Economic Operation and Control of Power System

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Week - 11

Lecture – 54

Hello and good morning everyone, welcome you all for the NPTEL online course on Economic Operations and Control of Power Systems. In today's class we will discuss about pump storage and gravity storage. So just a brief introduction about the pump storage, post World War II period saw the increasing installation of pump storage hydroelectric plants in the United States and a great deal of interest in energy storage systems. So the pump storage hydroelectric plant really picked up post World War II especially in US and across the globe now we can see the installation of pump storage plant to you know take care of energy storage requirement of a system. Methods are available for solving the coordination of hydroelectric, thermal and pump storage electric systems. Now there is a hydroelectric plant and there is a thermal power plant and pump storage electric system is also a sort of storage system maybe it is a hydro system or gravity storage is also a sort of storage system that we will discuss in later stage.

So when we have hydroelectric power plant and thermal power plant along with the pump storage system how do we coordinate all of them such that we will achieve the required objectives that is a little bit more challenging compared to a typical hydroelectric and thermal scheduling economic dispatch problem. However challenge in economic dispatch is proper commitment of an array of units out of a total array of units to serve the expected load demands in an optimal manner that means there let's say N number of total array of units out of which there is X number of array of units that you need to choose where X is less than N then we need to you know optimally choose what combination of X array of units would result in the most economical solution simultaneously achieving the required objectives. So the input output characteristic of a typical hydroelectric units that looks like this, this is a input, input is volume of water expressed in terms of acre feet per hour and the output is power which is expressed in terms of megawatt. You can see here as there is power demand which increases there is a linear increase in the volume of water which is required.

So which is a genuine requirement as well but after a certain limit there is a maximum power limit after which the requirement of volume of water would be non-linear that means there is a non-linear increase in volume of water which is not so suitable to operate at this zone especially. So this characteristic shows an almost linear curve of input of water volume requirements per unit time as a function of water output as the power output increases from minimum to rated load, this is the rated or maximum load as such. And then above the rated load the volume of requirements, volume requirements increases as the efficiency of the unit falls off. Basically the reason for increase in volume of water that means non-linear rise in volume of water is because of decrease in efficiency of the overall unit. The incremental water rate characteristics is shown below that means if you draw a characteristics where in Y axis we have incremental water rate which is dQ by dP and in X axis we have output which is power that you can see it is constant throughout until we achieve the maximum or rated value and over which now it is linear.

So because the, when as we draw the volume versus output it was non-linear so when you derive it you will get constant from minimum to maximum or rated and over which it looks like a linear characteristic curve. And then the input output characteristics of a hydroelectric plant with variable head is shown below. Typically practical hydroelectric power plant would operate in different variable heads single hydroelectric power plant also and there could be you know multiple hydroelectric power plants which may be operating at a given specific point of time with variable or different heads. So how do we you know manage them is a challenging task. You can see here for any given amount of power output let's say this is a power output.

So you can see here with 495 feet water head this is for 495 feet water head and this characteristics curve is for 450 feet water head and there is another characteristic curve which is given for 400 feet water head. You can see here for a given specific amount of power output or a demand let's say there is some amount you can see here the water requirement the volume of water required for different heads varies and in fact it is lower for the highest head which is 495 feet and it is highest for the lowest head which is 400 feet. So by this we will understand that you know operating a typical hydroelectric power plant for a given output demand it's really challenging because you require different amount of water release as such to meet out the energy demand. So this type of characteristic curve occurs whenever the variation in the storage pond that is forebay and afterbay elevations is a fairly large percentage of the overall net hydraulic head because there is a reservoir here and there is a lower reservoir and upper reservoir right so there is a turbine. So once the water present in the upper reservoir starts decreasing and there is a afterbay or lower reservoir so the water would increase at the lower reservoir so then this afterbay increase in water head would cause a different speed and water flow the inflow would vary because at the upper reservoir the water would decrease and the lower reservoir possibly the water would increase.

So this would, this is another reason and if this percentage variation is quite heavy then you can see such kind of challenges more prominent at this kind of scenarios. So scheduling hydroelectric plants with variable head characteristics is more difficult than scheduling hydroelectric plant with fixed heads. This is true not only because of the multiplicity of input output curves that must be considered, the maximum capacity of the plant will also tend to vary with the hydraulic head that's what we have discussed. For the last figure volume of water required for a given power output decreases as the head increases. You can see here:

$$\frac{dQ}{dH} \text{ or } \frac{dQ}{dV}$$

where, H represents here height if H increases then the volume of water required decreases so dQ by dH remains constant in that way.

So that means the volume of water, the slope would be decreasing as the head increases So that's what is been mentioned here. So let's discuss little bit about pump storage now. So characteristic exhibited by pump storage hydroelectric plant is shown below. Now it's pumping here as shown and this as we saw for a typical hydroelectric power plant. So these plants are designed so that water may be stored by pumping it against a net hydroelectric head for discharge at a more favorable time.

The objective is to pump the water from a lower reservoir to a higher reservoir or upper reservoir. So at a time where the load is low or the cost of operation is low and the power is drawn from the hydroelectric power plant by pushing water from upper reservoir to lower reservoir when the cost of electricity is high or the demand is high. So this is a overall round trip operation that we call it as pump storage hydroelectric power plant. So this type of plants was originally installed with separate hydraulic turbines and electric motor driven pumps. So what do you require is electric motors and a turbine, right? So in olden days, you know, we need to have, we were supposed to have the hydroelectric turbines and electric motor driven pumps separately and recent years there is a upgradation in the technology where reversible hydraulic pump turbines have been utilized.

That means a same turbine can operate both during generation as well as during motoring. So these reversible pump turbines exhibit normal input output characteristics when utilized as turbines. In the pumping mode however, the efficiency of operation tends to fall off when the pump is operated away from the rating of the unit because during pumping, as you keep on pumping the water from lower reservoir to higher reservoir, so you may be operating at a different operating points because the head would also keep varying. So and then one can see the efficiency also changes, maybe it changes from maximum efficiency point to the suboptimal efficiency operating points as well. So for this reason most plant operators will only operate these units in the pumping mode at a fixed pumping load.

So that's the reason, you know, most of the plant operators to ensure the round trip efficiency is high, they would tend to operate this pump storage plant at a fixed pumping loads. So the scheduling of pump storage hydroelectric plants may also be complicated by the necessity of recognizing the variable head effects that we have discussed. These effects may be most pronounced in the variation of the maximum capability of the plant. So it depends upon the maximum capacity of a plant to sustain this water inflow. So this variable maximum capacity may have a significant effect on the requirements for selecting capacity to run on the system and pump storage hydro plants may usually be considered as spinning reserve capability, that is they will be used only during periods of highest cost generation on the thermal units.

That means these pump storage hydro plants are not regularly utilized for the economic dispatch whereas they are used during those periods when it is at the most required, that means during highest cost of generation on thermal units. At other times they may be considered as readily available, that means spinning reserve, that means as we have discussed that certain amount of generation plant need to be kept ready for, to meet out some emergency scenarios, that means if there is sudden fall off of one single generation, we have discussed about this N minus 1 contingency scenarios where one highest or largest capacity thermal power plant may get disconnected from a system due to any reason. In such kind of scenarios there should be some minimum reserve, what we call it as spinning reserve power plants which need to you know pitch in. So that we can take care of the required load demands. So pumped storage plant could be one such spinning reserve option for the system operator.

So during periods when they would normally be pumping they may be shut off to reduce the demand, when idle they may be started rapidly. So this is one such important characteristics when they are idle they may be started rapidly and they may be shut off to reduce the demand, so unnecessarily power loss can also be reduced. So the characteristics illustrated before are for single isolated plants. In many river systems plants are connected in both series and in parallel, that is hydraulically they are connected in series and parallel. In this case the release of an upstream plant contributes to the inflow of downstream plants.

Let's say there is a release of water, let's say there are two power plants and there is different set of turbine generator combination present in two different hydroelectric power plants and if there is a release of water for hydro power plant 1, this water can also act as inflow to the hydro power plant 2. So we need to include these constraints as well. So how much of water release that I can do at hydro power plant 1 such that you know I would not exceed the inflow of water at hydro power plant 2 is another important challenge that we need to cater into. So the situation becomes even more complex when pump storage plants are constructed in conjunction with conventional hydroelectric plants. So hydroelectric plants as we have already discussed there are certain its own constraints that it should not, there are certain challenges that we have considered the navigation of water flow or river need to be considered and there is a constraint in terms of how much irrigation support that it can offer to or it should not also cause any flood to the downstream areas and all these constraints that we have discussed for a typical hydroelectric power plant and when we bring in pump storage also in parallel to it so that the complexity would further increase.

So the problem of the optimum utilization of these resources involves the complicated problems associated with the scheduling of water as well as the optimum operation of the electric power system to minimize production cost. So the final objective anyway is to minimize the production cost while taking into consideration all the constraints that a typical hydroelectric power plant as well as thermal power plant and pump storage plant individually may have. So then we will discuss little bit details about the energy storage. So electric energy storage at the transmission level where large amount of electric energy can be stored over long time periods is very useful. So ultimately you know if there is electric energy storage option available both maybe at the transmission level or at the distribution level it will be very helpful especially when we think about the future prospects where lot of renewables are pitching in in the system So we need to have sufficient amount of storage because renewables they themselves are volatile, they are intermittent and at times they are available in heavy quantity and there is a time where there is no availability of wind or the solar.

So we need to have a sufficient storage deployment at the transmission distribution corridor such that we will be able to operate the system at a given power frequency which is 50 hertz. So when the prices of electric energy are low for example at night then it is useful to buy electrical energy and then sell it back into the system during high price periods. This is a fundamental economic rule where when the demand is low then store them in either in terms of chemical storage, pump storage or gravity storage or could be green hydrogen any sort of flywheel, mechanical storage so many options that we have in our portfolio so any one of them or combination of them could be utilized such that we can store the energy and then release them when the demand is high or the price is high. Similarly for renewable generation source such as wind generator that cannot be scheduled is being operated then it would be useful to store electric energy when the wind is blowing and then release it to the power system when most advantageous what we call it as a dispatchable source. So we have a wind or solar power plant then when we have them so we do not have control about the amount of wind that is blowing at a specific time or the availability of the solar as well as we have discussed.

So when there is excess of solar and wind then the demand so it is better to you know store them in terms of any of these storages and you know operate them at its maximum capacity basically we discussed about maximum power point so it is intended to operate this renewable sources all the time at maximum power point unless and until for a specific scenario or for a different case studies where you need to have some inertia support that is a different but most of the time it is intended to operate them at a maximum power point tracking time or tracking point such that we can extract maximum power from them and if there is a shortage of load store them so that you can utilize for a better cause in future. So if there are seasonal variations such as in hydro systems we would like to store energy during high runoff periods and then use it later when runoff is lower that means if there is excess of water store them and then there is shortage of water then use them in appropriate manner. So parameters of electrical energy storage are some of the parameters that we need to know so that we can formulate the problem. Electrical energy capacity which is denoted as WOP which denotes the quantity of stored energy that is retrievable as electric power and rated power which is P rated this denotes the name plate value for the rated rate at which electric energy can be continuously stored or extracted from the storage system usually given in kilowatt or megawatt also referred to as the discharge capacity. So this is the name plate value of electric energy that can be stored or extracted from the storage system how much is the maximum capacity of inflow or outflow, a charge or discharge.

And discharge time that means T storage the duration of time that the energy storage system can supply a rated power given as:

$$t_{storage} = W_{op}/P_{rated}.$$

It will give you time that means at what rate that you can discharge and what is the amount of storage that we have in terms of its energy capacity. So then we get to know like what is the duration of time that we can support the given load using the storage. So and then there is another important parameter which is energy density available energy capacity per unit mass given in watt hour per kg. So this is a very important thing let's say for example we will take lithium ion storage. Lithium ion storage has very good energy density that means a small density of small volume of lithium ion battery can able to store good amount of energy as compared to its own family of storages let it could be of lead acid or nickel cadmium or any of them.

So lithium ion has a better advantage over these other storage units because it has that high energy density capacity where small volume of the lithium ion can have better energy storage. Henceforth it is more suitable for electric vehicles and other applications because you do not want to increase the size of electric vehicle just because of a storage you want to have more compact more sleek vehicles yet to achieve the requirement of the e-mobility. And then power density you see rated power per unit mass and this is given as given in watt per kg. So power density and energy density is very important to reduce the volume of storage and then parameters of electrical energy storage continued round trip efficiency. You see at the overall efficiency of consuming and later releasing energy at the point of common coupling with power grid also known as AC-AC efficiency that means round trip efficiency accounts for all conversion and storage losses and can be broken into charging and discharging efficiency.

So very important when we charge we use electricity from the grid to store it. So in between this storage unit and there is and the grid there are multiple interfacing elements there could be converters and there could be transformers it could be anything. So all of them would add up to the losses. So there is a round trip efficiency means during charging and there is during discharging. So how much is the total losses that is taking place that would decide which storage would be a most viable option for a specific application.

So you can see here efficiency round trip is equal to efficiency during charging time, efficiency during charging and efficiency during discharging both multiplied together that means if they are same one and the same let's for example understand that they are same then this is nothing but efficiency square of one way one trip. So cycle life is another important parameter which indicates the maximum number of cycles for which the system is rated. The actual operating lifespan of the battery is either the cycle life or the rated lifespan whichever is reached first because every battery has its own lifespan. There is no device which can give you infinite life. So there are different lifespans for different storages and we need to operate them such that will not increase their lifespan and over a period of time even if you try to use them beyond their lifespan their efficiency is so poor that it's not worth it to operate or use this storage anymore.

So this is a typical pump storage schematic or a layout that it would look like. So fundamental formula energy is equal to mass into gravity into height mgh. You see there is a upper reservoir of storage of water and there is a penstock. This is your penstock that means the water pipe that connects the upper reservoir with the downstream or a lower reservoir unit and then this water is flown through this penstock and then there is a pump which is connected to this and then once the pump or a turbine which rotates and this water is then collected at a lower reservoir and then to this pump or turbine is coupled a generator. This is a generator and this is a turbine and this generator would generate the electricity which is further if there is any frequency conversions required that is done using converters and then finally it is connected to the electricity grid.

So this is how a typical pump storage unit would look like. So just a small thing, so during the generator operation the water flows like this and then during the motoring operation or the storing operation then the water would flow in a reverse direction the water would flow like this. So that from water would flow from lower reservoir to upper reservoir during the motoring operation and water would flow from upper reservoir to lower reservoir during the generator operation. So most hydro units and pump storage hydro units can be brought online synchronized and brought up to the full capacity quickly as such these units can be counted in the overall reserve assessment if their time to come up to full capacity is considered. Reserves must be spread around the power system to avoid transmission system limitations often called bottling of reserves and to allow various parts of the system to run as islands if they become electrically disconnected.

So this we have discussed earlier also. We need to have spinning reserves also at different locations. If we have spinning reserves at one specific location then if there is a loss of line or fault or whatever may be the reason then the other part of the network may not be getting any support which is expected. So we need to have this reserve, spinning reserves being distributed across the transmission or a distribution network such that you know we will be able to meet out the expectation of the network even if there is a loss of one specific part of a system the other part of a network would be getting a continuity of a power supply so that we can enhance the reliability of the overall operation and especially during a case of islanding operation where a part of the network if it gets disconnected still it should have its own innate storage capacity such that the generation and demand balance would be met. So with this I will conclude and we will take up the rest part of the pump storage in a subsequent class. Thank you very much.