Energy Resources and Technology
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Lecture - 39
Magnetohydrodynamic Power Generation (Contd.)

Let us start today by recapitulating what we said in the last class on the subject of magnetohydrodynamics.

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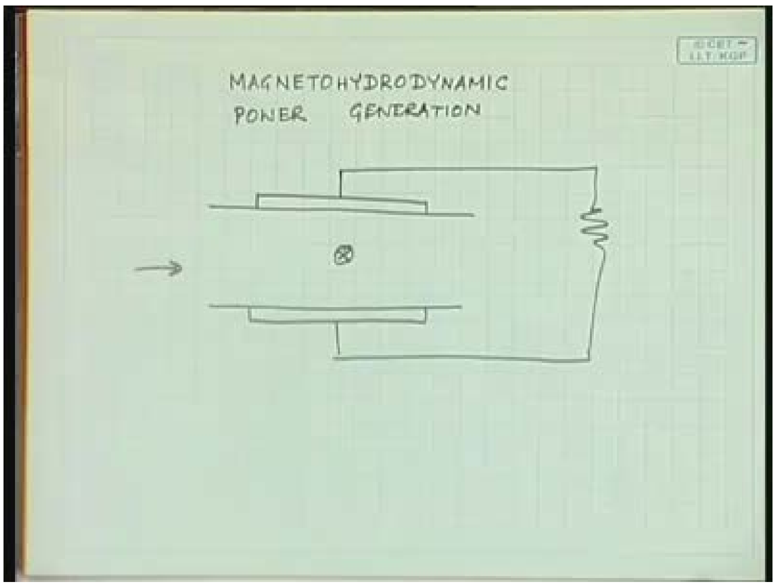

So, it was the topic of magnetohydrodynamic power generation in which the basic idea is that you have a hot gas created by burning of some gaseous or liquid fuel. That gas will be assumed to be in the plasma state which means that most of the molecules will have the electrons stripped off, so that you have ions and the electrons separately. That is the definition of the plasma and normally in a, in a gas that has been heated up by the usual fuels, you normally cannot reach that kind of temperature that will make it plasma, so the conductivity is artificially boosted by what is known as seeding. That means you inject a bit of potassium and caesium which adds to the level of ionization, so that you ultimately have a reasonable amount of conductivity in the gas.

So, the idea is that you will have a channel and through that that gas will flow and you put a magnetic field in this direction, so that this magnetic field will deflect the electrons and the ions to the two sides where there will be electrodes and the electrons would be deflected in one direction, the ions will be deflected in the other direction. In any case, the net result will be, there will be voltage difference produced between the two electrodes and if you connect an external load, then the current will flow, neat theory. But, ultimately when you actually want to make it there are certain scientific niceties that we have to understand and that is what we concerned ourselves with in the last class.

The first thing is that naively, one would assume that the electrons for example, will be deflected that is this way and it will reach, right.

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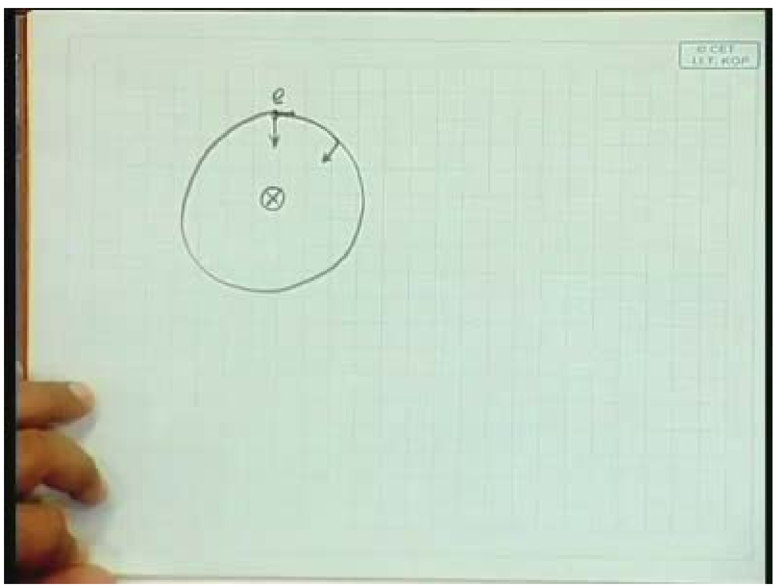

But, that is somewhat a naive assumption, because it does not really happen so, the reason being that if you have a magnetic field here and the electron say is going this way, an electron, then by the left hand rule you will, it feel a force along this direction as a result of which, it will be deflected like that. So far so good, but when it is in this position, it will no longer feel the force in this direction, it will feel a force in the radial direction. So, ultimately it is not difficult to see that it will traverse a circular motion, if it had the freedom to do so. But in reality, it does not have the freedom to do so, because there will be other ions and electrons around, so it will actually collide.

So, whether it will be able to traverse or what length of the arc it will be able to traverse that depends on the mean free path and the mean time between the, mean time between collisions. If that is small, then it will be able to traverse only this much. If it is large, then it will be able to traverse may be so much, on an average. So, we are taking about things on an average. But what is the main thing to understand is that because of this motion in arc, there will be two effects created.

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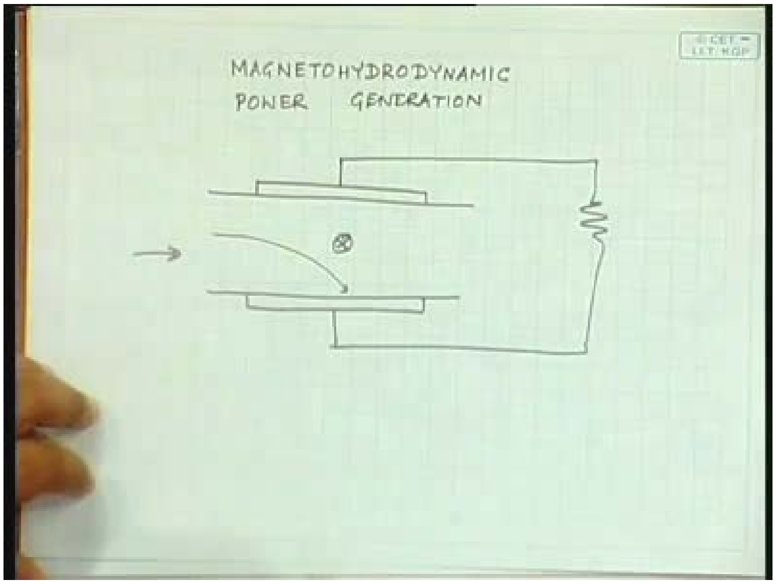

One, the one that we naively expected that means creation of a voltage. That is because the electrons are deflected this way which means there is a component of the velocity this way, this way, right and that is creating the voltage difference. So, let us analyze this.

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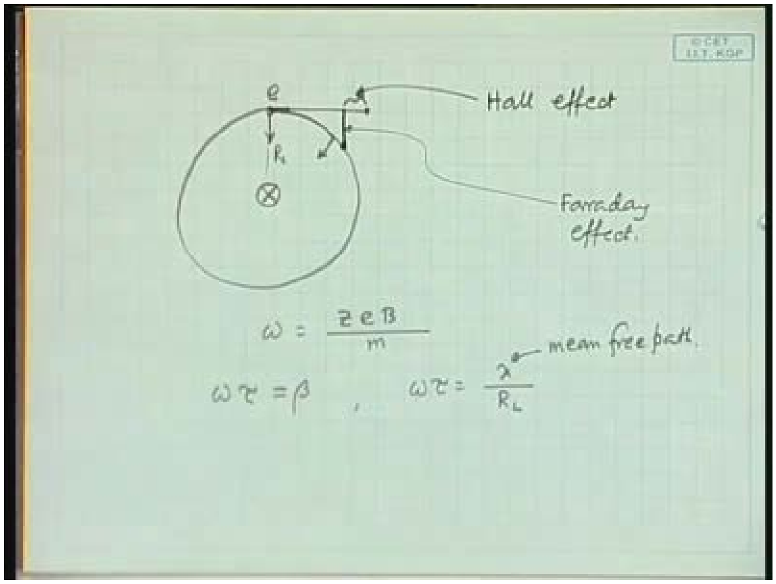

If you analyze this, you will find that if this magnetic field were not there, then it would, it would have travelled to this point. Because it is there, it has travelled up to say this point. So, it has moved in the y direction. y direction means this is assumed to be y direction, with this assumed to, the direction of the flow of the plasma, is the x direction and that is a y direction and this is z direction in which the magnetic field is there. So, there will be a motion in the y direction and this motion is what we want and this motion is called the Faraday effect. But in addition to that, there will be another motion. That is if there were no magnetic field it would have travelled to this extent, but because of the magnetic field in the x direction it has travelled only up to this extent, which means that the charged particles are sort of falling back from the rest of the plasma.

So, if you imagine yourself moving at the speed of the plasma that means you imagine yourself in the frame of reference of the plasma, you will see the electrons falling back, electrons falling back means a current in that direction. Say, the plasma is flowing in this direction you will see the electrons falling back. Electrons falling back means effectively a current, effectively a current in the direction opposite to the falling back of the electrons. So, there will be a current that is represented by this amount of the falling back. Yes?

Student: Sir, but will not it come back in that direction, because it will be following a circle?

No, no, it is not ultimately following a circle. It is following up an arc and after that it is undergoing a collision and again it is starting another arc. So, it is not really going round and round and round, in that case nothing will happen. This part is the Hall effect. That is what we discussed in the last class that this part is the Hall effect, which will be seen as a voltage that is generated in x direction which we initially did not anticipate. So, there will be a voltage generated in x and the y directions, there will be current in the x and y directions and when we talk about this kind of motion, there will of course be some kind of angular velocity, right and we have shown that the angular velocity is given by, omega is given by Z e B by m. e is electronic charge, Z is the number of electronic charge that are there in that particle. So, if it is an electron Z is 1, if it is some other ion Z could be a number and B is the magnetic field, m is the mass of that particle. So, that was the omega.

In addition to that we will have to consider, in order to, in order to quantify the extent to which it moves before it undergoes a collision, what will it be dependent on? The mean time between the collisions so that is tau. The larger the omega, the larger it will move before collisions and the larger the tau, the larger extent it will move. So, this whole thing how much does it move before the next collision that is quantified by omega tau which we had written as beta, just to shorten the notation. So, this omega tau is the quantity that we are now concerned ourselves, we are concerning ourselves with and if this radius is R L, then we had written that omega tau is lambda by R L, where lambda is the mean free path.

Obviously, this omega tau will depend on what? Omega will depend on B, the magnetic field, other things remaining more or less known; m of the electron is known, e of the electron is known, Z of the electron is known, so what is the variable thing? B, so omega will depend on B and what will tau depend on? The mean time between collisions, how many particles are there in unit volume and that will obviously depend on the pressure.

So, if the pressure is low and the magnetic field is high, you will expect this beta term to be high. If the pressure is high and the magnetic field is low, then you would expect the beta term to be low.

Now, let us see what kind of complication does it lead to?

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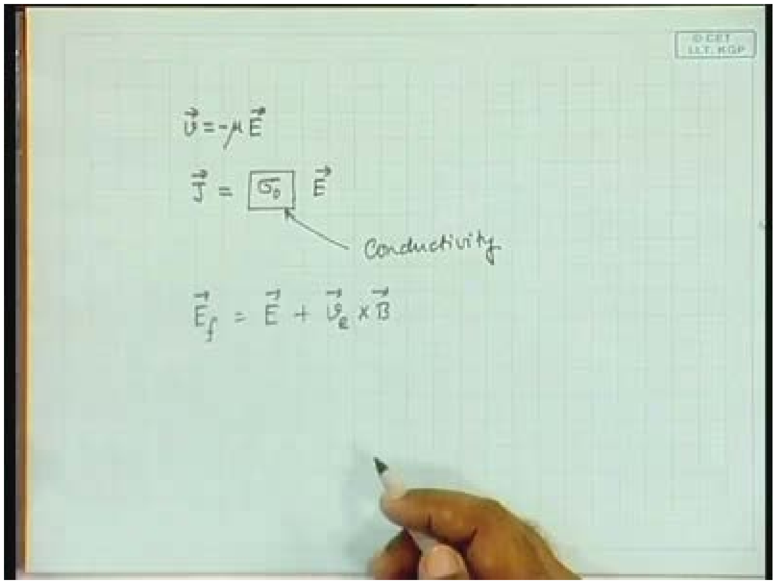

If the electric field is E, then each particle will move with a velocity v that is equal to minus mobility times E vector. If it is an electron, then the actual movement is in the opposite direction, so we will have put the minus sign. Now, from this we have, we were able to write that the current vector, current density vector, because here the current will not make sense all that much, because the current that is flowing through unit area, the current density that is that is given by some term times and this is nothing but your, written like the ohms law it will be current is equal to the, no, conductivity, conductivity times this. So, here it is the conductivity.

So, if you have the electric field this much, depending on the conductivity there will be current this much, we can straight away write that. Now, suppose there is a particle and there is an electric field induced. Because of the electric field it will move and because of the movement, magnetic field will work on that. So, the magnetic field working on the electron, moving electron will produce another electric field. So, the electric field will be a sum of two things. We can write the electric field effective is the electric field that has been induced plus the movement of the electron cross B. These are all vectors.

So, because of the electric field E, the electron moved with a velocity v e and because of that a v cross B electric field was additionally induced. So, the effective electric field will be this much. That was the logic and on the basis of that we had argued that there will be, these are all vectors in all possible directions. It will be difficult to write down equations in terms of each of these vectors, so we broke them down into the individual direction x, y and z.

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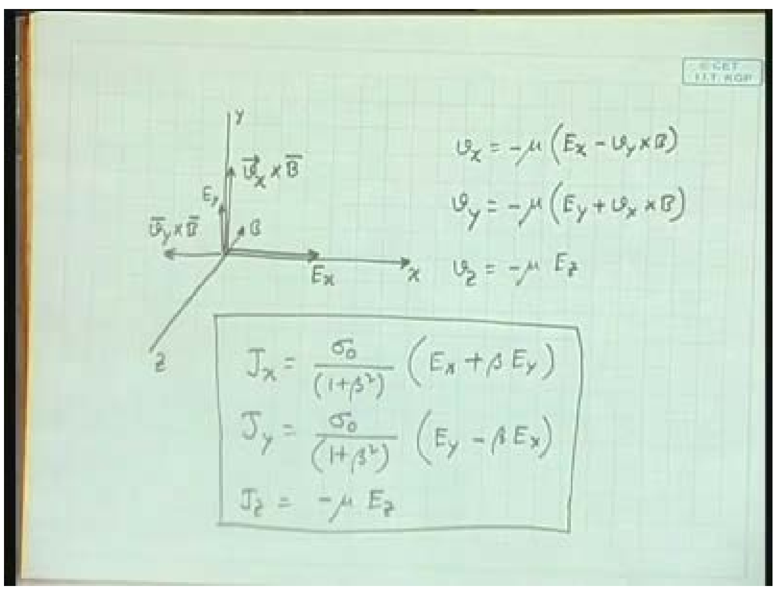

If we do so, then we can write the equations as, let me draw the coordinate axis and then it will be easier for you to understand. Here is the x, here is the y and here is the z. Because of the E x, there will be a E x and the v in the x direction, B is in the z direction. If there is a component of the velocity in the x direction v x, because of the B there will be an additional voltage induced that would be in which direction? v cross B; v cross B, it will be in the y direction that will be v x cross B.

Similarly, if there is a velocity component in the y direction what will be the result? v y cross B, in which direction will it work? This was the B direction, remember; v x v y cross B that direction. So, this will be the direction of v y cross B, right and nothing will really happen in the z direction, because any motion in the z direction will be unaffected by the magnetic field. Based on this, we can write v in the x direction, resultant B, will be minus mu of the E which will now be, which will now be E x minus v y cross B, E x minus v y cross B.

Now we are writing in scalar terms, so that it is easier for you to, us to manipulate. v y is minus mu. It will be, there was the E y in this direction, E y plus v x. These are not really cross because we are now considering scalars, so it will be just multiplication sign. v z is into … Now, here you notice that v x is a system of equations in which v x appears in the left hand side as well in the right hand side. Here also v y in the left hand side as well as in the right hand side. So, you can solve this equation and extract these outside. Once you have extracted v, you can write the expression for the current density. That was the simple logical structure with which we were proceeding and in solving this we had reached the equations J x, current density in the direction of x, would be sigma naught divided by 1 plus beta square E x plus beta E y and J y is sigma naught by 1 plus beta square. I am not doing this proof all over again, you can easily do that on your own.

So, these were the equations with which we were proceeding. Notice that here is the current and here are the voltages. So, it is sort of a representing the, what?

Student: …

Because, the

Student: …

Because, the other terms are not affected.

Students: …

No, it is, there is no electric field in the, no there is no electric field in the z direction, because the structure is …

Student: …

Yes, magnetic field is in the z direction only. That is why this is unaffected.

Student: …

Same thing, yeah, mobility, it is written in mobilities term, but it is effectively that. So, we have these equations with which we will proceed and now a general understanding, whenever you have any generator, be it a DC generator, AC generator, a photovoltaic generator or whatever, there is an open circuit voltage and the moment you load it, you will find the voltage across the terminals will reduce, right. That you, that you have found in the photovoltaic panels; that you have found in the DC machine. In the DC machine you called it by a say a specific name.

Why did it reduce? Because there was a back EMF, there was a back EMF. So, the actual induced voltage is the generated voltage minus the back EMF, we were writing that way all the time. Here also there should be something like that.

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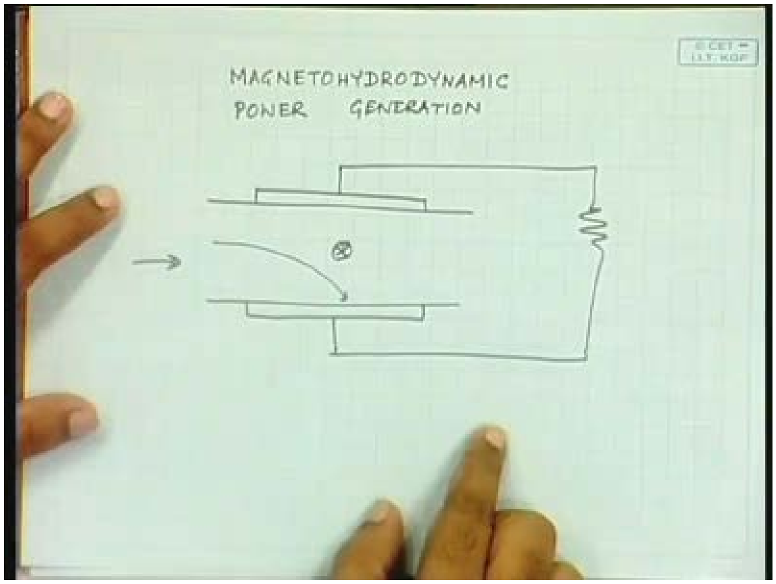

That means when you say that there is an arrangement something like this and you have this one cut off, there will be some voltage induced and then when you connect the load, current starts flow and then at that time, the voltage that is seen across the terminal will be different that some kind of resultant voltage that you see. In between there is the equivalent of a back EMF that will come into the picture.

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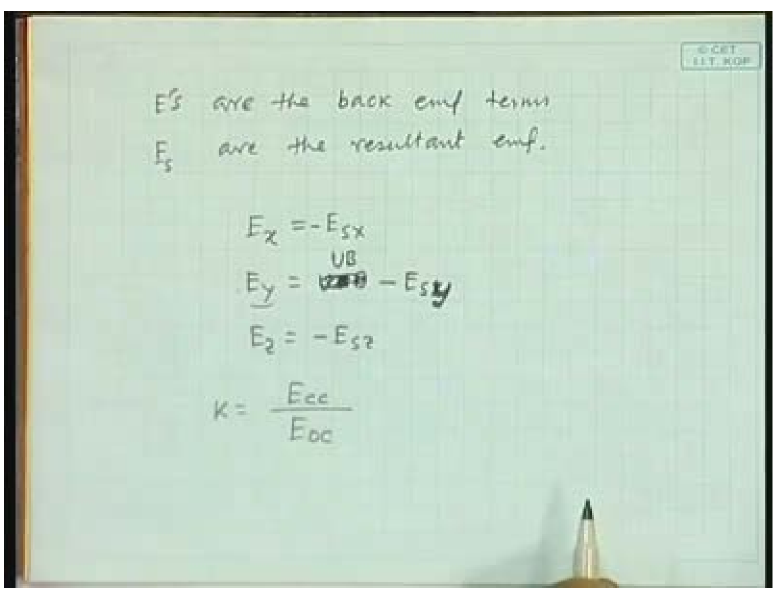

So, if we say, if we give the name E and E S, so E's are the back EMF terms and E s are the resultant, then we can write, again in x, y and z directions, E x is the back EMF in the x direction since the current is in the y direction, so therefore we are, that is what is seen as the E sx, no not really, minus. E y will be the generated EMF minus the resultant value. So, generated EMF is the velocity U cross B that will be the generated EMF minus E sx. E z is nothing but the same thing minus E sz. So, you see, it is not x, this is times or I will, I will simply write UB. What?

Student: Sir, minus E sy.

Yes, you are right, sorry. So, what it says is simply that if you have it open circuited, then your E s and E xs are the same. Then, the back EMF E y E sy, okay, consider now the situation when the output is shorted and output is open. So, in these two cases this will represent the voltage that is internally generated minus the resultant. That is the resultant is you can also see it this way, the resultant is UB minus E y that means the generated EMF minus the back EMF is the resultant EMF. That is what we have written, but we have deliberately written E x, E y, E z in the left hand side, because we will generate our equations that way.

In addition to that we have to understand one thing. That is suppose this one generates a particular voltage when open circuited and another voltage when close circuited, then how much is the loading? How do you quantify that? Simply by, the voltage when it is close circuited divided by the voltage when it is open circuited. That will represent the loading, extent of loading. So, we had defined a loading factor K which is the E closed circuit by E open circuit. On that basis, we had gone on to analyze the different types of image de generators. Let us go ahead.

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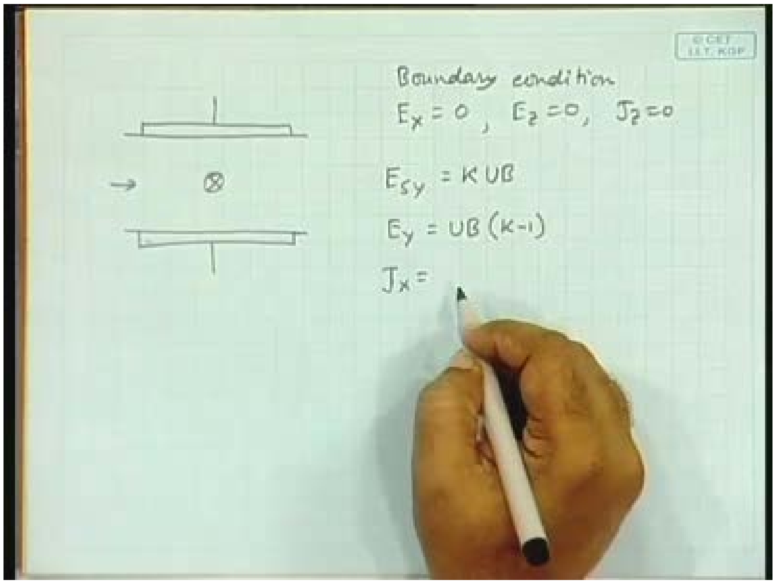

So, when we go to the next stage, we will see that suppose we have the channel like this, the magnetic field like this and the electrodes like this, so it is flowing like that. If it is like this, then we have already imposed some kind of a boundary condition. What is the boundary condition? We have forced the voltage only to be in y direction. Because this is a long electrode, there cannot be any voltage in the x direction. Why? Because, they are shorted, this side and that side are shorted by the electrode itself, right. As a result, there will be no voltage in the x direction. So, we have imposed a boundary condition. We were so far writing general equations, but now we have imposed the boundary condition that E x equal to zero.

We also have the boundary condition that E z equal to zero. There is no voltage in that Z direction and E z equal to zero and also, of course there will be no current in the z direction, so J z equal to zero. These are the boundary conditions that we have imposed by having the electrode structure like this. The result of forcing the voltage to be in the y direction would be that the current will not be in the y direction, right. We have already decided, we have already concluded that the current will then be in a direction different from that. That means there will be some current flowing in the electrode itself. Is that clear?

The logic is that we have decided, because of the Hall effect, there will be the Hall effect, here we have seen the Faraday effect, but there will be the Hall effect in that direction, but still we have forced the voltages to be the same. As a result, there will be current in this direction. Current will be in the, not in this direction, but somewhat this direction. What is the meaning of current being in this direction, the resultant current being in this direction? Current will flow like this that will flow out through the outside circuit. But, there will be additional current flowing through the electrodes that will be lost. Let us quantify this.

In quantifying this, we had said that E sy is, now it will not exactly be UB. Why? Because, because of this factor, because of this factor your open circuit voltage was UB. So, closed circuit voltage, the voltage that is ultimately imposed will be K times UB, so it will be times K. U is the velocity and B is the magnetic field, K is the loading factor. So, E y will be, by this, UB minus K UB which is ... and you have your E x is zero, so J x, we have already written down that, is this.

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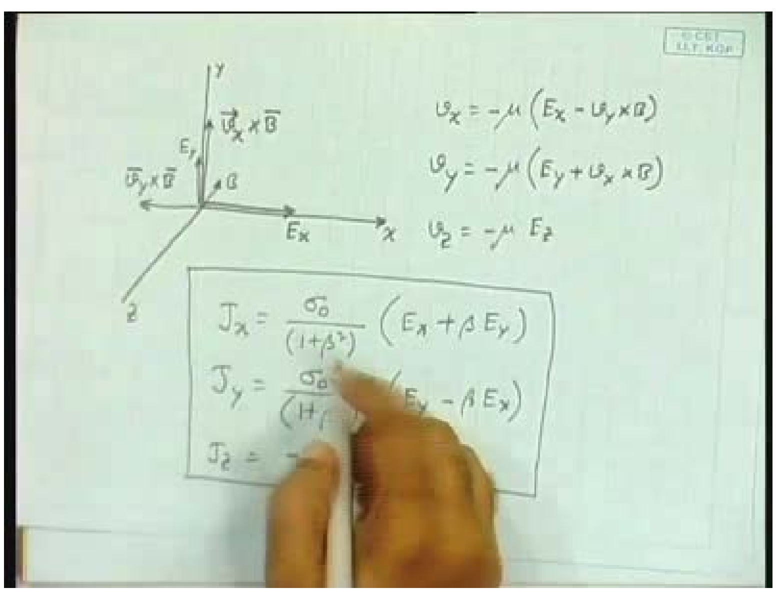

So, we have to just write down this here.

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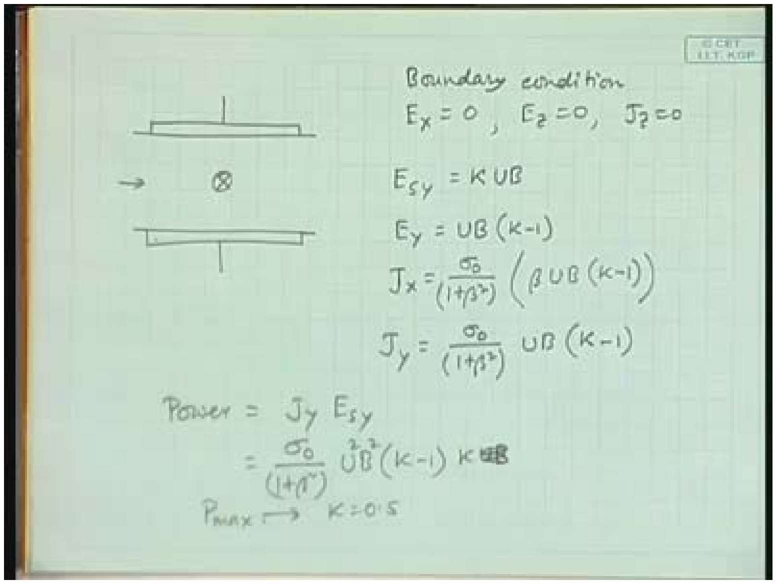

Sigma naught 1 plus beta square by here E x is E x is zero, so this will only remain, beta E y which is … Fine, this is okay. J y will be sigma naught by 1 plus beta square, it will be UB K J y, use this, E y is there, x is zero, so E y we will write and J z is, obviously we are not concerned with J z really. So, we are concerned with these two. We are concerned with how much is the power flow and the power, power per unit volume is J y times the resultant voltage E sy. This is equal to sigma naught by 1 plus beta square UB K minus 1 times E sy is K UB, right. So, this becomes U square B square and this.

Student: …

So, now we had proceeded to find out for what value of K does the power maximize and if you just differentiate this term with respect to K, you will find that it maximizes at K is equal to 0.5. So, we had concluded P max happens at K is equal to 0.5. We had actually proceeded over this point in the last class, so we go ahead from there. We notice a few problems here. One, that there will be a current in the x direction. This current, this current and this current is actually not taking part in the power production loss. So, that is something that is undesirable and its quantity, we can see, depends on the beta. So, we conclude that for situations where the Hall effect is large, this generator will not perform very efficiently, because of this term. Because, this, see conceptually it is like this. The voltage is like this, but the current is like that, only this component of the current is taking part in the power, so much this is removed the angle, that will determine how efficient it is and the angle depends on beta, clear.

The larger the beta, the larger the angle and therefore, this generator will not work efficiently for large beta. Just recall, what caused the large beta. The large magnetic field, but the large magnetic field was also necessary to produce a large Faraday effect. So, we come into sort of a situation where we need something. We need a higher beta, a high magnetic field, B and the moment we do that, we find that Hall effect is increasing. So, that is something undesirable. But, we will later see that that effect we can overcome by some other means. But, is that clear?

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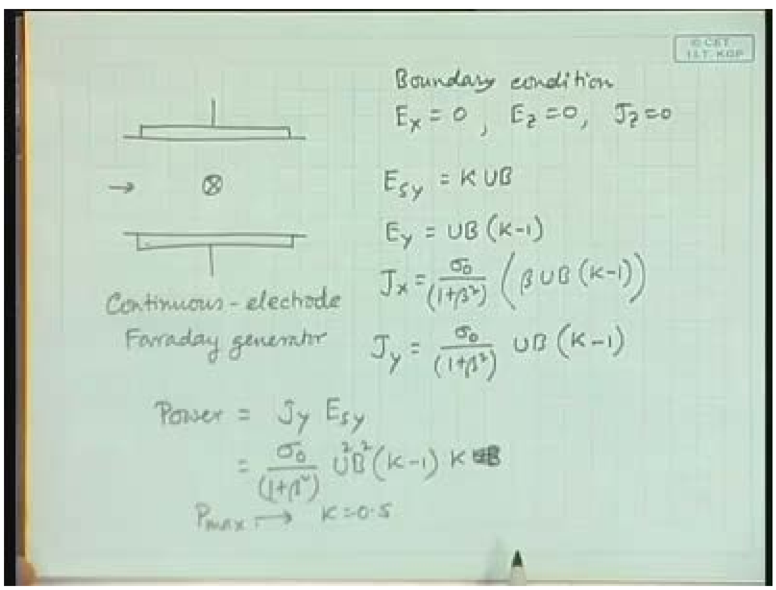

Now, this configuration of the generator is called the continuous electrode Faraday generator, good. Now, in order to overcome the problem that I just pointed out, people have invented other ways of utilizing that power.

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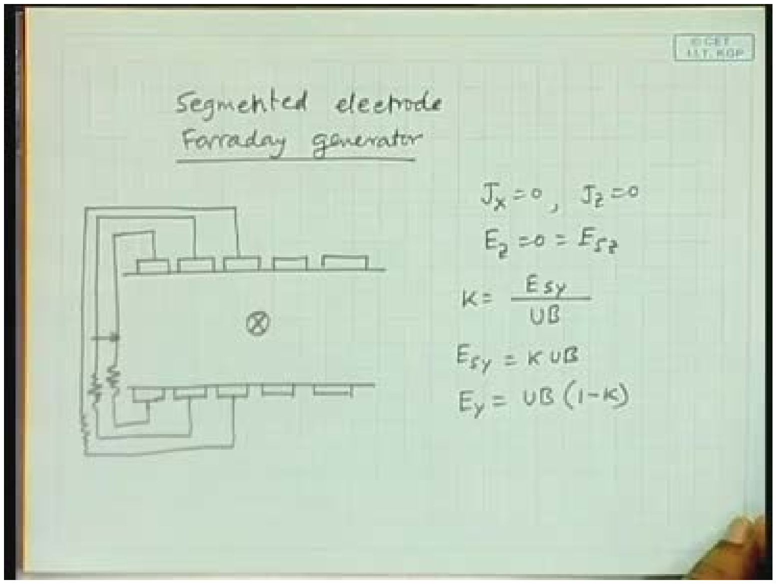

One of the things that are really used in some of the practical situations is what is known as segmented electrode, segmented electrode Faraday generator. The segmented electrode Faraday generator is one in which this is the flow direction, this is the magnetic field, these are all, all right, but in order to avoid the flow of the current in the x direction, we breakup the electrode into a number of separate electrodes like this. In between, there would be insulations, so that this electrode is not connected to this electrode. As a result, the current cannot flow in that direction, but the result will be of course that, well this electrode is connected through a load to this electrode, this electrode is connected through a load to this electrode and so on and so forth.

As a result, the current, the voltage is forced to be in this direction. No, the current is forced to be in this direction. Current is forced to be in this direction, but nothing prevents there to be a voltage difference between these two electrodes. So, if we force the current to be in this direction, there will be a voltage difference in these electrodes. So, there will be E x. In the x direction there will be a voltage. In the earlier case, by having a continuous electrode we prevented voltage to be in that direction, but now there will be a voltage. But, will that be a problem? Let us see.

In this case, so, I do not have a different colour. In any case, let me schematically show you. The load structure will be like this and so on so forth. All this will be connected through separate loads; that is important. They cannot be put parallel, because in that case it will be the same as the continuous electrode. In that case what have we done? What is different theoretically between this configuration and the earlier configuration? Here, the boundary condition is that J x is zero, right. The current cannot flow in this direction, we have prevented it. Of course, J z is also zero. What about the voltages?

Only E z is zero. This is also equal to E sz. But, the other two things are zero. E x remain, remains, E y remains, J y remains. So, let us see now how the equations will be like? K is the open circuit voltage in the denominator, closed circuit voltage in the numerator. So, that is the definition of K in this case. So, we can write E sy is K UB and E y is UB. So, on that basis, we continue. Now, we can write the equation for this. Let us see what it leads to. Here, that is J x which should be equal to zero, right.

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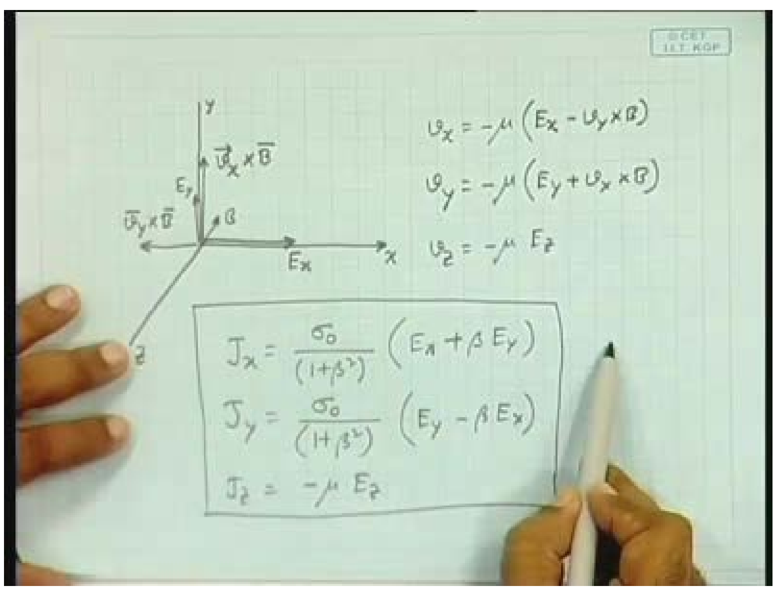

So, let us write …..

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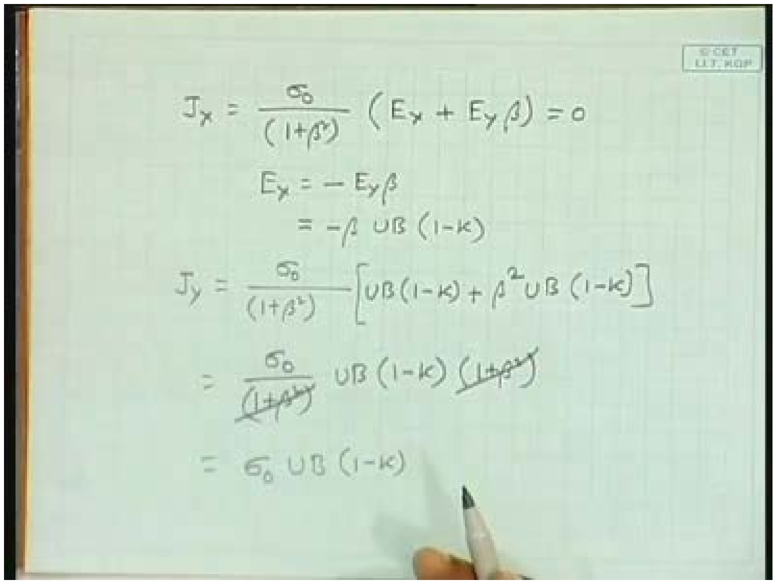

J x equal to sigma naught divided by 1 plus beta square E x plus E y beta. This is equal to zero. This will be equal to zero when E x is equal to minus E y beta, right and E y we can substitute. It will be minus beta, E y was here, UB 1 minus K, fine. The transverse current J y, again we can write sigma naught by 1 plus beta square, J y was E y minus beta E x, both these remain, both these remain; so, let us write E y first. E y is UB 1 minus K, then minus beta E x. E x is this, so plus beta square UB 1 minus K, fine. We have substituted here. This is sigma naught by 1 plus beta square, here UB 1 minus K comes common, UB 1 minus K into 1 plus beta square, right. Because it cancels off, okay, let me write it and then try to figure out what the meaning is. Because it cancels off, the y direction current is independent of the Hall effect, so there is no dependence on the Hall effect directly.

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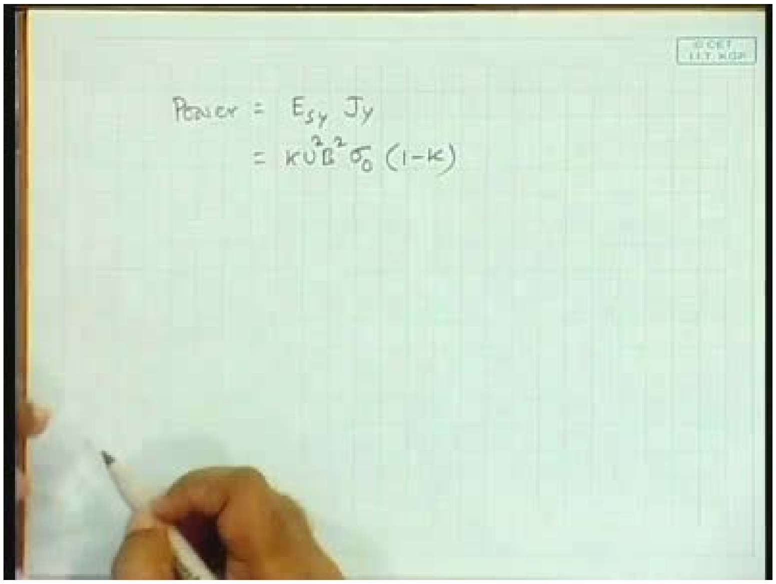

So, we can we can now write the power per unit volume is E sy J y. E sy is, E sy was in our case K UB. Now, J y was sigma naught UB, so it will become square into 1 minus K. This is also independent of beta. The power generation is then independent of the Hall effect. So, that is the major advantage of the segmented electrode Faraday generator that independent of the Hall effect you generate the power and that is why this configuration has the maximum power output, out of all possible generator configurations. Is that clear? But, you can see, still see some elementary problems with this.

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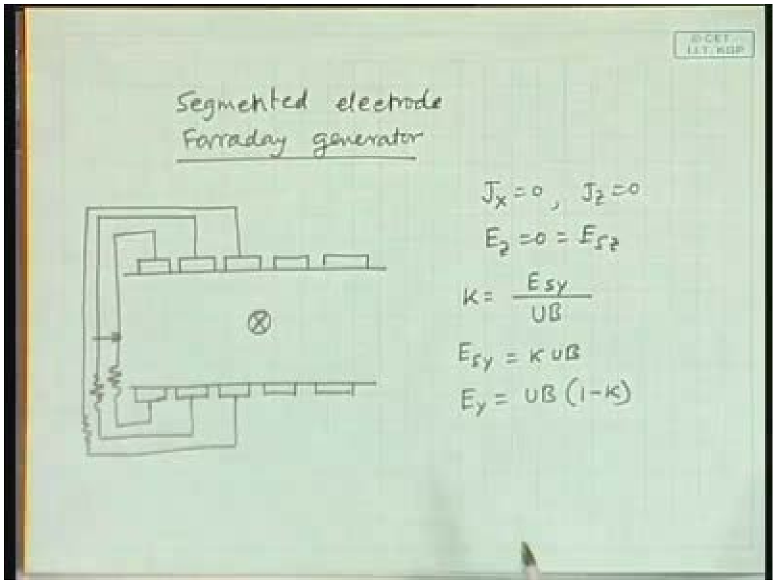

There will be a multiplicity of loads. Each opposite pair of electrodes will have to be connected to separate loads, right. Now, that can apparently look like a hurdle. For example, here there will be one light, here there will be another light or a fan, here there will another something, so obviously that will be a problematic arrangement. No, not really, because all these are essentially like separate DC generators, right and nowadays, you have the power electronic converters available, by which all these different voltages, all this will be at different voltages, all these different voltages can be converted to a single DC voltage and then that can be converted to AC voltage to be fed into the line.

So, from here the way I have shown really, this is not the actual configuration that is used. These are individually connected to separate DC to DC converters, each converting it to a single DC voltage to be connected parallely and then we convert it to, we either use the DC voltage for some purpose where DC is the required input or we simply feed it to the line by converting it into AC by inverter. So, this is not really a big hurdle. But, when this MSD generator started being used, that was 60's, mainly they were used in the erstwhile Soviet Union, there are many combined cycle power plants there that where the topping cycle is magnetohydrodynamic, but then the power electronics was not all that developed and that is why this was considered a big problem. That is why many of these are still in the continuous electrode Faraday generator mode.

There is another generator that is considered in situations where we use superconducting magnets, so that the B is very high and at the same time the pressure is low. Pressure being low means what will be the, what will be the palpable effect of that?

Students: High beta.

High beta; that means the tau, the mean time between collision will be large. So, it will be high beta. So, if you have deliberately created a high beta, then people thought why not use the Hall effect and not the Faraday effect, because the Hall effect will be then larger than the Faraday effect, right and that is why another configuration of generator is used that is called the Hall generator.

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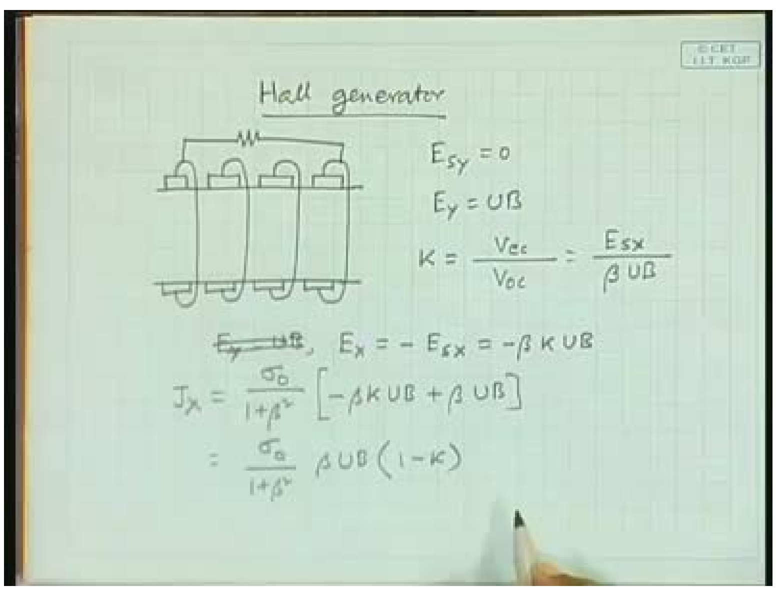

That is called the Hall generator. It is not difficult to figure out the structure of the Hall generator, because here there will be this channel and there would be the separate electrodes, remember. But now, you are trying to utilize the Hall effect which is in the x direction, not in the y direction. So, what you do is these are shorted bringing the x voltage to zero, y voltage to zero. As a result, there would be a voltage gradient here and you can then connect a load like this. So, that is the configuration of the Hall generator. Obviously, this will not be used in the Faraday effect at all. We had started by thinking that we are, we are devising a method of using the Faraday effect, but here the Faraday effect is nullified, shorted and we use only the Hall effect. So, in that case what is the boundary condition we have imposed?

The resultant voltage in the y direction is zero. So, we have imposed E sy is zero. So, E y will be the generated voltage, Faraday voltage, will be the back EMF. So, the Faraday voltage UB that is generated in the y direction that will be nullified by that; so that is what the equation is. As a result, there will be no resultant voltage in the y direction, because they have been shorted. In this case of course, we need to redefine the K, because so far we were defining K in one way, but now the whole thing is in the x direction. So, we will need to redefine the loading factor which will be, it will still be V closed circuit by V open circuit, but now the closed circuit voltage will be in the x direction E sx, fine and in the denominator, open circuit is no longer UB. The amount of the open circuit voltage in the x direction is beta times UB, right. So, that will be the definition of the K.

Now, let us see what the result of this change is. You will have E y, we have already seen this is equal to UB. This is, this is already written. So, let me not write it again. Let us see what happens to x direction. E x that is what we are using. It will be minus E sx that is what we have already written. That will be, we can write again …., minus beta K UB. E sx is beta K UB with the minus sign here, from here. So, we have written the E x. What will be the J x and J y? x direction current will be there, y direction current, yes will be there, because we have shorted it. So, we, there will be x direction current, J x. It will be, we can write the equation that we have already written, 1 plus beta square.

Now, here J x is this E x plus beta E y, which we will substitute. E x is minus beta K UB minus beta plus beta E y plus beta equal to beta UB comes common, right, so that is the x direction current.

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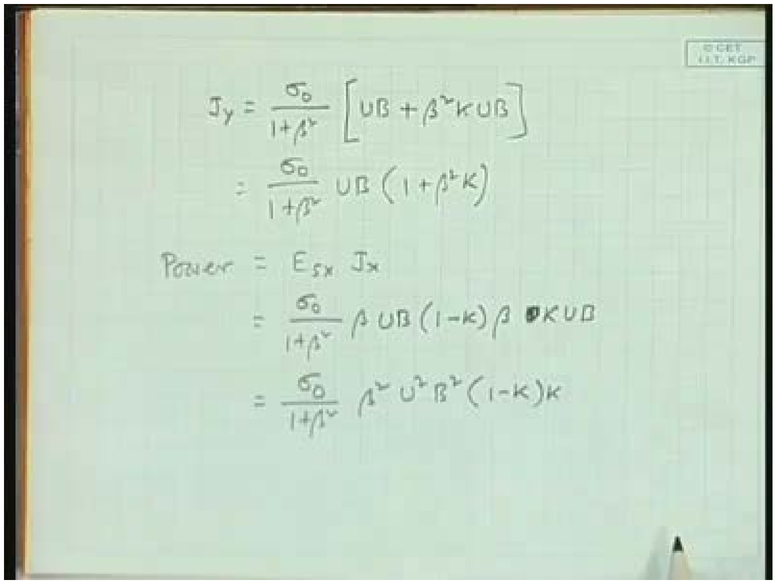

y direction current will be, its value is E y minus beta E x. E y is UB, beta E x, beta E x, E x is this. That would be, it will be plus beta square, beta square, beta K UB. It becomes then, UB becomes common sigma naught by 1 plus beta square 1 plus beta square K. It was minus and then minus is separate. Now, how much is the power? Power in this case will be x direction voltage times x direction current E sx, J x. Substitute, you have, E sx is this, beta K UB and J x is this. So, if you substitute, we will get sigma naught by 1 plus beta square beta UB 1 minus K, right, yes, 1 minus K again beta K UB is equal to sigma naught 1 plus beta square times again beta square U square B square K is there.

So, you notice, this term beta square by 1 plus beta square tells that the higher the beta, the higher the power output of this case. This term tells that in this case also, the power maximizes at K is equal to 0.5. So, this configuration, this generator configuration would be used mainly in the cases where you have the channel operating at a low pressure, near vacuum pressure and the B is very large. In fact, these have also been used progressively. The advantage is that there is only one load. So, how would you picture this whole idea of MSD being actually applied in practice?

These can be applied firstly, if you have some kind of a gaseous fuel, which we have. The Bombay High produces a lot of methane and methane can be used as a raw material or fuel for this kind of a system. We can also have coal converted into gaseous fuel by the coal gasification techniques that you have already learnt in this course. Then, all the impurities are taken off. That means after the gaseous fuel is produced that is cleaned, so that what flows through this is not the unclean coal fuel or gas, but rather a gaseous fuel burning which is a clean gaseous fuel.

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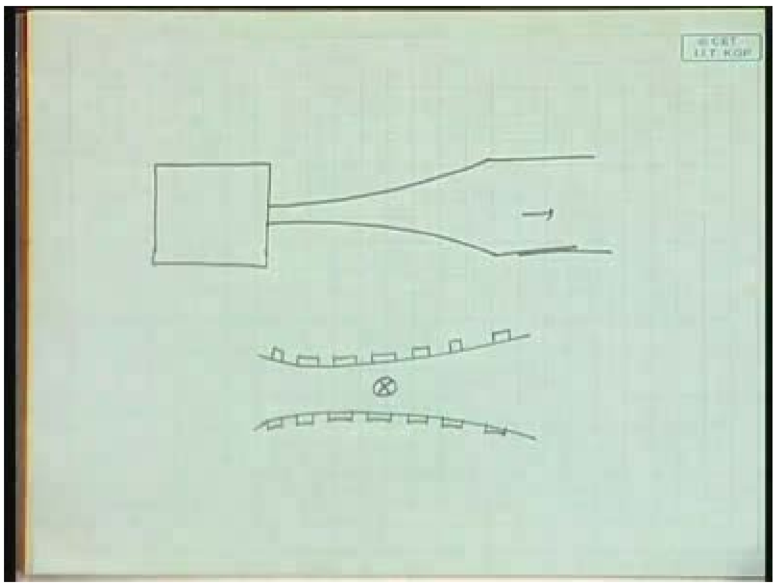

So, the arrangement would be something like this. There would be a combustion chamber. From here there would be this nozzle like thing coming out. So far, we were drawing as if it is a, it is a parallel channel. But it is not really so, because it has to flow at a high velocity and high velocity is produced always in a nozzle like situation. So, it is like this, not really like this. It is like this, it sort of tapers inwards for some length and then it goes out and all these are then covered by the segmented electrodes. A magnetic field is produced and in order to produce a large magnetic field you need a, for example the kind of magnetic field that when one pictures in this situation would be like 4 to 6 tesla and for that a normal magnet will be out of question, because the magnetic field is proportional to the current and the I square loss, I square R loss is also proportional to the current square. So, there will be a lot of loss unless it is superconductor. So, these are mostly pictured with superconducting magnets.

So, there is a magnetic field created in this direction and this output then goes to a conventional, this is still pretty hot, this output after having extracted some amount of power out of it, this output goes to a conventional Rankine cycle power system. That means here there would be the usual boilers, usual super heaters, usual reheaters, everything generating steam, generating electricity from the steam. So, this is usually used as a topping cycle, where the high temperature, high enthalpy gas is partly utilized to extract an energy, a part of energy out of it, without going through the Rankine cycle, because the Rankine cycle will have the inherent limitation of the efficiency of 1 minus T 2 by T 1. Here, that limit does not apply. The limit is higher, so you can at least in this part of the cycle reach an efficiency that is higher to that. So, that is the basic idea of magnetohydrodynamic power generation.

Thank you!