**Economic Operation and Control of Power System**

**Dr. Gururaj Mirle Vishwanath**

**Department of Electrical Engineering**

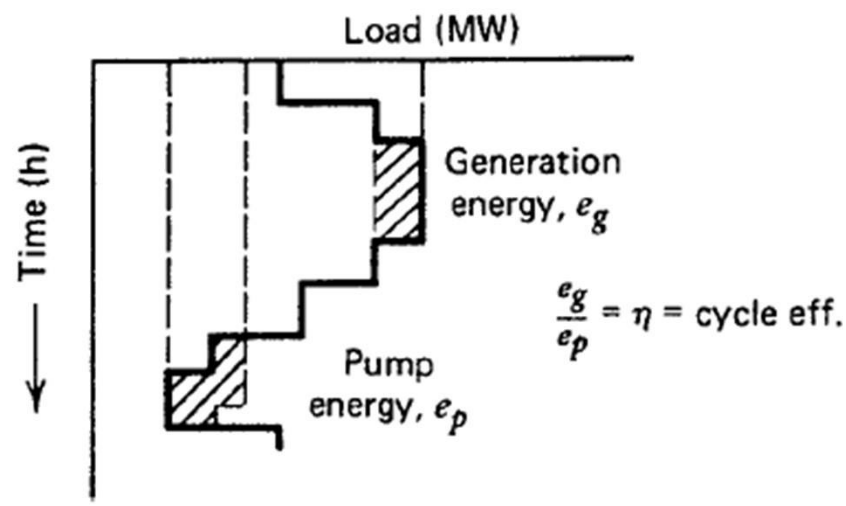
**IIT Kanpur**

**Week - 11**

**Lecture – 55**

Hello and good morning everyone, welcome you all for the NPTEL online course on Economic Operations and Control of Power Systems. We will continue our discussion with respect to pump storage hydroelectric power plant. So pump storage hydro plants are designed to save fuel cost by serving the peak load, a high fuel cost load with hydro energy and then pumping the water back into the reservoir at light load periods that means at a lower cost load. So basically what we are trying to do is we are going to utilize the potential energy of the water stored in a reservoir, upper reservoir during a time when there is fuel cost rate is quite high that means at a peak demand, so that generate the electricity and pump it into the grid, so that we can reduce burden upon thermal power plant and during off peak hour or a lower cost load conditions, so we can use the water which is present in the lower reservoir, pump it back to the upper reservoir so that it can be further utilized during the next peak hour condition. So the composite thermal system input output characteristics for the pump storage hydro plant is as shown below, you can see here, so this is the additional cost which is incurred as you pump the water from lower reservoir to the upper reservoir, you will be consuming electricity from the grid, so this is additional cost included because of pumping but in a way eventually because your generation is happening at a much cheaper rate, much higher rate in the sense that you will be having a better savings. So the cost incurred for pumping will be lower than the generation outcome that means the generation output that you get from a hydro power plant, so that there will be net saving from hydroelectric or pump storage perspective, otherwise there is no point in running a pump storage plant if you are not getting any profit out of it.

So pump storage, operation of pump storage hydro plant should consider the load cycle, a typical load cycle is as shown below, you see here there is a load which is shown here and there is a time. So at a specific given time when the generation or the demand is quite high, you can see here let us consider this as a demand, this is the demand, so demand is quite high in the axis, so and at this duration it is recommended for generation, it is recommended for generation, there is a peak time that you are generating. While in the other condition in the load curve you can see here where the load is quite less, let's say this is the load and this magnitude is lesser than the peak loading condition, so in that scenario you can see here we are pumping the energy that means you are utilizing electricity back from the grid to pump it to the reservoir, so there will be net saving as we told. So during the entire cycle there is a efficiency which we had discussed in the last class as:




Where, $e_g$ = generation in MWh

$e_p$ = pumping load in MWh } for the same volume of water

Then the cycle efficiency is $\eta = e_g / e_p$ ($\eta$ is typically about 0.67)

So the pump storage plant is operated until the added pumping cost exceeds the savings in thermal cost due to the peak sharing operations. So until the system is economical so we can run this pump storage plant and storage reservoirs have limited storage capability and typically provide 4 to 8 or 10 hour of continuous operation as a generator, so this there obviously there will be some limitations. So pump storage plants may be operated on a daily or weekly cycle as well, when operated on a weekly cycle pump storage plants will start the week say Monday morning with a full reservoir, so it depends upon case to case studies but when it is operating on a weekly cycle basis so you should ensure that on the Monday morning, on the day starting you have full reservoir so that you can use with a generation as a first interval depending upon the situation. So the plant will then be scheduled over a weekly period to act as a generator during high load hours and to refill the reservoir partially or completely during off peak hour, off peak periods. In some systems the system operator will require a complete daily refill of the reservoir when there is any concern over the availability of capacity reserves, in those instances the economy is secondary to reliability.

If you are more concerned about the reliability that means you may not look into the economical aspects so it depends upon case to case study again. So let's try to solve the pump storage hydro scheduling using lambda gamma iteration, so some of the assumptions before we go for a procedure, so constant head hydro operation this is the assumption that we are considering, usually in any hydro power plant that we have already discussed the head will not be constant throughout the operation, there will be some variation because when you are pumping there will be increase in the volume at the upper reservoir, when you are generating there will be decrease in the volume at the upper reservoir, so the head keeps varying but yet for the easy of analysis we consider it to be constant over a period of analysis. An equivalent steam unit with a convex input output curve, so we consider it to be convex input output curve for the steam power plant and a 24 hour operating schedule each time interval equals 1 hour, in any one interval the plant is either pumping or generating or idle any of these cases pumping, generating or idle, idle will be considered as just a limiting case of pumping or generating. Beginning and ending storage reservoir volumes are specified and pumping can be done continuously over the range of pump capability, pump and generating ratings are the same and there is a constant cycle efficiency, so this is how a typical pumped hydro power plant looks like there is a upper reservoir you can see here, this flow rate, water flow rate Rj it is given as and there is a volume of water which is stored in a upper reservoir which is mentioned here as Vj, this is the volume of water which is stored and this same water would flow through the penstock you know and then there is a powerhouse and there is a lower reservoir. So, as I already told during generation water is released in this direction during generation and during pumping the water is pumped back from lower reservoir to the upper reservoir.

So, there is a pumped hydro power plant and there is equivalent steam thermal power plant, this is a steam thermal power plant and they put together they are serving the load, this is the load. So the problem is set up ignoring reservoir volume constraints to show that the same type of equations can result as those that arose in the conventional hydro case and the figure below shows the flow of water and equivalent electrical system as we have discussed just now. So some terminologies:

$r_j$ = inflow (acre-ft h)

$V_j$ = volume at the end of interval (acre-ft)

$q_j$ = discharge if generating (acre-ft h)

Or, $w_j$ = pumping rate if pumping (acre-ft h)

Intervals during the day are classified into two sets:

$[k]$ = intervals of generation

$[i]$ = intervals of pumping

So both the units are same but different terminologies to help us discriminate whether it is a term associated with the generation process or a term associated with the pumping process. So intervals during the day are classified into two sets, so k is the duration or the intervals number of intervals during the generation process and we have I which is corresponding to the intervals of pumping, so both generation and pumping and could be some idle scenarios all of them put together we have 24 hour schedule.

So the reservoir constraints are to be monitored in the computational procedure, the initial and final volumes are:

- The initial and final volumes are

$$V_0 = V_s$$
$$V_{24} = V_e$$

- The problem is to minimize the sum of the hourly costs for steam generation over the day while observing the constraints.
- This total fuel cost for a day is (note that we have dropped $n_j$ here since $n_j = 1$ h)

$$F_T = \sum_{j=1}^{24} F_j \left(P_{sj}\right)$$

So, some of the fuel cost of each generation put together then finally for all the intervals it is not only for one interval, for all the intervals that fuel cost is given as FT and the objective is to minimize this FT.

So we consider the two sets of time intervals because pump storage unlike a typical hydro electric power plant where there is only generation happens, here we have to consider two different set of scenarios where in one scenario there is a generation intervals that we need to consider, in another scenario there is a pumping interval that we need to consider. One thing the students need to note it, notice that you know when there is a generation which is happening you cannot have pumping, if pumping is happening the generation cannot happen, so both cannot happen simultaneously, so they are mutually exclusive events as such. So let's consider the first case where there is a generation intervals, so as we have already discussed the number of intervals put together is K, so the electrical and hydraulic constraints are, so this is a electrical constraint, this the first equation indicates the electrical constraint here the summation of load, load at that specific K interval plus loss because of course there will be some electrical losses, load plus loss put together this should be equal to the generation. What is the generation? Generation is happening from the thermal power plant at that specific interval

☐ We consider the two sets of time intervals:

**Set 1**: $\{k\}$: **Generation intervals**: The electrical and hydraulic constraints are

$$P_{load_k} + P_{loss_k} - P_{s_k} - P_{H_k} = 0$$
$$V_k - V_{k-1} - r_k + q_k = 0$$

These give rise to a Lagrange function during a generation hour (interval $k$) of

$$E_k = F_k + \lambda_k\left(P_{load_k} + P_{loss_k} - P_{s_k} - P_{H_k}\right) + \gamma_k(V_k - V_{k-1} - r_k + q_k)$$

**Set 2**: $\{i\}$: **Pump intervals**: Similarly, for a typical pumping interval, $i$,

$$P_{load_i} + P_{loss_i} - P_{s_i} + P_{H_i} = 0$$
$$V_i - V_{i-1} - r_i - w_i = 0$$
$$E_i = F_i + \lambda_i\left(P_{load_i} + P_{loss_i} - P_{s_i} + P_{H_i}\right) + \gamma_i(V_i - V_{i-1} - r_i - w_i)$$

☐ Therefore, the total Lagrange function is

$$E = \sum_{\{k\}} E_k + \sum_{\{i\}} E_i + \varepsilon_s(V_0 - V_s) + \varepsilon_e(V_{24} - V_e)$$

Here, the end-point constraints on the storage have been added.

☐ In this formulation, the hours in which no pumped hydro activity takes place may

☐ be considered as pump (or generate) intervals with

$$P_{H_i} = P_{H_k} = 0$$

- To find the minimum of $_T = \sum F_j$ ,

the first partial derivatives of $E$ is set to 0.

**Set 1**: $\{k\}$: **Generation intervals**:

$$\frac{\partial E}{\partial P_{s_k}} = 0 = -\lambda_k \left(1 - \frac{\partial P_{loss}}{\partial P_{s_k}}\right) + \frac{dF_k}{dP_{s_k}}$$

$$\frac{\partial E}{\partial P_{H_k}} = 0 = -\lambda_k \left(1 - \frac{\partial P_{loss}}{\partial P_{H_k}}\right) + \gamma_k \frac{dq_k}{dP_{H_k}}$$

**Set 2**: $\{i\}$: **Pump intervals**:

$$\frac{\partial E}{\partial P_{s_i}} = 0 = -\lambda_i \left(1 - \frac{\partial P_{loss}}{\partial P_{s_i}}\right) + \frac{dF_i}{dP_{s_i}}$$

$$\frac{\partial E}{\partial P_{H_i}} = 0 = +\lambda_i \left(1 + \frac{\partial P_{loss}}{\partial P_{H_i}}\right) - \gamma_i \frac{dw_i}{dP_{H_i}}$$

- For the $\frac{\partial E}{\partial V}$, we can consider any interval of the entire day—for instance, the $l$th interval—which is not the first or 24th h.

$$\frac{\partial E}{\partial V_l} = 0 = \gamma_l - \gamma_{l+1}$$

and for $l = 0$ and $= 24$

$\frac{\partial E}{\partial V_0} = 0 = -\gamma_1 + \varepsilon_s$ and $\frac{\partial E}{\partial V_{24}} = 0 = \gamma_{24} + \varepsilon_e$

- From the last equation, it may be seen that $\gamma$ is a constant.
- Therefore, it is possible to solve the pumped-storage scheduling problem by means of a $\lambda$-$\gamma$ iteration over the time interval chosen.

It is necessary to monitor the calculations to prevent a violation of the reservoir constraints or else to incorporate them in the formulation. So we need to ensure that the constraints will not get violated so that need to be monitored and it is also possible to set up the problem of scheduling the pump storage hydro plant in a form that uses linear programming. So as we have also discussed about linear programming technique for a typical thermal power plant so using linear programming approach for pumped hydro pumped storage hydro scheduling along with the thermal power station scheduling will give you better results as well. Let us move on to the next topic which is detailed discussion or an overview about different types of energy storage technologies apart from pumped hydro storage system which is used in different capacities in a power system. So the first one is compressed air energy storage CAES and then we have flywheel which is a mechanical type of storage.

Then we have SMES superconducting magnetic energy storage which is a magnetic type of storage and there is we have a super capacitor, the batteries which is electrochemical storage type. In the electrochemical storage type we have numerous options. So one could use lead acid batteries, sodium sulphur, lithium ion, metal layer battery, fuel cell and again ultra capacitors which is same as super capacitor and then in terms of flow batteries we have three types. We have polysulphide bromide flow battery. This polysulphide bromide flow battery is also a very typically used application for grid storage and there is a vanadium redox battery flow battery type, vanadium redox battery flow type.

So in this case vanadium is used as a energy carrier basically. So the advantage with the vanadium redox flow battery type is it has good life cycle that means 10,000 to 15,000 or more than 20,000 also. But the disadvantage with the vanadium redox flow battery type is the efficiency, round trip efficiency that to be calculated between charging and discharging is quite poor. So the another type of flow battery that we see is zinc bromide flow battery. So this zinc bromide flow battery is used for a typical application where the diesel generator is also employed.

Let us say in a remote isolated area where you may be having solar and for a backup because solar is intermittent energy source you may need to have backup. So if you are using some diesel generator type and the combination of this diesel generator and the solar if they have to be optimized we need to have a battery type as well. So zinc bromide flow battery would help to improve the efficiency of the entire system especially the diesel generator. And then we have fuel cell and hydrogen storage. Nowadays there is lot of investment being planned from the central government level regarding green hydrogen.

So that means there is a renewable energy source. The renewable energy source is utilized to store the electrical energy in terms of green hydrogen and then the green hydrogen is used back to in the case of extreme scenarios where there is no renewable energy source available then this stored hydrogen can be reutilized to provide electricity to the system. So this is an overview that we will discuss a little bit in more detail about each of them. So storage technologies that make up the long and very long storage time categories are pump storage, compressed air storage as well as some of the other battery types. So there in terms of duration of storage we have categorized in terms of four types where is very short duration, the duration time could be 0 to 20 seconds. So it is used for end user protection 1 to 4 megawatt or more than 20 megawatt could be a capacity seen at this level and short duration 10 minutes to 20 hour, so up to 2 megawatt end user reserves and then long duration 1 to 8 hours greater than 10 megawatt generation, load leveling, ramp following, these are the typical areas where we use this kind of storages which can provide a long duration backup and then we have very long duration which is

1 to 7 days in terms of days where it is used for seasonal and emergency backup or the renewable energy backup as well.

So first we will take up this compressed air energy storage. The philosophy is very simple. So there is a electrical energy input to a motor and then you compress the air basically. There is air that you go for compression and then you store it basically and when you compress it there is an increase in temperature. This is one such limitation in this type of storage unit handling the thermal shoot up in energy that means increase in temperature.

So this is a typical constraint that one can see for enhancing the capacity of compressed air energy storage at a very long capacity or a long duration is quite challenging here and then there is release of this energy, whatever energy that you have stored by compressing the air that you release it and then when the air is relaxed now and it is expanded and this energy is been transmitted to the generator, now the electricity is produced which is further sent back to the grid. That means there is electrical energy in, is used for compressing the air, then storing that energy and in the reservoir where there is a thermal shoot up you need to have proper insulation techniques to ensure that you know you will not lose the energy and then the releasing of this compressed air storage when you expand it, now air become much cooler and then it will help to run a turbine connected to a generator where the electricity is produced. So the first ever compressed air energy storage plant was established in Germany and then still it is functional, expanding that capacity to a very large capacity is a challenge that we have discussed now and then there is a second type of energy storage which is flywheel energy storage. So here what is happening is there is a mechanical type of storage because there is a grid here and there is a power electronics converter interfacing, there is a motor generator combination basically what we are trying to do here is there is a big rotating mass and then you take electrical energy, you apply it to a motor which will make this rotor rotate at a very high speed and then use back this energy during the absence of the grid or there is a shortage of electricity at the grid level, then utilize the high speed rotating mass then to make it behave like a generator and then pump the energy back to the grid. So flywheel energy storage sees a very wide range of applications, it is also used in spacecraft applications, NASA utilizes this flywheel energy storage very frequently and there is a defense application, small electronics application, grid storage application, there are multiple areas that we can see the usage of flywheel energy storage type and then there is a superconducting magnetic energy storage type.

In the first application we discussed there was pumped hydro where we utilize energy in terms of water, using water resources and then we discussed about compressed air energy storage where we utilize air as a energy storage medium and then we discussed about the rotating mass that is a mechanical storage type and now we are discussing about magnetic energy storage type. Here it consists of the polytonic interfacing unit, this is a polytonic interfacing unit and there is a cryogenic cooler, there is a refrigerator which is required to maintain the temperature for a superconducting material. Here there is a superconducting coil which utilize the electrical energy and store the energy in terms of magnetic energy and this energy is stored there in the superconducting coil which is released back to the grid when there is a requirement. So this SMES is also a very important type of storage unit that is seen at the grid level you can see here, half Li square. So it depends upon the amount of current which is used for storing energy in terms of magnetic material, in the magnetic material and then we have supercapacitor.

So we know what is capacitor, so now it is a supercapacitor, it is a very high power density device. In fact SMES, superconducting magnetic energy storage device is also a very high power density device that means if you need energy at a very quick interval of time that means at very high capacity of power is required to be stored and pumped back to the grid in a very short duration SMES, superconducting magnetic energy storage type could be a very good option and so supercapacitor similarly also can cater to the need but the energy density of a supercapacitor is much smaller as compared to the superconducting magnetic energy storage type. So the expression for energy storage is half CV square here, now there is a grid and there is a DC bus AC to DC conversion happens and there could be a bidirectional converter here. So then this superconducting, so supercapacitor is being placed, you can control the charging and discharging rate of this supercapacitor by controlling the bidirectional DC to DC converter. So everything we need to ensure is on a frequent basis we need to monitor the state of charge of this supercapacitor at any given point of time the charging rate or discharging rate should not exceed beyond the capacity of the supercapacitor, so that need to be monitored.

So the supercapacitor is typically used for microgrid applications where you have other storage type could be the high energy density type of electrochemistry, battery storage type could be present in the system. So in order to improve the life scale, life cycle of the batteries, chemical storage batteries the supercapacitor runs in parallel with them so that it can take care of the high power density requirement of a microgrid and the high energy density requirement of a microgrid is been taken care by the chemical energy storage type which could be lithium ion, lead acid, nickel cadmium and anything it could be. So this is a typical modelling of a supercapacitor, so there is a series resistor and this is what is your capacitor and there is a small inductance that we consider and then there is a parallel resistor as well. So the ideal capacitor is defined by the surface of electrodes and width of the ions and this is the expression that we can see. The series resistor indicates or it defined by the quality of carbon deposition on the aluminium current collectors defined by the electrical conductivity of the carbon and defined also by the ionic mobility of the electrolyte as well.

So the leakage resistor, the overcharge beyond the decomposition limit of the electrolyte is a reason for the presence of the leakage resistor in the modelling and redox reaction impurities, redox reaction of functional groups on the edge of carbon particles and electronic conductance through the separator as well. And inductance indicates for high frequency behaviour and usually it is neglected if you need a detailed modelling inductance could be also engaged. So the complete equivalent circuit looks like this, you can see here there are many capacitors which are connected together, basically this supercapacitor is a combination of innumerable number of capacitors though the size looks very small but the capacity is in terms of farads where typical rating that I can suggest is 57 farad, 16 volt. That means there are multiple combinations of the capacitors which are combined in series parallel fashion such that you achieve this 57 farad. So usually the filter capacitors and all that we see is in terms of microfarad or milli farad but this supercapacitor is in terms of 57 farad but the size remains very small.

So the cell, the balancing of the voltage across different capacitors is a typical challenge in the case of supercapacitor design. And then we come across electrochemical battery type, there is a grid again similar to the type of supercapacitor control, there is AC to DC and there is a DC to DC bidirectional converter again here, there is a bidirectional converter and then there is a battery. Now this battery also is connected to a battery management system which will ensure that the health of a battery would be monitored at any given point of time and ensure that the life cycle of a battery would be enhanced. So the thermal handling and the state of charge handling, the damage that it could happen, the scenarios, all these things will be taken care by this battery management system. So what are the typical types of battery types that one can see is lead acid battery, sodium sulphur, nickel cadmium, nickel metal nitride, lithium iron and lithium iron polymer.

So lead acid battery is a very fundamentally used across different applications, very cheap but the disadvantage is the energy density is very less as well as the other challenges in the lead acid batteries, it can be exploded and it is quite bulky in size, so may not be suitable for many applications, could be electric vehicles also, it is not so suitable. So because the size would make the electric vehicle very bulky and there is a sodium sulphur, sodium iron based batteries which is a very popular type in terms of the resource material available in this country especially because India as a subcontinent is covered three side by water, saline water, we can get sodium out of it but the technologies need to be evolved to make it a viable solution and then there is a nickel cadmium battery. One of the typical disadvantage with nickel cadmium battery is the energy density is quite high compared to the lead acid battery but the problem is it suffers due to dreaded memory effect, what we call it as dreaded memory effect. What is this is, let us say you purchase a nickel cadmium battery and you, it so happens that you utilize it on a frequent basis to discharge it up to 50% of its maximum SOC on a frequent manner for a quite a long duration of time. So over a period of time the nickel cadmium battery would forget its capacity that it can be discharged below 50% as well, though originally it is designed to be discharged as a 10% or 20% or so but due to its frequent discharge up to 50%, it has far less capacity has forgotten its capacity so that it can be discharged even below this capacity of 50%.

So this is one of the typical disadvantage that one can see in nickel cadmium battery and then we have nickel metal hydride type as well which is you know almost similar to the nickel cadmium but the dreaded memory effect may not be seen here. So the very popular battery type is lithium ion because the energy density is quite high and it is very much suitable for electrically vehicle application, defense applications, space applications, various applications. The characteristics are very much suitable for very high fast charging and discharging, everything is fine, the problem is it is quite costlier because as a country like India we do not have lithium resources. So most of the lithium resources are seen in Australia, African countries as well as in China, US and all but in India we do not have lithium based resource material that makes it a very tough task for us to scale it up in a large scale for a grid application.

So that is a quite challenging task for us. So henceforth we are looking for alternative application, alternative battery storage type. So hopefully sodium based batteries could do the needful job in future. So battery equivalent circuit, so R internal model, this model is composed of an ideal voltage source representing an ideal and constant open circuit voltage of the battery connected in series with the resistor R internal. Thevenin battery model, the Thevenin's battery model is a complete form of the R internal model type where a parallel RC dipole is added in order to represent the transient effects related to the battery discharge. So RC network battery model type, the RC network battery model is an extended form of the Thevenin model where additional RC networks are connected in series along with the internal resistance because any voltage source will also have its own internal resistance as well.

Along with this we can also include RC network as well. The idea is to model additional internal voltage drop of the battery occurring with different time constants. So this makes a battery model more accurate as compared to just constrain the resistance. The number of RC dipoles must be chosen depending on the required accuracy of the model or the error between the simulated and measured curves of a given charge or discharge profile. And then we need to know about the battery management system. So battery management system is needed to increase the battery lifetime and reduce the battery ageing effect.

As we have discussed, these are the two important objectives of having a battery management system. Any battery manufacturer would also give you battery management system, BMS. So the main tasks of BMS are cell voltage monitoring, cell voltage balancing because balancing of the voltage across different cells is very important.

Otherwise, some cell may get damaged and further leading to the breakdown of the entire battery system and current monitoring, temperature monitoring, the protection aspects, state of charge calculation, charging and discharging, other functions like real time clock, memory, pre-authentication, so many objectives are fulfilled by using BMS. So what are the factors that affect the performance of a battery? One is the state of charge.

So typically it is suggested not to discharge, let us say below 20 percentage and not to charge frequently above 90 percentage. Even you might have observed in your own cell phone batteries that if you frequently discharge it let us say 5 percentage, 3 percentage or below 10 percentage, the battery life would degrade very quickly. So and even charging beyond 90 percentage is not so recommended. So typically it could be in the range of 20 to 90 percentage that makes the life of a battery, that improves the life of a battery over a good duration actually. So mode of discharge is also another important factor and the charging rate and discharging rate we call it as 1C, 2C, 3C coulomb charging and other things.

So 1C is very quick charging and discharging rate that means the entire capacity of charging, charge rate of a battery whatever SOC is there that can be discharged in one hour that is what it mentions as 1C. If it is a 10C battery that means you can, the entire capacity of the battery can be discharged comfortably in 10 hours. So lithium ion is one such battery type which can support this 1C charging and discharging. That means you go for a electric vehicle charging station, you cannot wait for 10 hours to get your battery to get charged.

The quicker is the better. So you want to have such kind of battery storage which can support you quick charging. So that is what I told lithium ion supports all these features. And there is temperature. So the battery life is very much depending upon the operating conditions. So extreme weather conditions could be lower temperature or the higher temperature will surely have an impact on the performance of a battery type.

And charging voltage, age and storage conditions. If storage condition is not properly maintained so that can also affect the life of a battery because there should be proper air circulation, proper ventilation should be there so that you can evacuate the thermal heat that is been accumulated because of this charging and discharging cycles and also this depends upon the design aspect as well. Some important terms, capacity is given by integration of IT DT, you know DQ by DT is what is current. So basically this is nothing but the charge and then depth of discharge. DOD is very important term as well.

Let us say you have a battery capacity of 100 ampere hour. So usually the rating of the battery is denoted by this term as ampere hour. How much current that means amps for how much duration hour. So let us say this is the capacity of this battery 100 ampere hour and then you discharge at a rate of 20 amps for 20 minutes let us say, 20 minutes. Then how do you calculate depth of discharge? It is very simple.

You have to do 20 into 20 by 60 because for hour we are discussing. So 20 by 60 divided by 100. So this will give you one third. So around one third of, this can be in terms of 33 percentage or so, 33 percentage, 20 by 60, just a minute. So 20 into 20 by 60, this comes out to be one third of 20 which is nothing but 16.66 percentage. So the depth of discharge is 16.66 percentage. So one can easily tell what is state of charge. If you know depth of discharge, then SOC is 100 minus 16.66 percentage. This could be around 83 percentage. So state of energy, this is energy at any given point of time with the energy stored and losses in energy storage.

Loss due to power transfer, that means charge and discharge, this is a constant alpha into P square. Loss due to self-discharge is P0, this is expressed as P0, this is again state of energy and total loss is alpha P square T plus P0 and state of energy is, state of energy at any given point of time is initial state of energy plus the loss which is happening divided by energy. So ultimately you will get the state of energy at any given point of time.

So another type is flow batteries. This I have already discussed. So there is a grid and there is a power conditioning unit. Basically there is electrolytes which are used and you store the energy in terms of flow battery types. So this is used for renewable energy application basically. And then we have fuel cell and hydrogen storage.

So what is happening here is there is a fuel input. So fuel cell input could be hydrogen and then if you use the, you know, you separate this hydrogen ions then the electricity is carried and then you mix it with the oxygen then water is taken out. Hydrogen ion with oxygen then the water is been taken out. So this is during the discharge rate, sorry during the discharge, that means you are producing the electricity. So during charging that means you are storing the hydrogen. So you, the input is water and then you separate the ions, oxygen is been taken out and this hydrogen is been stored here by using the electricity which is available externally and then this hydrogen is stored in a tank basically.

So again this hydrogen during the discharge cycle this is used to produce the electricity. So but the disadvantage with the hydrogen storage as of now is the round trip efficiency is around 30 to 40 percentage only. So efficiency is very poor but there is lot of scope to improvement as, for improvement as well and the whole world is planning to invest on this green hydrogen. So just a table indicating the different comparisons of energy storage types. So in terms of energy density and power density you can see here. So in terms of power density there is no comparison for super capacitors and capacitors, high power density device but for in terms of energy density you can see a battery and fuel cell could be a good option or flywheel as well.

And then in terms of life cycle and efficiency you can see. So the efficiency of lithium ion is good and it lies in the range of 1000 to 10,000 life cycle whereas the pumped hydro the efficiency is also reasonably very good and the life cycle is also very good. Similarly flywheels as well. So metal layer type of energy storage the life cycle is very bad as compared to the others. So just to summarize the energy storage, the importance of energy storage in smart grid or the power system area is renewable integration applications, off grid power that means if there is no electricity board available still you want to maintain the reliability of the supply then you can use for off grid applications and to flatten the load curve. That means if there is a peak at some time and you need to flatten the curve so you can use this battery type to charge or discharge so that you can reduce the burden upon the grid.

So these are the typical areas where the energy storage is used in power system level. So with this we will conclude. Thank you very much. .