Energy Conservation and Waste Heat Recovery
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Lecture - 54
Energy Storage Systems – IV

Welcome back to the next lecture of Energy Conservation and Waste Heat Recovery. So, today we will continue our discussion on Energy Storage especially on the Mechanical Energy Storage Technologies. And as told in the last class, today we start our discussion on Flywheels, ok.

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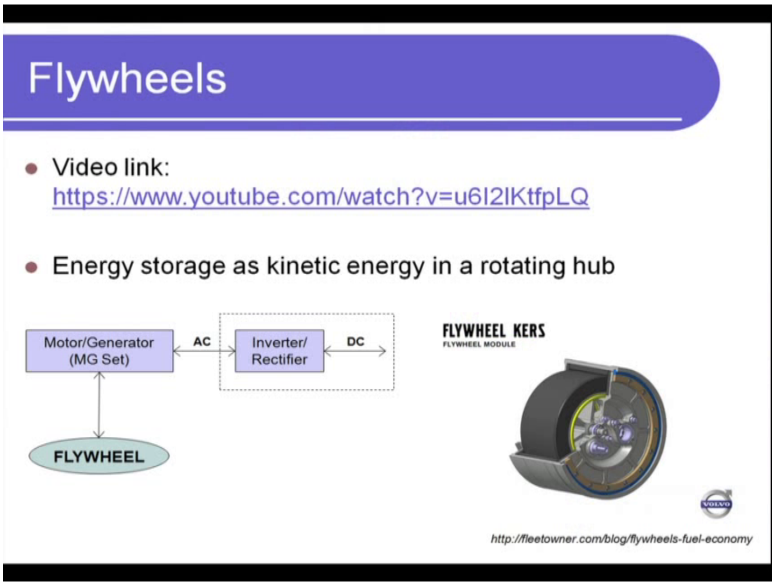

So, what is the flywheel? To start what I am going to do is, I am just going to play a video over here from this link and then, we will talk about it. This kind of in a nutshell captures how a flywheel works and then, we will talk about what a flywheel is.

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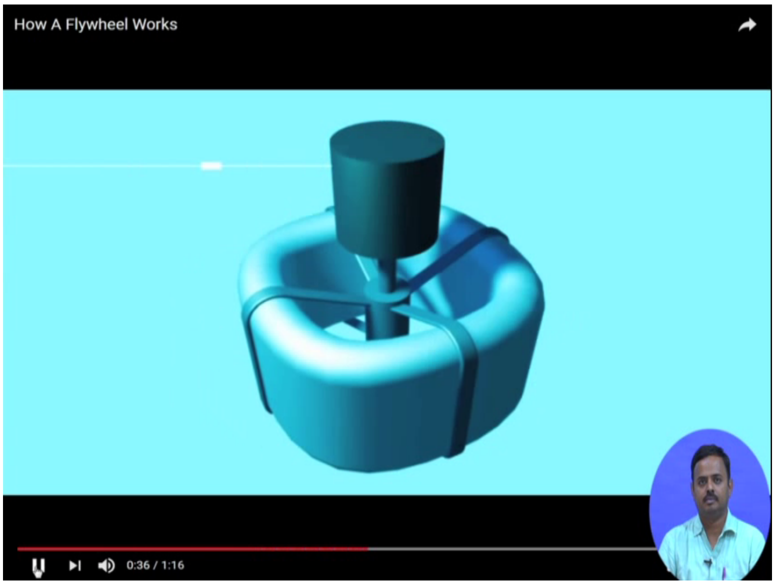

Energy storage fly wheels have very high performance to work on simple principles. To understand their operation, it is best to start with the electric motor generator.

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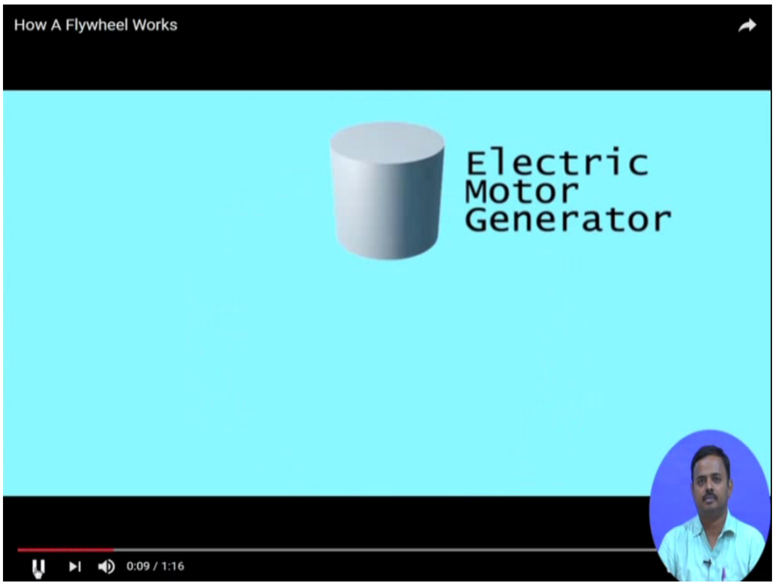

An electric motor and generator are really the same machine running in opposite directions.

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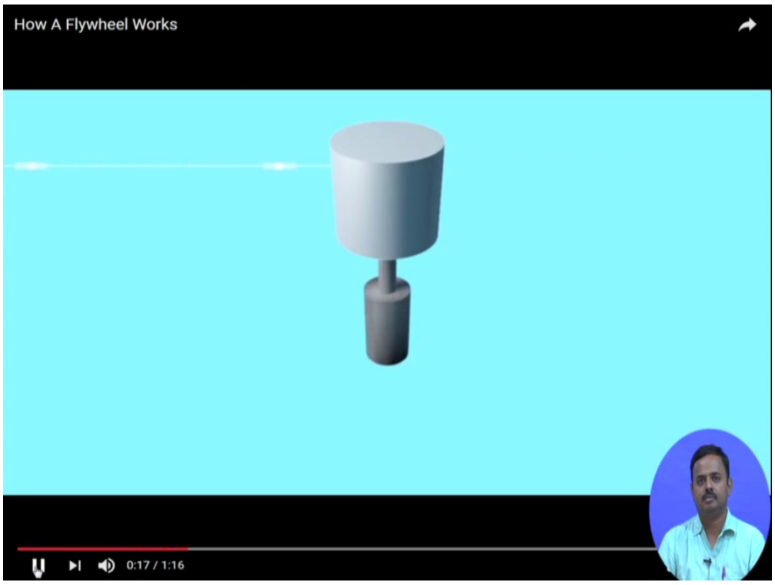

When you put electrical energy into a motor generator, it turns into mechanical energy on the spinning shaft. That is a motor.

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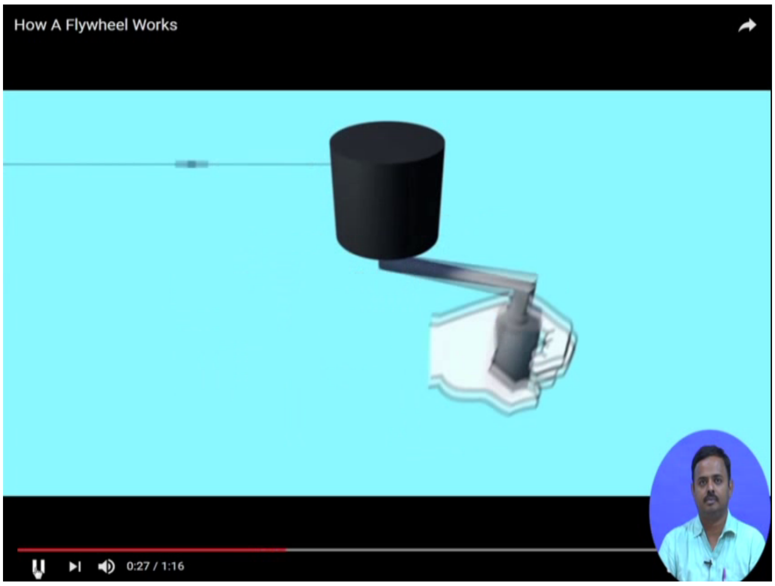

When you put mechanical energy into the motor generator by spinning the shaft, you can draw electrical energy back out. That is a generator for an energy storage flywheel. We hook a motor generator up to a wheel. When we put electrical energy into the motor generator, it accelerates the wheel storing that energy as momentum on the wheel. When we want our electricity back, we let the momentum of the spinning wheel drive the motor generator regenerating our electricity and slowing the wheel because we run our flywheel in a vacuum and on very good bearings, we do not lose much energy over time. Velkess has invented a new way to make energy storage flywheels at very low cost. So, that video nicely captured how a flywheel works.

So, as you can see a flywheel, it is a rotating member as we know and with a shaft which can be rotated by using external energy and then, the kinetic energy, the energy that is stored in the form of kinetic energy can be retrieved later. So, when it is connected to a generator and it rotates the generator that is what we saw there. So, flywheel over here as the schematic is showing a rotating device and what is happening is, it is connected to a motor generator set, ok.

It is the same machine. The way you operate, it can act as both as a motor and a generator. When we actually supply external energy in the form of electricity, it acts as a motor and that imparts energy to the flywheel and the flywheel starts rotating and then, if we somehow are able to maintain this rotating motion of the flywheel and later on use that rotating motion and the kinetic energy, due to the rotating motion and connect that to a generator, then we would be able to extract electricity out of it, ok.

Now, both the input and output to the flywheel because we are using a motor or a generator has to be in the form of AC or alternating current. If you want to have the final output in form of DC or our input electricity is in the form of DC, we would need an inverter or rectifier as the case may be. So, this is essentially what a flywheel is. So, let us quickly write down some points on flywheel.

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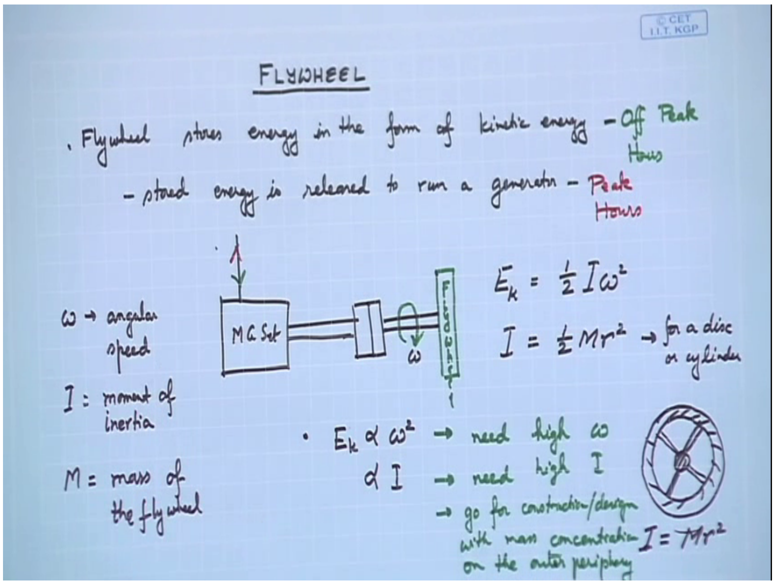

As we know that I would write down something that some of the points that we discussed flywheel stores energy in the form of kinetic energy and this definitely is going to be during off peak hours, right and the stored energy is released to run a generator and this is during peak hours, clear. So, this is what we saw.

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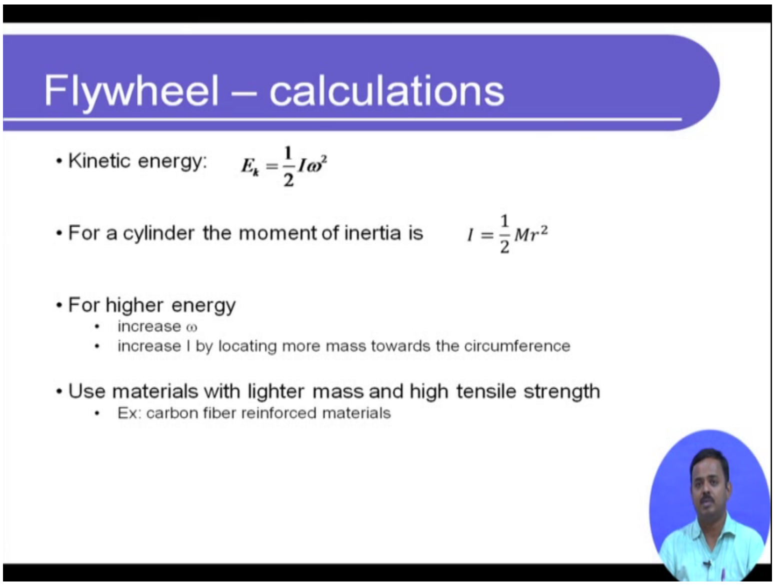

So, now if we want to do this, if you want to do some quick calculations; so let us talk about, let us just draw this. I have mg set and of course, this is during off peak and the red is during peak, I would have some kind of clutching mechanism and then, I have this flywheel and this fellow is rotating. So, what happens is the kinetic energy that is stored if I write it as ek, it is going to be half i omega squared where omega is the rotational speed, angular speed what is its unit radians per second, clear. What is i? I is the moment of inertia and for a rotating disc, it is going to be half m r squared, clear.

So, this is what I am showing here also in the flywheel calculations on the slide. As we can see here, we have the kinetic energy as half i i omega squared and for a cylinder. So, for a solid cylinder or a disk, it is half m omega squared, where m is the mass of the flywheel. So, if you look at this, what are some of the points that we see directly. If you want to store a lot of energy, I can do it in two ways. One is by increasing the angular speed. So, therefore ek is proportional to omega squared is proportional to i. So, if we need to store a lot of energy, we want high omega and we want high i, clear.

Now, for high omega that is good. So, if you need high omega, then what happens. The good thing is it goes as omega squared, however we do not need if you have a very bulky flywheel. It does not help. We would rather not have a very bulky flywheel. We would like to have it lightweight, but it shows here that if I have to increase the moment of inertia, I either need high mass or high radius which means either a heavy material or a very large flywheel which both of which go contrary to what we say that we do not want a very bulky flywheel.

So, what can we do? So, what we can do is, say this one i omega squared is for a disc or cylinder, however if you imagine that instead of a solid disc what I have is you know an annular disc like the spokes of a cycle wheel, right. Most of the mass is concentrated along the circumference and then, we connect it to the hub by some thin members like the spokes of a cycle wheel, the wheel of a bicycle which is also similar to you know the flywheel that was shown in the video that we just saw. You remember it look like something like this. So, most of the mass was concentrated on the periphery. There was of course a central hub and then, there were connecting rods like this.

So, in this case i actually is mr square no half. So, this is what it is. So, actually i is as you recall from a mechanics, it is calculated as an integral over of the mass over the i mean it is like rdm from 0 to r and if you do that for this one since most of the mass is located on the side, it comes out to be mr squared, clear. So, if we do this, then what happens by without increasing the mass or the radius, I directly doubled my moment of inertia. So, I would say is then here go for construction or design with mass concentration on the outer periphery. It is possible, ok.

So, that is what I am saying that you can. So, for storing higher energy, we increase omega or we increase the moment of inertia by locating more mass towards the circumference. Now, what are the kinds of omega or the angular speeds that we are talking about? If we talk about rpm, flywheels can easily rotate at rpms of about 30000, even 50000. Actually in some of the lab scale experiments, there has been a demonstration of running flywheel at even 100,000 rpm very high. So, this is how fly wheels operate and this is how it stores energy.

So, what we typically do is, we may actually use materials with lighter mass and high tensile strength. For example, carbon fiber reinforced materials. Why light and mass? As I said we do not need it to be very bulky because remember from mechanical consideration, you also have to hold this flywheel in place, make it rotate. You have to think about bearings and so on. So, a lightweight flywheel is always good. Even if your mass goes down a little bit, what we can do is, we can concentrate that mass as we just discussed in the previous bullets, we can concentrate it along the circumference and go for a higher angular speed which I said it is possible, ok.

Why is high tensile strength required? The high tensile strength is required because we are talking about very high rpm. So, extremely high centrifugal force in the radial direction and the material needs to be able to or material needs to be strong enough to be able to withstand these high stresses. So, that is why the material that we used to construct a flywheel is important. What else is important?

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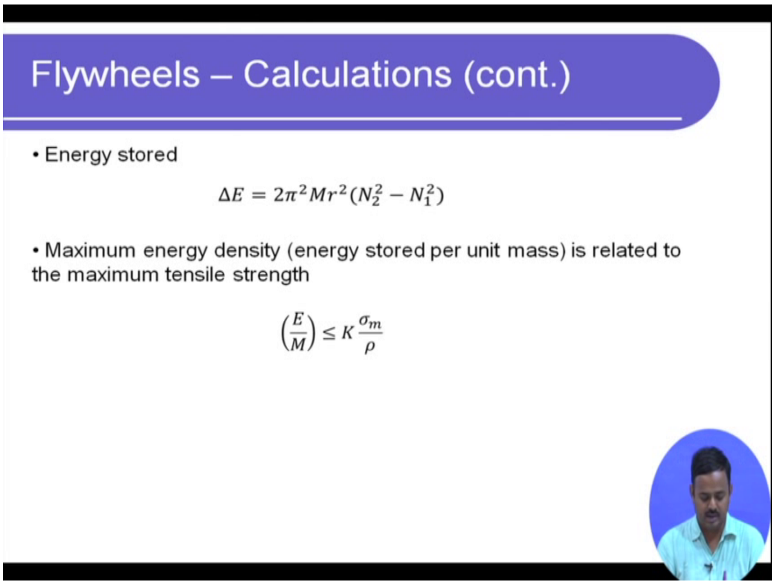

We will come to that. Before that let us talk about some of these energy storage calculations continues that.

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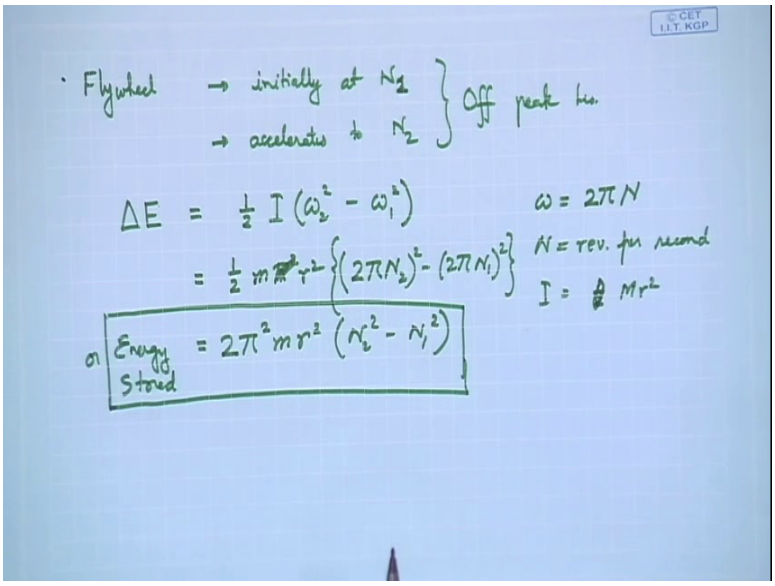

So, let us say the flywheel was running at initially at N1 sorry N1 and then, accelerates to N2 and this is during the off peak hours.

So, then what is the additional energy stored, right? It is half i omega 2 squared minus omega 1 squared, clear. Now, remember what is omega 2 pi n n is revolutions per second or 2 p i f frequency. If it is rpm, if N is rpm, then it will be N by 60. So, N is revolutions per second and not rpm. So, if this is the case and let us again consider i is half, sorry let us consider that high is mr squared again we are talking about this. So, what I will write is half m r squared, where we using capital R or small r, no small r. Sorry half mr squared and then, this will be 2 pi N 2 squared minus 2 pi N 1 squared.

So, I can write it as 2 pi squared m r squared N2 squared minus N1 square. So, this is what I have written in the slide also. So, this is my energy stored when during off peak hours, I rotate the flywheel and accelerate it from an angular speed of omega 1 to omega 2, clear. Now, what happens then once I have energized it, I need to store this energy clear, but what are the problems? If I want to store it which means the flywheel has to keep rotating and not slow down. Now, is that possible? It is not possible because if I keep it rotating, then what happens is it is going to have air friction and it will slow down.

There are also the mechanical bearings on which the flywheel rests, right. There is a shaft on to which it is attached and it is rotating. So, there will be some bearings and this bearing will also have some losses. So, we are going to come to that how do we minimize those, but before that we also talked about the high tensile stresses that results because of this high speed rotation. So, as a result of that we need to ensure that you know the stress that is generated is less than the maximum tensile strength that the material can withstand. So, that is what is shown in the second equation over here that if I look at the maximum energy density which energy stored per unit mass is related to the maximum tensile strength in this form.

So, the maximum energy that you can store per unit mass must be less than or equal to k which is a constant and is a function of the material sigma m which is the maximum tensile strength of that material over rho which is the density of the material. This directly comes from solid mechanics. So, we need to make sure that this is what we need to satisfy if we choose a material. This is what limits the maximum amount of energy that we can store, otherwise the material is going to disintegrate because during the rotation and motion, it will not be able to withstand the tensile stresses, ok.

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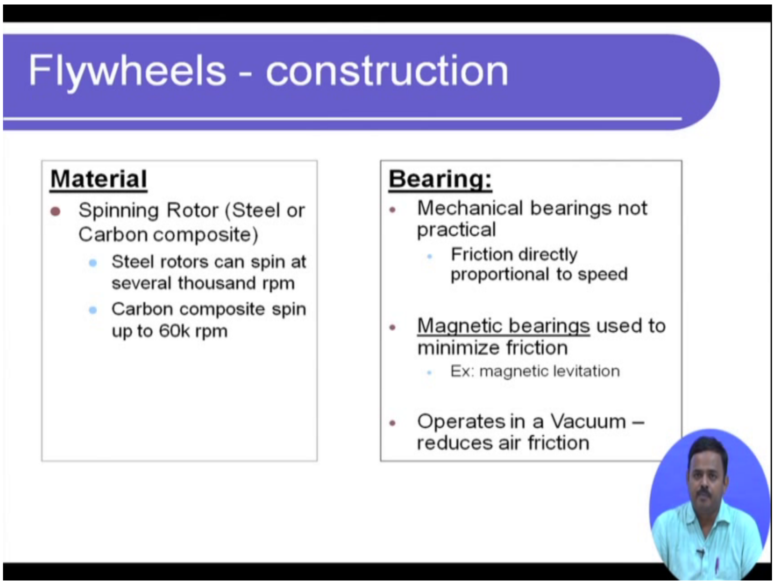

So, this is what the construction becomes important. The material, the spinning rotor which is steel or carbon composite carbon reinforced materials are used because they are strong and they are light. See steel bloaters can spin at around several thousand rpms, but carbon composites can go up to 60000 rpm, clear. Let me take a little detour over here. When we talk of flywheel, one of the first applications that come to our mind is IC engines, right as mechanical engineers. Well, the other place where flywheel is used which these days we do not see in our houses that commonly, but when I was growing up, it was probably common in every household that was the sewing machine with a pedal.

The sewing machine also uses a flywheel. So, that is a completely mechanical manual type that we saw in IC engines. As mechanical engines when we studied mechanical engineering, we came to know that the ic engine that the cycle consists of four segments, four strokes; the suction stroke, the compression stroke, the expansion stroke which we also call the power stroke and then the exhaust stroke four strokes. However, out of these four, it is only the expansion or the power stroke that generates power, ok.

So, what happens during the other three. So, that is why we use a flywheel. So, during the power stroke the energy is supplied to the flywheel which keeps it rotating and during the other three that energy is extracted by the transmissions system and that is how when we write, we do not feel that we feel it is a smooth ride, but actually the power is only given at during the power strokes. So, ideally we should have this kind of a motion, but that is what that is we do not see that because it is a flywheel that absorbs the additional energy during the power stroke and then, releases it during the other three, so that we have a smooth ride, ok.

So, that was a little detour, but trying to understand how a flywheel works in terms of practical application here, we are seeing a completely different application which is energy storage where IC engines is also energy storage, but here we are also seeing another example and remember flywheels cannot store a lot of energy, however what it is done is, it can use to stabilize a system when it supplies that additional energy for a small amount of time, so that the system can run smoothly, alright.

So, let us come back to the discussion here we are talking on materials. So, steel rotors can spin at several thousand rpm and the reason I take the detour is if you know if you have noticed during when you are driving a car, you have an odometer which shows rpm. In many cars, it is there in the typical rpm that we see. We restrict ourselves to 3000-4000 that kind of rpm. Actually even if you go beyond 2000, its engine becomes a little noisy. So, I mean normally safe drivers do not go beyond 2000-2500 like that we change the gear, so that we do not go above, however the steel rotors in that is good enough, but if we really want to go to like 20000 rpm, 30000, 50000, 60000, then we need these more sophisticated, more strong materials which are like carbon composites. So, that was the material.

Now, what about bearing? So, the mechanical bearings are not practical because there is friction and the friction is proportional to speed. So, therefore, if you have mechanical bearings to support your flywheel, then we are going to lose that kinetic energy. So, that is why we cannot use mechanical energy. What we use is magnetic field magnetic bearings. So, one of the examples is magnetic. You know the magnetic levitation that we talked about. So, magnetic levitation is nowadays used. Even we have trains running on magnetic levitation. Why? It is so that the friction is reduced. So, here also if we want to use fly wheels for high density storage systems, energy storage systems where we want to store the energy for a longer period of time, then what happens is we have to minimize friction.

We cannot use mechanical bearings, we can use magnetic bearings where there is a magnetic field that supports the flywheel and there is also, it is a little more involved. We are not going to go to the details, but there is also other opposing magnetic fields to hold it in place because otherwise if you just have magnetic field in one direction; it may even fly away, but let us not get into those details. It is possible to have even magnetic levitation technology to hold the flywheel in place and in that case, there is hardly any bearing losses.

The other source of loss that I talked about was air friction. So, therefore, you can operate, we have to operate it in vacuum. Of course, perfect vacuum is never possible, but once the flywheel is housed in a chamber which is evacuated, so that air friction is very low, how long can a flywheel retain its kinetic energy. Well, if you have magnetic bearings and if you can maintain close to vacuum conditions, it can retain, it can keep running for almost 6 months it has been shown, ok.

So, the period of storage probably can be quite large if you use flywheels for energy storage. Now, one thing that I, the last thing that I want to mention however is that what if it fails, what if it fails? We have talked about a special material that can withstand high tensile strength with high tensile strength etcetera, all that is fine, but what if its fails because we are talking about something that is rotating in a extremely high speed, ok.

So, the good thing is that the design is such that for the material construction and design and I am not getting into the details, but it suffices to know that the construction is such that if the material fails, if it breaks or cracks, it immediately disintegrates into small pieces. So, you really do not have a large chunk coming out at very high speed which if it hits something can be fatal at those high speeds. So, what it does is immediately disintegrates into small pieces and then, you also have the housing, so that these pieces when it goes and bangs against the housing wall, the force is not strong enough because the mass is small and that is how we keep it safe.

So, once again we started by discussing what the flywheel is. So, flywheel is a rotating member which can be rotated and accelerated or basically the angular speed can be increased by supplying additional energy and this we do during off peak hours when we have additional electricity generation. So, we use it to run a motor that supplies energy to the flywheel. So, kinetic energy goes up because its angular speed goes up. Then, what happens once it has reached a certain rpm which will be dictated by the materials tensile strength and therefore, what is the maximum angular speed it can have for a given design, we will stop supplying additional power through the motor.

The flywheel is housed in a casing which is typically evacuated, so that air friction is minimized. Also, the bearings are special typically magnetic bearings, so that the bearing losses are also minimal. So, in this scenario when it is rotating at certain rpm, it can keep rotating with minimal loss of energy or rpm. Next what happens is during peak hours when I need this additional electricity; I attach the shaft of a generator to this sly wheel. Therefore, what happens is the kinetic energy of the flywheel is used to rotate the generator and thus, produce electricity. Of course, as it rotates the generator, its speed is going to come down.

So, the rpm is going to fall from that omega 2 to some lower value let say finally to omega 1 or even lower we do not know, but that is how we generate the amount of energy that will be released. So, the flywheels typically are not used for very high amount of energy storage, but it can supply high power in short bursts and therefore, it is typically used to stabilize the system and supply that additional burst of energy for a small period of time. We also talked about its construction in the sense that we typically do not have a solid disk or a cylinder, but instead go for a construction with the mass is concentrated on the outer periphery.

So, that way what happens is, we can have higher moment of inertia because it goes as mr square instead of half mr square in case when the cylinder or the disc is solid and the other thing from design point of view, we would like to have a lighter mass because that is easier especially we were talking about magnetic field. It will be easier to hold the bearing hold the flywheel in its place because with a magnetic field strength of lesser intensity because the mass is lower and we would like to compensate and have high energy storage by increasing its rpm because today’s technology enables us to go to really high rpms in flywheels, ok.

Last, but not the least the design is such that if it fails, it disintegrates into small pieces, so that we do not really have very hazardous condition, we do not have large chunks of a material at such high speed flying around, so that kind of wraps up our discussion on flywheel. And in the next class, what we will do is, we would look at another means of energy storage.

Thank you very much.