Physics of Renewable Energy Systems
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Lecture 23
Pumped Hydroelectric to Flywheels (Mechanical Energy Storage Systems)

Welcome. Let us continue our discussion on mechanical energy storage systems. In the previous lecture, I had talked to you about the compressed air-based energy storage system which are classified under the subheading mechanical energy storage systems. We had also seen the diabetic, adiabatic and isothermal based compressed air energy storage system.

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Let us today discuss the next two technologies which are going to be useful for India. Those are the pumped hydroelectric and flywheel based mechanical energy storage systems.

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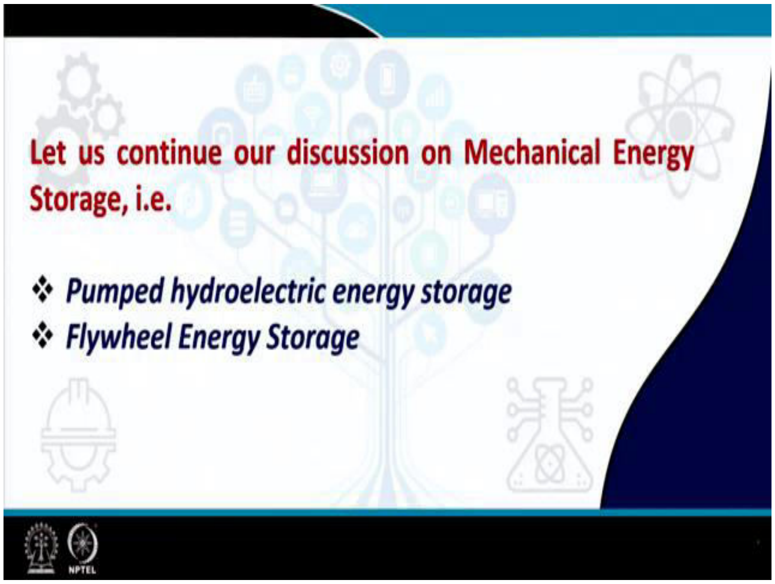

In today's lecture, you will get the basics of pumped hydroelectric storage system and also, we will spend appreciable amount of time to explain the working and the principles of flywheels.

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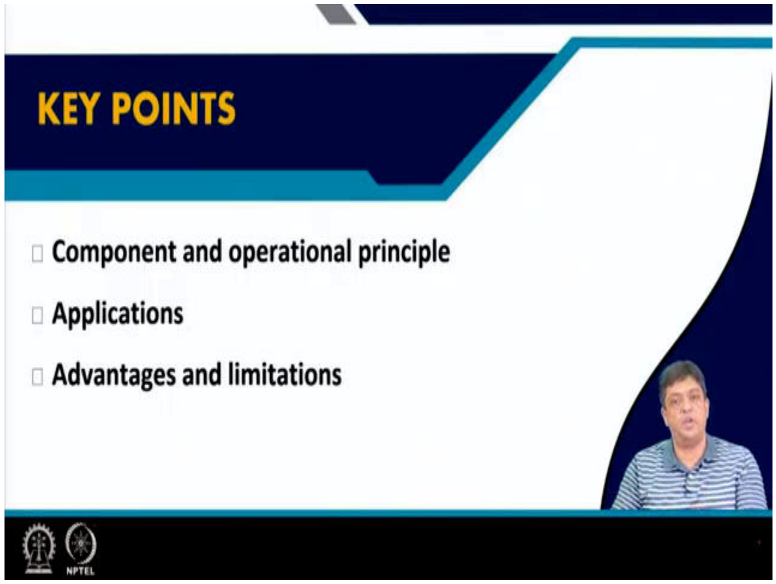

You will see the component and operational principle both for pumped hydroelectric and flywheels, the range of applications which can be associated with these two technologies, and the associated advantages and limitations with each of these technologies.

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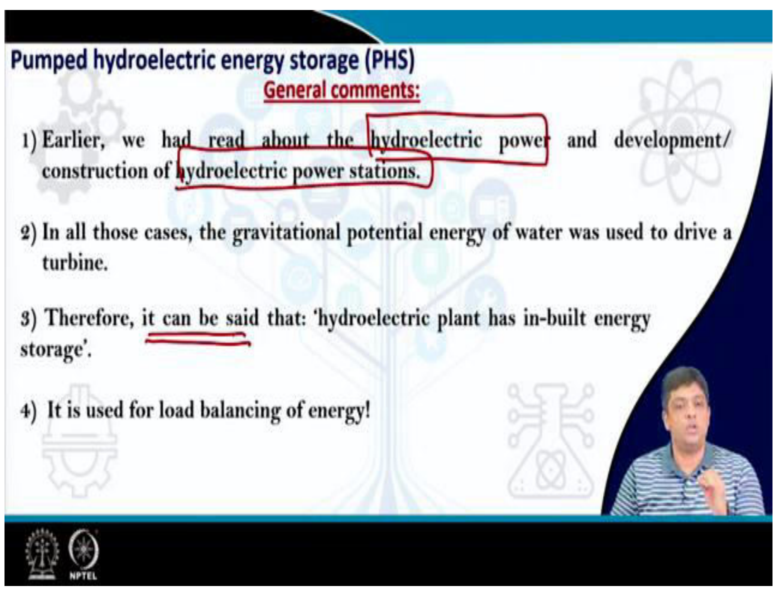

Now, pumped hydroelectric systems. If you remember, when we were talking about the water-based systems for energy generation, we had talked to you about the hydroelectric power and also the hydroelectric power plants. We had talked to you about the construction, the operation, the advantages and the disadvantages of the hydroelectric power stations.

In all those cases, we had seen how the potential energy of water was used to drive a turbine when the potential energy of water was converted into kinetic energy when the water was flowing down the penstock and then reaching the turbine and then you could run the turbine and the generator was subsequently delivering the electrical output, conversion of potential energy to kinetic energy.

And therefore, it can be said that hydroelectric plant has an inbuilt capacity of energy storage, inbuilt capacity, because it is actually storing energy in the form of potential energy. Hence, it has the inbuilt capacity of energy storage. If you are storing energy and not driving the turbine when the requirement is low, then the whole system acts as storage.

But when you allow the conversion of this potential energy to kinetic energy because of the flow of water from height to, a height which is lower than the height of the head of the water, then you can generate electricity. When would you like to generate electricity? When that demand is there from the end user side and therefore, you can say that this technology can also be used for load balancing of energy.

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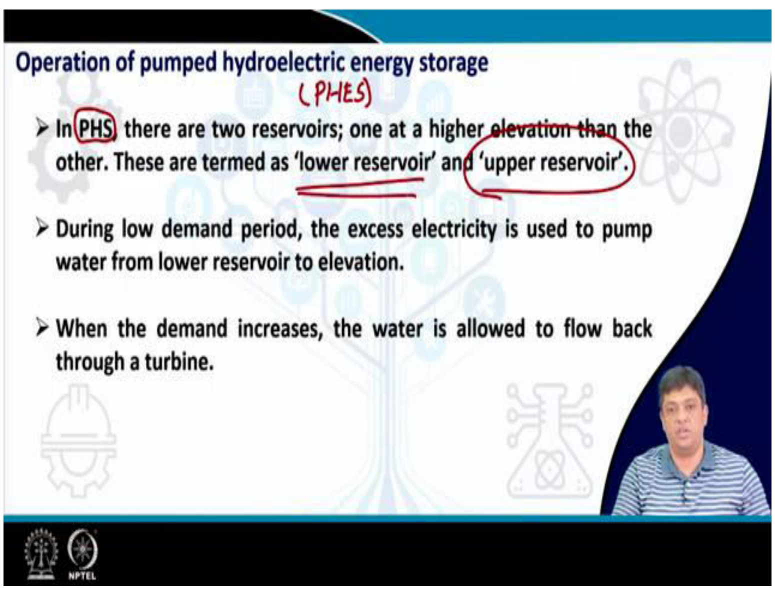

Let us see how does the pumped hydroelectric energy storage system works, which is classified under the heading of mechanical energy storage system and you will find that the operation is slightly different, but mostly similar to that of a hydroelectric power plant in let us say pumped hydro electric energy storage system or you can simply write as PHS.

So, in PHS there are two reservoirs. What was the condition in hydroelectric plant? You were actually having one reservoir at a height. But here we have two reservoirs one at a higher elevation and the other which is at the lower level and they are termed as either upper reservoir or the lower reservoir if you consider the reservoirs at the two levels. Therefore, the one which is at the higher level is called the upper reservoir and the reservoir which is at the lower level is called the lower reservoir.

So, now, we have two reservoirs. Reservoirs, what is the purpose? It is going to store water and then supply water and the flowing water will drive your turbine that is the purpose of reservoir. Very good, I hope you remember. During the low demand period, the excess electricity is used to pump water from lower reservoir to higher reservoir. So, from lower reservoir, you pump the water to higher reservoir. So, you have actually consumed that excess energy and pump the water.

Now, this water goes and gets stored in the upper reservoir. And so, you have the conversion of potential energy, kinetic energy and then potential energy. When the demand increases, you reverse the process. You use the process very similar to the one which is used in hydroelectric plants. What will be the process? You will use the water which is at a higher level that is the upper reservoir, let it flow down the penstock and then hit the turbine, turbine will drive the generator and you will have the electrical output. This is what is the way the whole system works?

So, I hope compared to hydroelectric plant, there is an extra step which must be clear to you. What is that step? That you are forcing the water from lower reservoir to upper reservoir when the demand is actually low, but you are still generating electricity.

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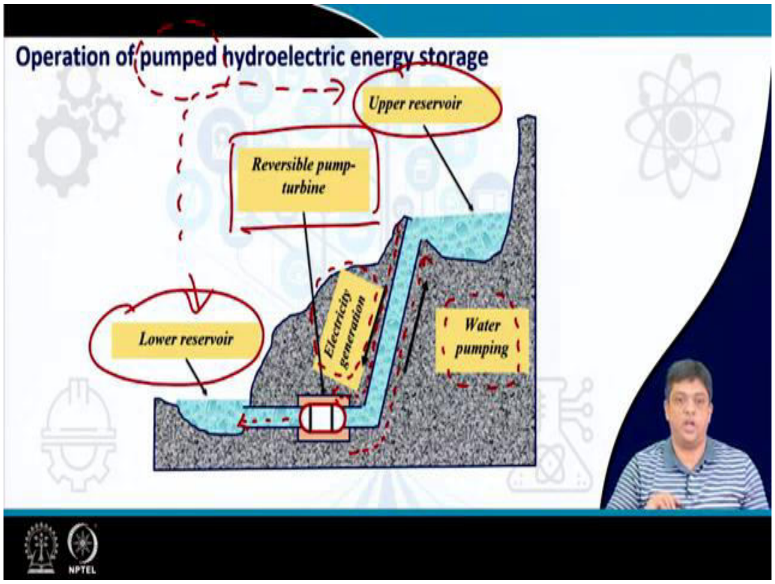

And this is the schematic to explain everything which was written in words in the previous slide. So, you have the lower reservoir. It is at the lower height. Then you have the upper reservoir which is at the higher elevation. You have a reversible pump turbine which is in the channel connecting the lower reservoir with the upper reservoir. So, in the channel, you have a reversible pump turbine that means when the water is pumped either from the lower reservoir side or the upper, sent down from the upper reservoir the turbine can actually operate.

While you are transferring energy from lower reservoir to upper reservoir, this pump will move up and that is the energy consumed for water pumping. So, you will push the water up the penstock and you will reach upper reservoir. In the case when you are generating electricity what will you do? Very simple, you will let the water flow down and then hit the turbine, turbine will drive the generator and electrical output. Once the turbine has done the work, it will allow the water to pass through.

And the difference from hydroelectric plant, you will not let the water to flow downstream, here you will collect the water in the lower reservoir that is the additional concept you should remember. So, this becomes the overall process. Rest everything remains the same regarding the discussion on hydroelectric plant. What should be the head height, you generally take as 0.1 H_0, then you must have the proper design of penstock. You must ensure that you do not have turbulent flow. You need streamline flow.

So, all the discussions we had during the operation of hydroelectric plant also hold good here in the pumped hydroelectric energy storage system. And this is the operation of the first mechanical energy storage technology which I wanted to discuss today.

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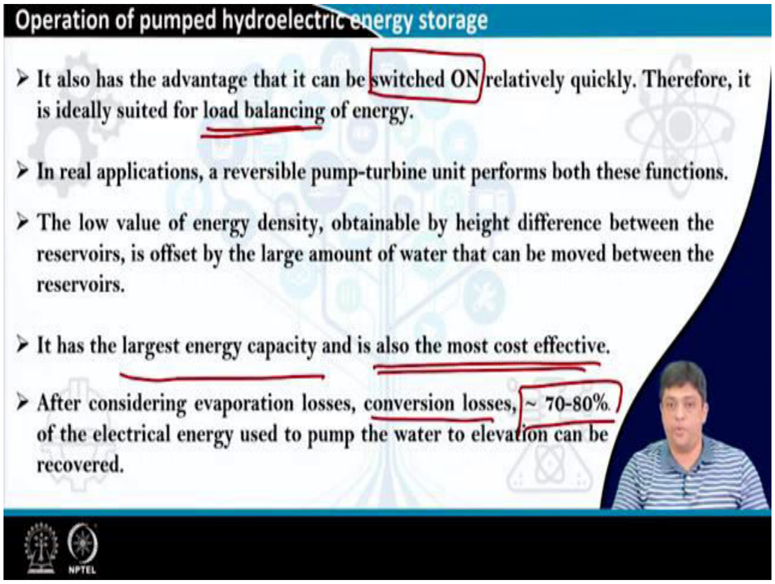

So, let us see the operation details once again and also the advantages which are associated, and finally, I will give you some hint about the limitations. Now, suppose, you have electricity which is there, which is driving the turbine and the electricity is driving the turbine means what, it is pumping the pump which is actually forcing the water to be pumped from lower reservoir to upper reservoir and this process can be quite fast, and therefore, the whole technology can be switched on relatively quickly. So, it has a very fast response time.

The moment you want that you need an electrical output, what you need to do, reverse the flow in the pumped turbine and what it will happen, it will now ensure that the water is now flowing from the upper reservoir to the lower reservoir and then you have the electricity generation. Hence, the whole process becomes ideally suited for what? It becomes ideally suited for load balancing. And this is an extremely critical process when you are talking about grid stability, you are talking about efficient use of electricity, grid balancing or load balancing is an extremely critical process.

In real application, the reversible pump turbine performs both these functions. What are these functions? Either allowing the water to flow from the upper reservoir towards lower reservoir or forcing and pumping the water from lower reservoir to the upper reservoir. But you see the low value of energy density which is obtained by the height difference between the reservoirs is offset by the large amount of water that can be moved between the reservoirs. So, you have reservoirs. And what is the difference in this height you can obtain.

You cannot have pump in a way that the water is pumped from lower reservoir to upper reservoirs over hundreds and hundreds of meters which you have seen is required for hydroelectric plant that water is flowing down up in the mountains and then it is flowing down the mountain and then you install or construct a dam to run the hydroelectric plant. But the construction limitations, means that the height difference between the lower reservoir and the upper reservoir in this case will be limited.

So, then the conversion of potential energy to kinetic energy which is going to drive the turbine will be also such that the efficiencies will be low because the energy which you are talking about, energy difference is also quite low. So, how can you actually offset this? You can offset this by increasing the amount of water which can be moved from one region to the other. So, you actually increase the amount of water, the volume which will flow through that will offset the limitations coming in because of the height difference limitation that is associated while you construct the two reservoirs.

It has the largest energy capacity amongst the technologies which we have discussed till now and is also quite cost effective. Now, considering that you have two reservoirs, also you have large reservoirs, then you will have the evaporation losses, you will have conversion losses, because you are converting from potential energy to kinetic energy, kinetic energy to potential energy, again from potential energy to kinetic energy and kinetic energy to potential energy and you are also using turbines.

So, you have processes which are associated in the conversion processes and they lead to conversion losses. Considering both these major losses, you will find that 70 to 80 percent of the electrical energy used to pump the water to elevation can be recovered. So, that is a significantly high efficiency with which the system can actually operate.

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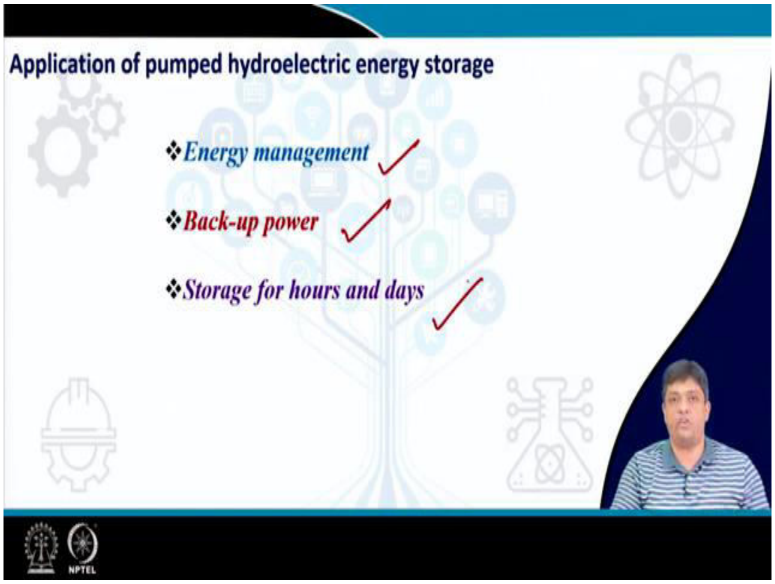

The design is simple, the construction is simple, the mathematics associated to explain the power outputs is simple and has been discussed earlier. Because of these things, the application of pumped hydroelectric energy storage technologies is in various places, it is predominantly used for energy management, backup power and storage for hours or for days and days.

You may have the systems which are not being used for many days, but suddenly they may be required to support and cater to the increased demand from the user side. And then these kinds of pumped hydroelectric energy storage systems can be switched on very quickly so that they can come in and contribute in maintaining the grid and ensure load leveling and balancing. So, these are the major applications of pumped hydroelectric energy storage.

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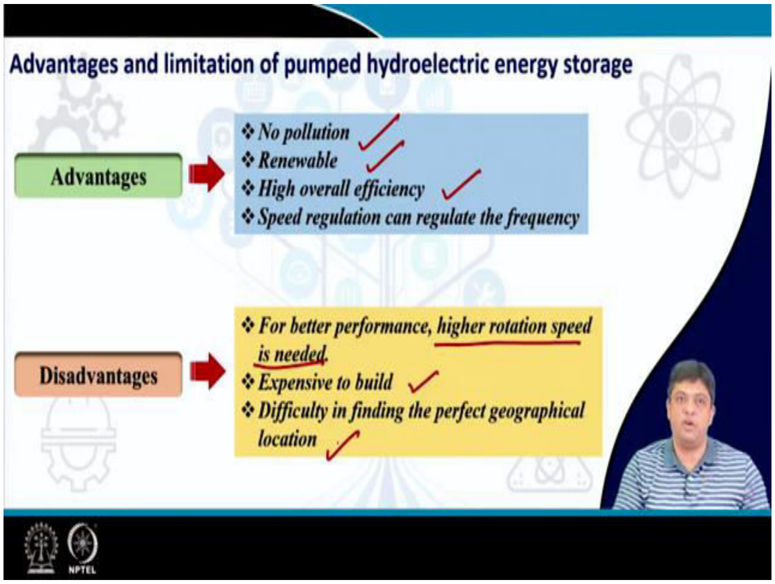

They are mostly, once they are constructed, mostly they do not have any contribution towards pollution. It is, I am saying after they are constructed. So, they do not increase the pollution level after they are constructed. While the construction process is going on, it is a different issue. It is a renewable based system. The overall process is quite efficient and it is a quick process. The switch on time is quite fast.

The disadvantages associated with this pumped hydroelectric energy storage are; it requires higher rotation speeds of the turbine, because of the height difference between the lower and the higher, or the upper reservoirs is limited. So, to offset or you will be sending in lot of high volume of water down, but the kinetic energy would be slightly lower. So, that has to be taken care that the rotation speeds can be increased so that the output can be enhanced.

We had seen earlier that construction of the hydroelectric plant itself was expensive when you are talking about just single reservoir. Here you are talking about another reservoir, so you are talking about minimum of two reservoirs. The cost immediately increases. Hence, it is expensive to build and it is difficult to find a perfect geographical location to construct such kind of pumped hydroelectric energy storage system which delivers all the characteristics you demand from the storage technologies. These are the major disadvantages, but there are enormous advantages associated with the technology.

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The next technology which is becoming quite useful both at small scale level to very high levels of storage is the flywheel-based energy storage technology.

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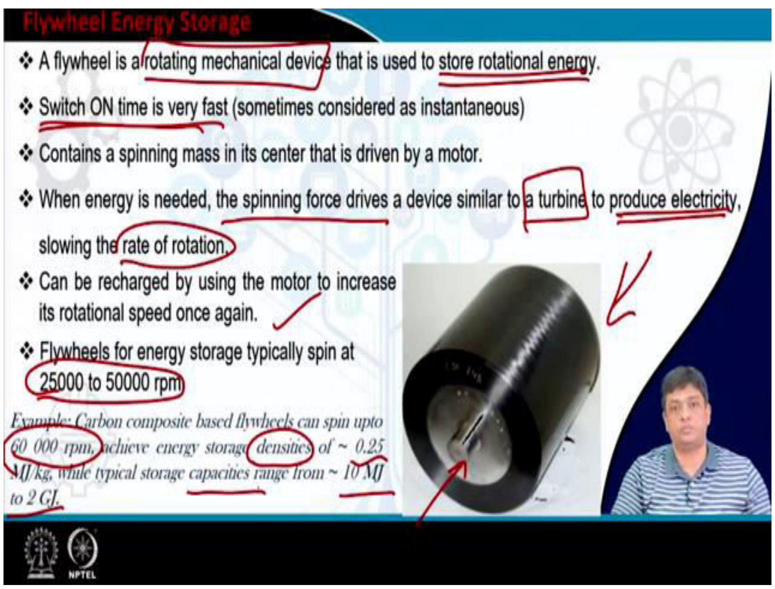

A flywheel which you can see from the figure is a very simple technology. What is it looking like? It is simply a rotating mechanical device. It is a rotating mechanical device. If this device is rotating, it is able to store rotational energy. The massive advantage of flywheel-based energy storage technology is that the switch on time is very fast and sometimes it is also considered to be near instantaneous. You switch on the flywheel and you can start talking about the storage and the extraction is also quite instantaneous.

It contains a spinning mass, the mass which is spinning, in its center that is driven by a motor. So, the motor drives the mass which is at the center and then it is driving the spinning mass. When energy is needed, what will you do? Simply the spinning force drives a device similar to a turbine to produce electricity. If you are extracting energy, what will you see? You will see that the rate of rotation will actually slow down because you are extracting energy from the flywheel.

To maintain this, this flywheel can be recharged by using a motor, which can once again increase its rotational speed. Typically, the flywheels for energy storage, they spin at an RPM of 25,000 to 50,000 and you can also have carbon based composite materials which are used to fabricate these flywheels. These carbon composites have the advantage of high mechanical strength, but they have much lower weight. Hence, they can spin at a faster rate than what is mentioned in the earlier case.

And it has been seen that the carbon-based composite materials which are used to fabricate a flywheel can lead to a condition where the flywheel can actually rotate at RPMs as high as 60,000. This can be associated with energy densities in the range of 0.25 mega joules per kg and the corresponding typical energy storage capacities will be then in the, will then be in the range of 10 mega joules to 2 giga joules. So, you can see that you can actually have flywheel-based storage technologies which have very high capacities.

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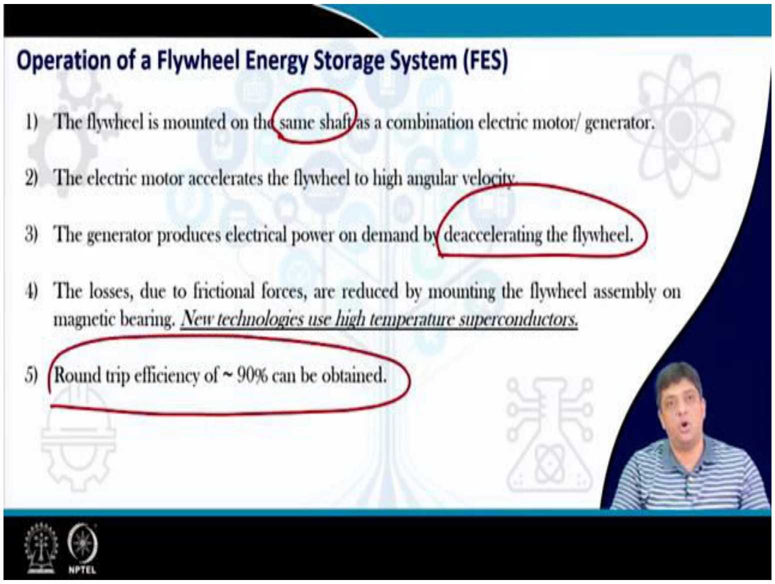

Once again, the flywheel is actually constructed on the same shaft as a combination of electric motor and generator. Same shaft is very important to understand. The electric motor accelerates the flywheel to high angular velocities. The generator produces the power. When it produces the power, when the demand is there. While the power is being delivered, what will happen, there will be deacceleration of the flywheel. So, power is delivered by deaccelerating the flywheel.

Now, you have a motor generator combination on the same shaft, the mass which is spinning is at the center, and therefore, you will have frictional forces which may appear. These losses can lead to appreciable lowering of the efficiency. To counter this loss which is linked with the frictional force, nowadays the system is so mounted that there is an assembly of magnetic bearings and then they do not allow the surfaces to come in contact and they allow the free motion and hence the frictional forces induced losses are minimized.

In fact, there are new technologies which are using high temperature superconductors and are opening new areas of applications for superconductors. Suppose, one day you get a condition where super conductivity is obtained at room temperature, then you can use that material in these bearings and you will find that there are no losses due to frictional forces, because the bearings which are based on superconductors will not be resulting in any resistance. Even then just by using magnetic bearings, the round-trip efficiency of 90 percent can be obtained in these systems.

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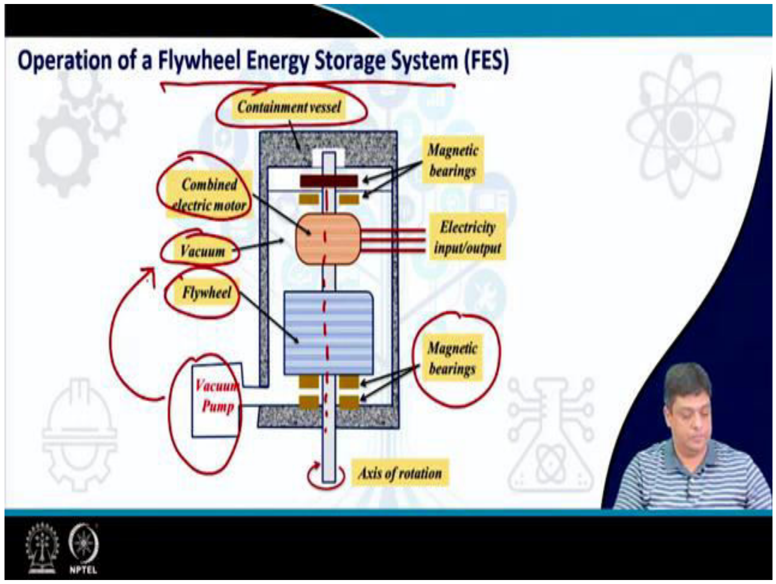

And this is the schematic which describes the complete flywheel energy storage system. Obviously, you will have a container vessel where the whole shaft is actually contained. Now, you have the central axis and this is the axis of rotation. Second, what would be there? You will have vacuum. So, the losses can be reduced. And you have the combined electric motor generator unit, the most important component flywheel which is a rotating.

And then you prevent the losses due to frictional forces by the use of magnetic bearings, because when the rotating mass or the spinning mass is moving, you do not want any kind of frictional forces between the two surfaces to come into picture and you allow the free spinning of this central mass. Vacuum pump, to ensure that you can have the vacuum in the container which is having the total assembly.

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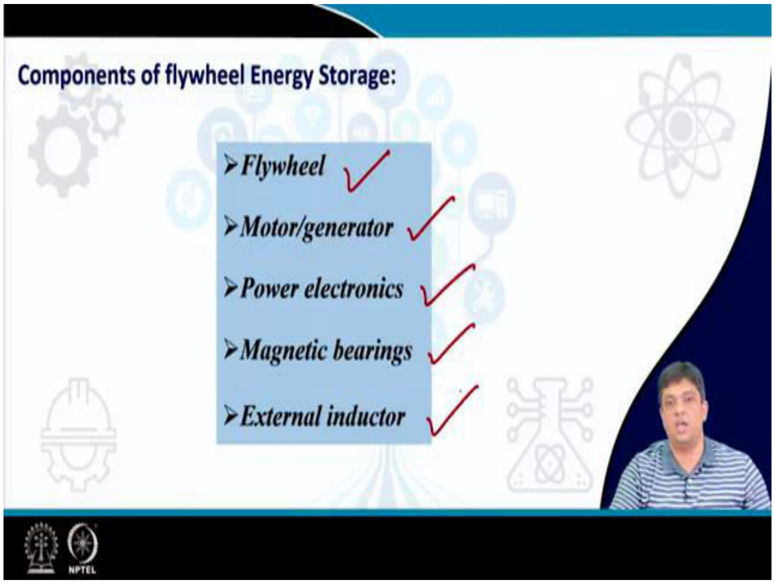

So, the major components become flywheel, motor generator unit, the power electronics, magnetic bearings and external inductors.

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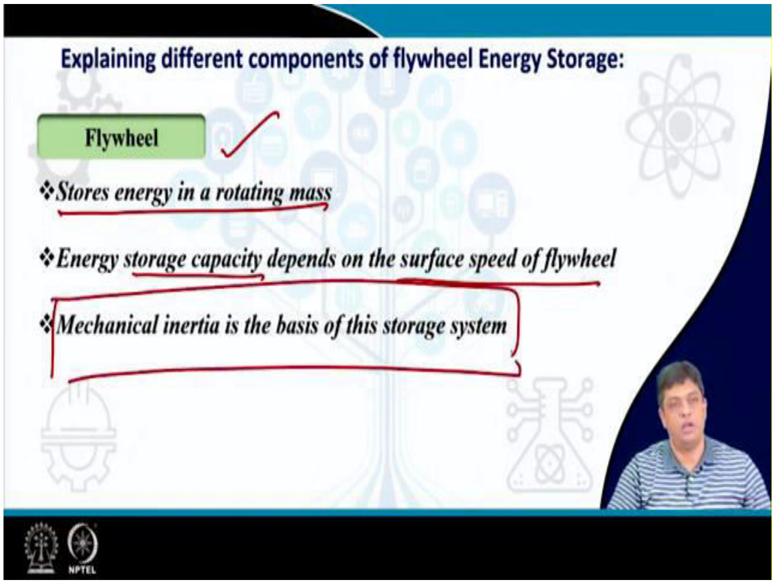

What are the purposes of each of them? Flywheel, most important component as the name suggests. What is it going to do? It stores energy in the rotating mass. The storage capacity will depend on the surface speed of the flywheel. And mechanical inertia is the basis of this storage system of the flywheel-based storage system.

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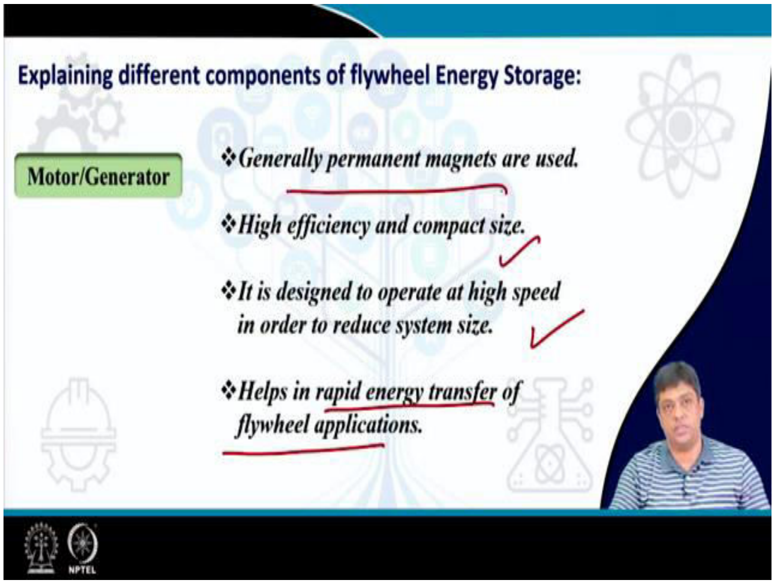

Second component, motor generator unit. Obviously, what are they going to do? They are there to ensure that there is a rapid energy transfer in flywheel. It is, therefore, so designed to operate at high speeds in order to reduce the system size. It is highly efficient and compact. And for this you generally use permanent magnets.

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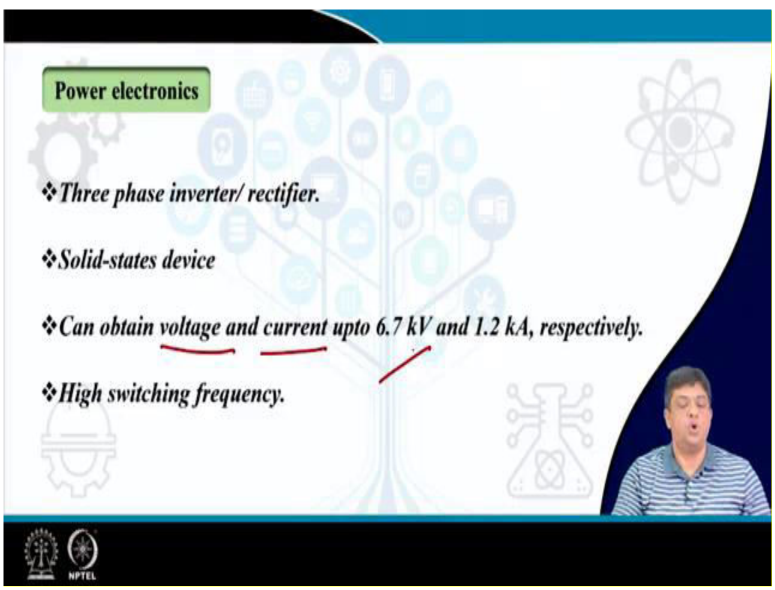

You have the power electronics which are going to manage the voltage and current outputs. So, generally using this combination of three phase inverters, rectifiers, the solid-state devices you can obtain voltage and current in the range of 6.7 kilo volt and 1.2 kilo amperes, respectively, and they can have high switching frequencies also all controlled by the power electronics.

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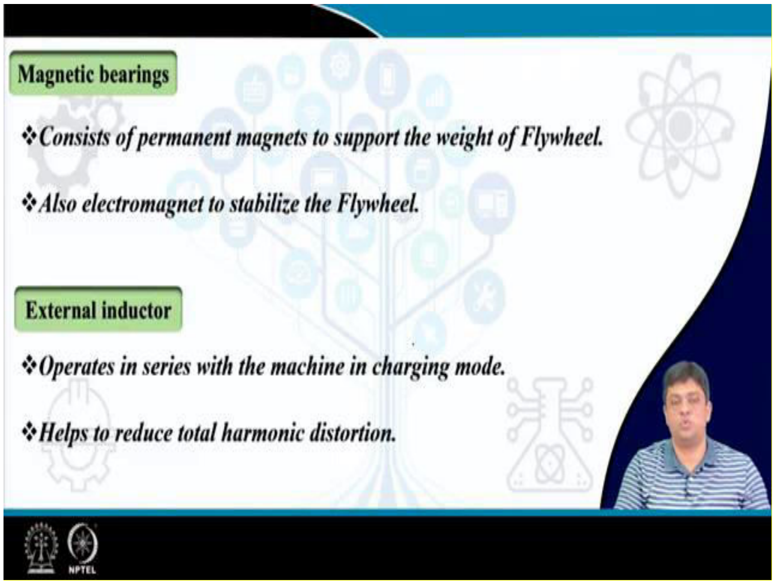

The role of magnetic bearings consists of magnets to support the weight of the flywheel, also it stabilizes the flywheel. Finally, the external inductor, it operates in series with the machine while it is in the charging mode and it helps to reduce the overall harmonic distortions which can be seen in such kind of devices.

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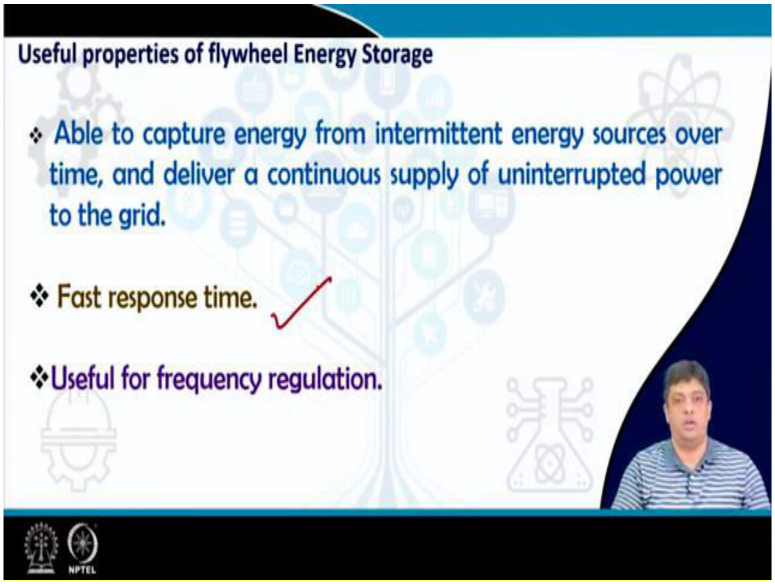

If you are able to make this design, ensure the construction in a way that all the requirements are fulfilled, then you will be able to capture from intermittent sources over time and deliver a continuous supply of uninterrupted power to the grid.

Because, suppose, you have a source which has induced the spinning of the flywheel, then the wheel is having the motion, it is continuously spinning and as it is continuously spinning, you have also ensured that the losses due to frictional forces are minimized so the motion can be sustained and the moment you need supply to the grid this can be deaccelerated and the induced current or voltage can be delivered to the grid.

And because acceleration or deacceleration in this spinning mass can be quite fast, the overall system has a fast response time. And the major advantage comes it helps in frequency regulation and thus contributes in the grid stability while ensuring that excess or intermittent energy is stored in it.

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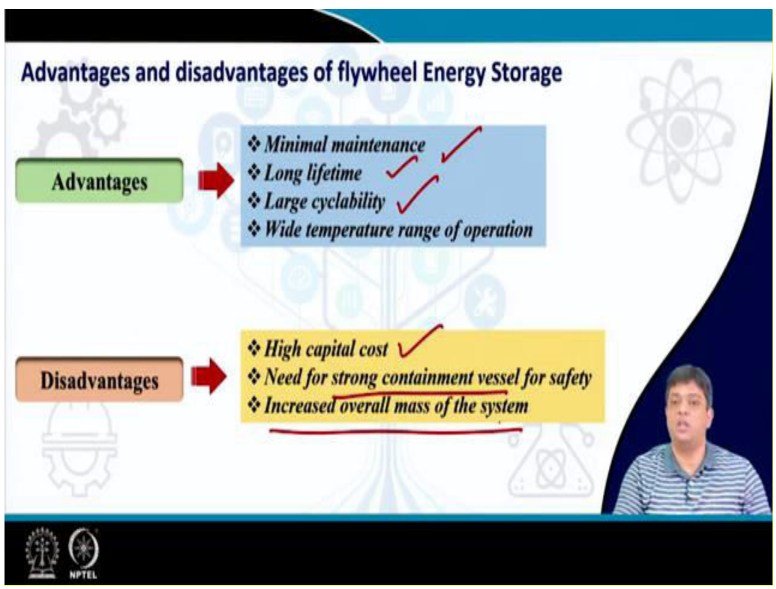

So, simple design with minimal maintenance, long lifetime, large cyclability and it can operate with stable output over a wide temperature range, because the components you are using to fabricate this can operate and are able to deliver performance over a wide range of temperatures. But still the cost factor is high.

To ensure safety of the device itself not the safety of the grid, the safety of the whole device is also critical. For that you need a very strong containment vessel. And because of such heavy mass which is contained in this container, which is itself quite bulky, you have a system which can be of mass that is considered to be on the higher side.

So, there are a lot of opportunities to develop materials which can deliver the same mechanical parameters required in a flywheel, but they also ensure that the weight of the overall device or the system can be brought down then this technology will become very useful and a lot of research and development are going on in this field. And you will find these details in the published literature which will discuss about the types of materials which are used to fabricate the next-generation flywheels.

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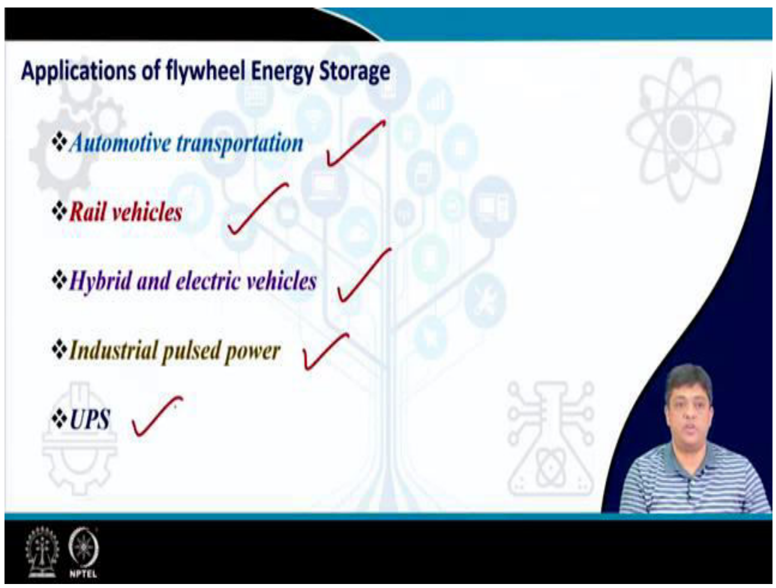

Once you have a working flywheel-based storage system, it is used in automotive transportation, rail vehicles, hybrid and electric vehicles, industrial pulse power outputs or uninterrupted power supplies or UPS.

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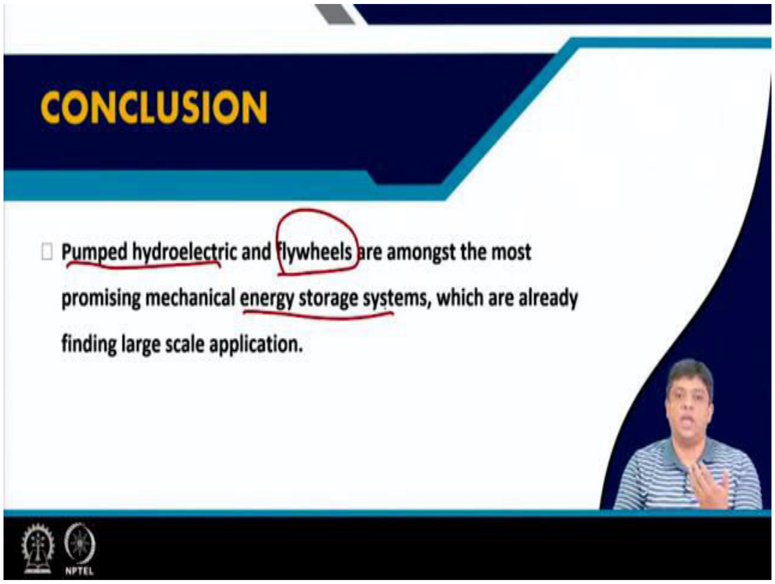

Hopefully, in today's lecture I have been able to convince that there are two mechanical energy storage systems namely the pumped hydroelectric and flywheel-based energy storage systems which are quite promising and are already finding large scale applications. But there is a lot of work which needs to be done to make this technology acceptable both for large scale use and also becomes viable for the industry in terms of cost and they also have low carbon footprint while they are being fabricated. So, a lot of different aspects are still open which need to be answered and as they are answered you will find the importance of these two technologies will increase even further.

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These are the references which were used today. With this, I finish this discussion on mechanical based energy storage technologies and I know that you are looking forward to the discussion on lithium ion batteries which will be classified under the subheading electrical based energy storage technologies. So, from next lecture onwards let us start one of the most useful and visible energy storage technology in today's world and that is lithium ion batteries. That will be discussed from next lecture. I thank you for attending today's lecture and have a nice day.