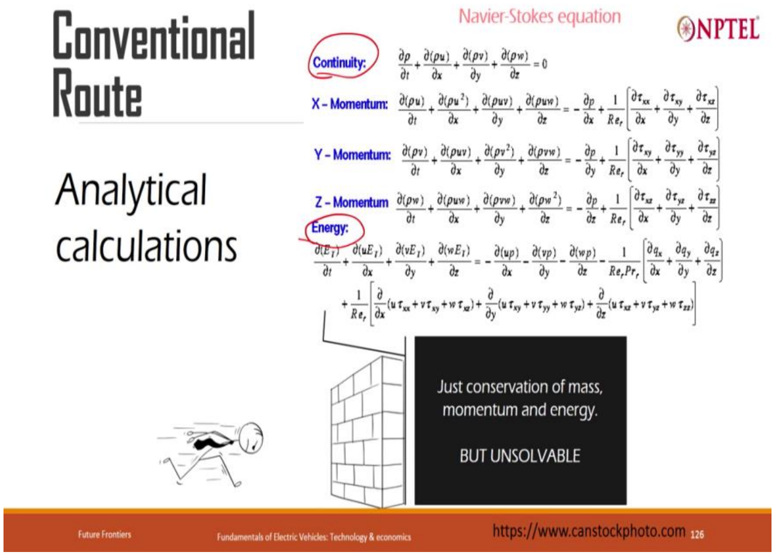

Conventionally the design of motors involves coming up with concepts that is the act of creativity of the designer. It is almost a miraculous act with any rational it comes from intuition, it comes from experience and things like that. And we tried to perform calculations based on the design on the design concept and we already discussed that continuity equations is Kerckhoff's first law energy conservation is Kerckhoff's second law.

There is also a momentum term all of these are common to all flows we can apply it to all the flows that we discussed in the motor also. But this is 200 volt set of equations which has not being solved till today because they are very complicated only special case is have been solved. So analytical calculations will only take us up to a certain distance and then we will hit her. Hit against and solve all.

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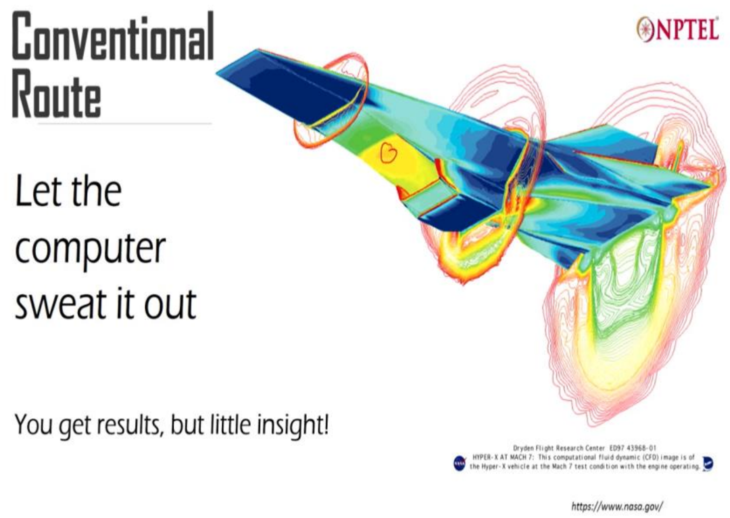

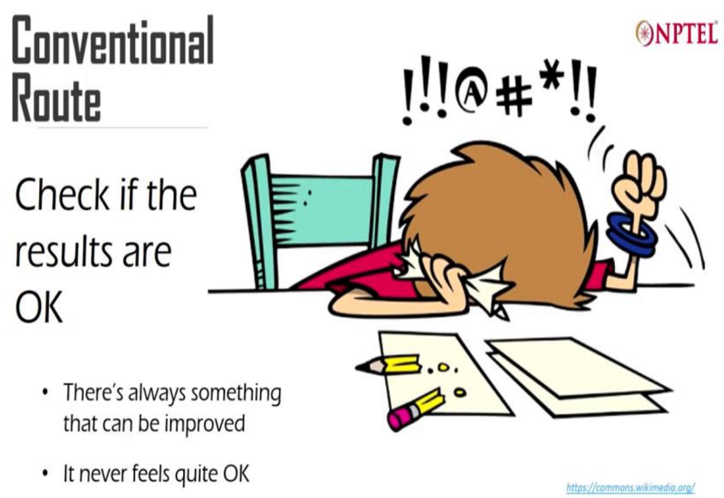

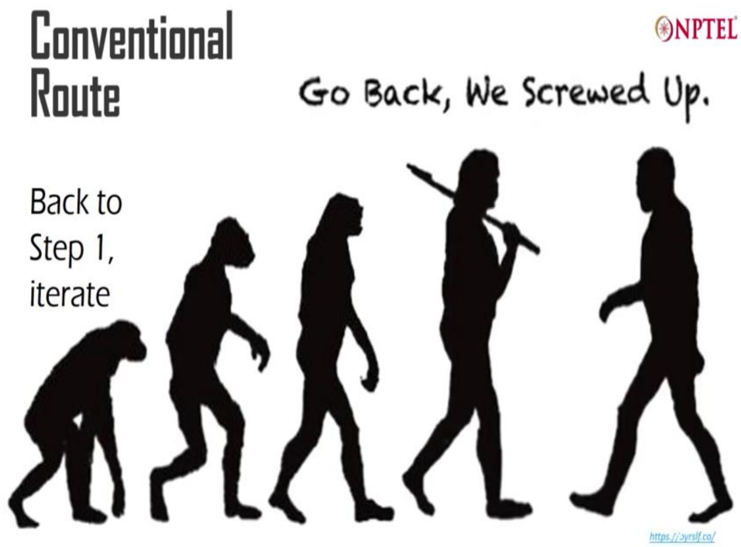

So, the next thing that we will do is we will just setup a schema in which millions of calculations per second can be done by a computer. And then it will gives us results and this is all right will get the results but we will not get much insight supposing I say I am finding that there is a little discoloration over here. I do not want it I only know that there it is there but I do not know how to get rid of it.

So, using my guess work again I will make some changes in the design again go through the simulation and see whether the thing is gone away but the computer itself will not be able to tell me that because of this you have got this temperature profile there and you have to changed it. So, what we do is we get the results we start with the design we actually start with some requirements in the design process then we come up with the design which may think will meet the requirements.

And then we go through a elaborate sequence or activities to get a result that verifies if my requirements are met or not. So when I get the results I have to compare it with my requirements and see whether the results are okay. Usually they are not somethings will be okay somethings will not be then what we do? I always (())(20:12) or something should be improved this is not quit okay.

I want a little bit more efficiency with this temperature not good many things I will find problematic so what do I do after this if I am not satisfied with the results at again start from the beginning after making some changes. So this is a very TDS process of alterative design trail and error.

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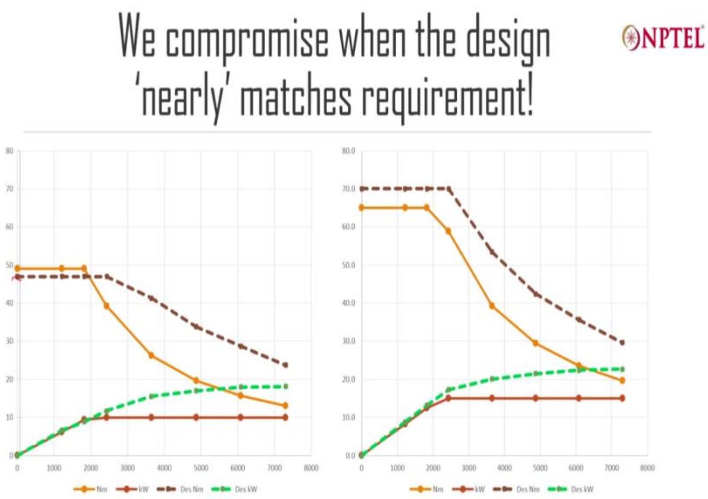

And finally when the design nearly matches my requirements I say okay now it is fine. It is time to just go on. Let us start making it so what you see here the dotted lines are the results of the design whereas the planes lines are the original requirements I started with and it is matching in some critical parameters that is matching but there are some deviation. It is alright I can leave with it. I am getting a slightly less torque than what I wanted, I wanted 49 but I am getting 47 it is okay. So this is a sort of compromise way of designing.

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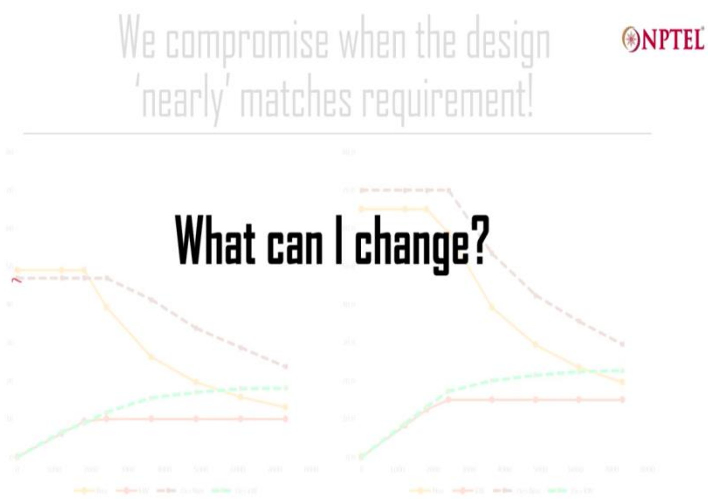
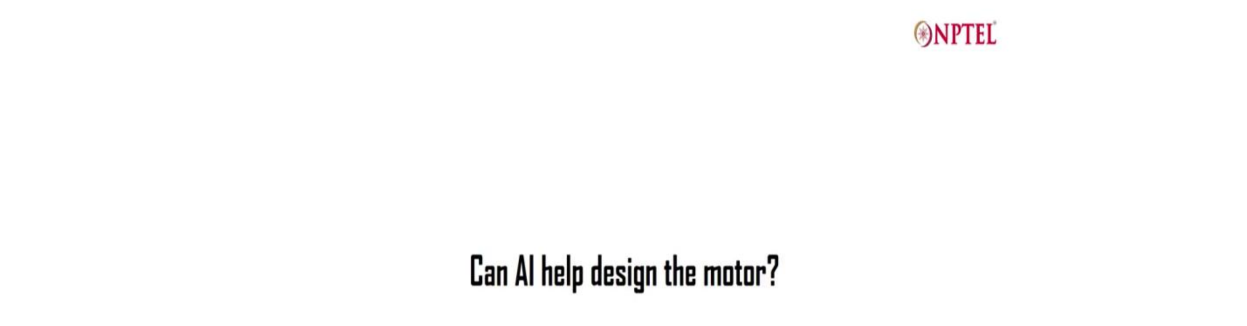


How?



And If I wanted to improve this further then I do not know whatever I have I have already done some 10 cycles 10 alterations of design and whatever is obvious I will change. I will change some geometry or I have changed the air gap I have changed the winding pattern. And number of turns whatever I was easy to do I have done. Now it is very complicated if I do anything to improve one thing. Something else will get effected so it is not clear what I can do. So this is where the question is can we use AI.

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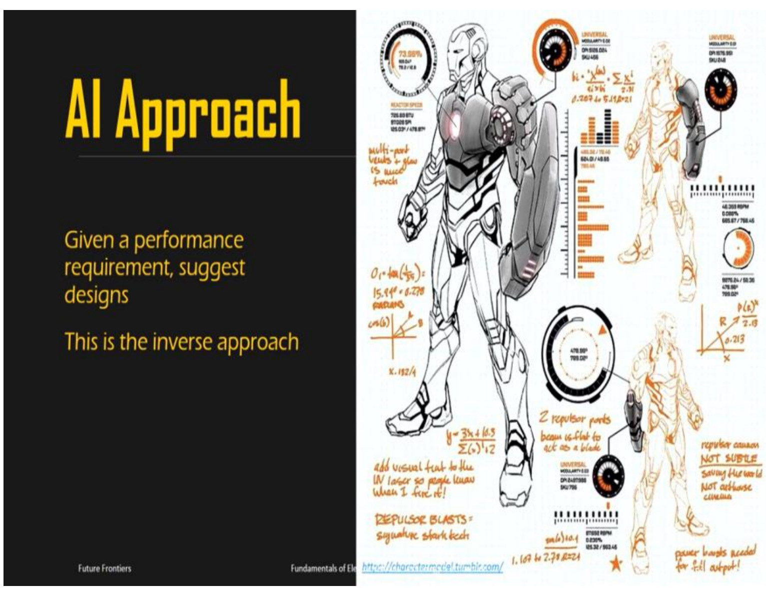

The approaches that we come up with the design we only specify the requirements to the AI system and the AI system generates design that meet the requirements. We hope it will be able to do it in a manner that is much more aligned to the design requirements than a alterative and unpredictable human effort.

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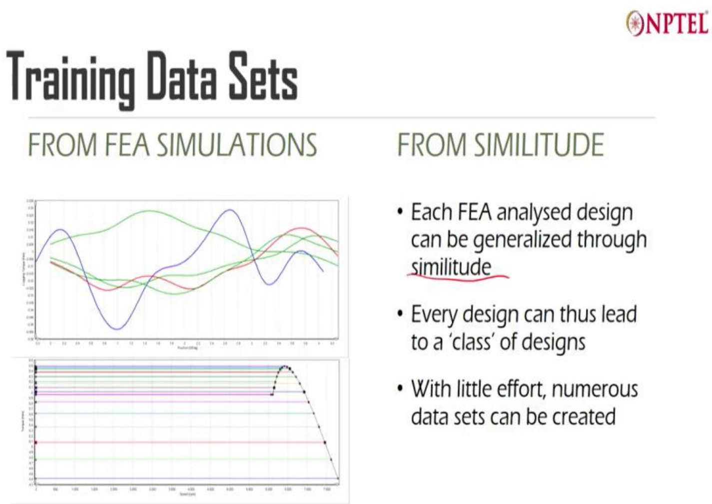

And for any AI system we first have to train the system by showing it a large number of examples now we do not have millions of motors. For example, we face recognition to distinguish between the face of a dog and face of a cat millions of terabits of photographs serf it to the system. We do not have so many motors to experiment and generate data and feed it to the AI system.

But what we can do is we can generate some samples by doing designs using the conventional FEA solvers and we also know for example we already know that inductance is proportional to the square of the number of turns. So, if I have design results for one which I write in the form of row in the spread sheet. One column for every parameter then if I change the number of turns form 2 turns to lets us say 3 turns then I know that the number of turns is multiplied by one and a half.

Then the inductance will increase by 2.25 so just by changing one parameter generated one more design. I can go on like that so this method by looking at 1 design and similar design I can generate by changing some parameter that is called similitude I can use that to multiply the number of design I have. And also each design can be made run at different operating conditions of torque speed ambient temperature and other things and I can generate further more.

So, I can generate a few 1000 designs without too much effort not millions but we do not need millions in this case because the variability in behavior in the case of say natural phenomenon like biological phenomena like dogs and cats and their phases and skin color and fur is very wide but here tight set of physic is integrating the behaviors.

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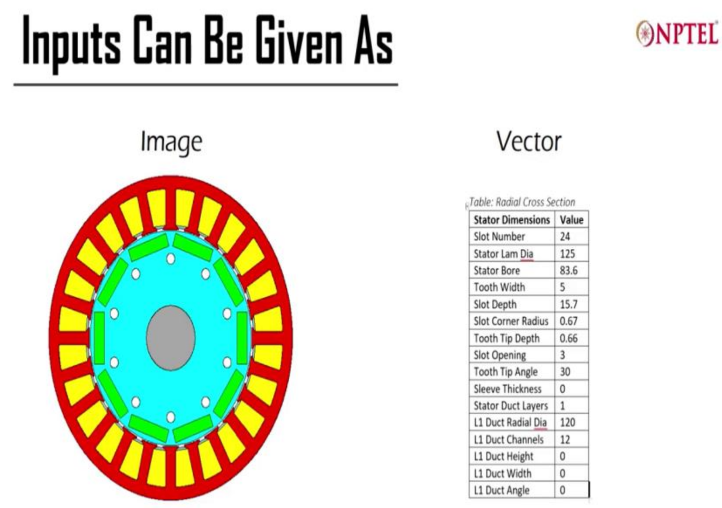

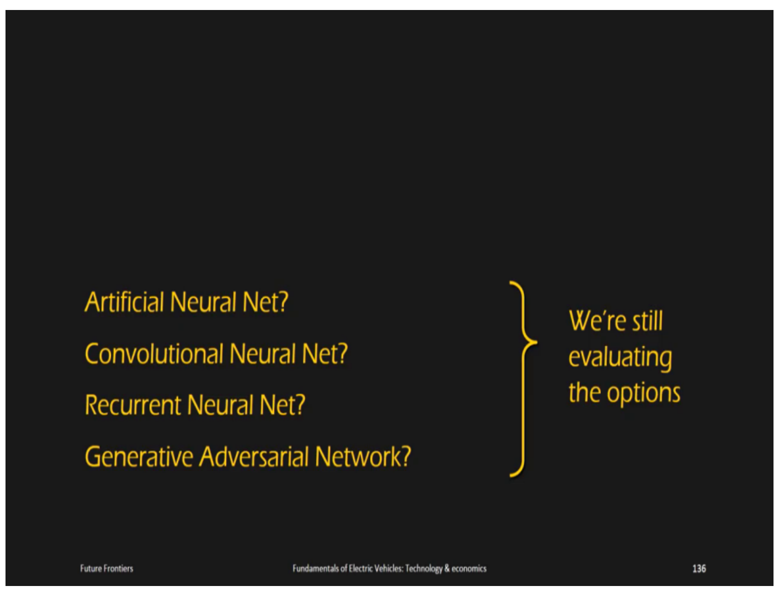

And having decided how to generate data how to do you provide the data to the AI system you can define it as an image or as a vector different frame works take different forms of inputs. We can provide an whatever form there is appropriate. There are different architectures of AI which I would not go into detail because this is course on artificial intelligence and we are still evaluating the options of which framework will work best for our application.

So with this we come to the end of the course thank you all. I think young professionals like you it is very heartwarming that you are all enrolled for this course. Andin India is probably going to be one of the largest markets for electric vehicles and even today even if you look at a category like rickshaws every year one million or more than a million rickshaws are getting added and every one of them run on important motors and controllers which is a shame.

Just like we are one of the largest markets for cellphones but all our cellphones are imported so but since this is the early stage of the way in electric vehicles. I am sure smart people like if you join this effort early on we can build every motor and controller needed for India and for the world here in India design as well as build. Thank you.