

A Study of Motor - Generator Topologies for Pumped Storage Applications

S.R.Mohanrajan, S.Vamsi Krishna, L.Narayana Reddy, A.Surya Teja, B.Vishal

Abstract—Pumped hydro is one of more economic and reliable storage mechanisms for plants with higher capacities. To make the pumped storage system more effective, the best machine suited for this purpose must be used. Present paper deals with the comparison of various possible machines in pumped hydro systems. Synchronous machines, fixed and variable speed induction machines and doubly-fed induction machines were compared for pump and turbine applications. The possible configuration and basic characteristics of each machine are described for pumped hydro application.

Keywords—Doubly Fed Induction Machine, Fixed speed systems, Pumped hydro storage, Variable speed systems.

Introduction

The main essential quality of the grid is that the electric power generated should be equal to the power demand at any time. If they are not equal, then there is a chance of losing synchronization and it could lead to tripping of load and in worst cases, tripping of the grid itself. So there is a need for a sustainable technology that can meet the demand whenever needed. There is also a need of effective integration of new energy generating mechanism, its energy storage and transmission. All these together will improve not only the reliability of grid but also the cost incurred in meeting them. A storage system helps in improving the capability of system to provide energy when it is needed and store the energy whenever it is produced in excess. There are many energy storage technologies like Lead Acid Battery Storage and Lithium Ion Battery Storage, Superconducting Magnetic Energy Storage, Fly Wheel Storage and Pumped Hydro Systems (PHS). Among these the pumped hydro storage technology is found to be more optimal when storage capacity and efficiency were compared [1].

In future, pumped hydro storage will be among the most reliable technologies available for grid power storage. In the past decade, there has been a

tremendous increase in the wind and solar energy generation due to tax incentives and other policies. So developing the Pumped Hydro Storage plants near the places where there is a heavy chance of wind and solar energy generation can lead to improved strength and reliability of the distribution system and it will reduce the need of additional fossil-fuelled generation.

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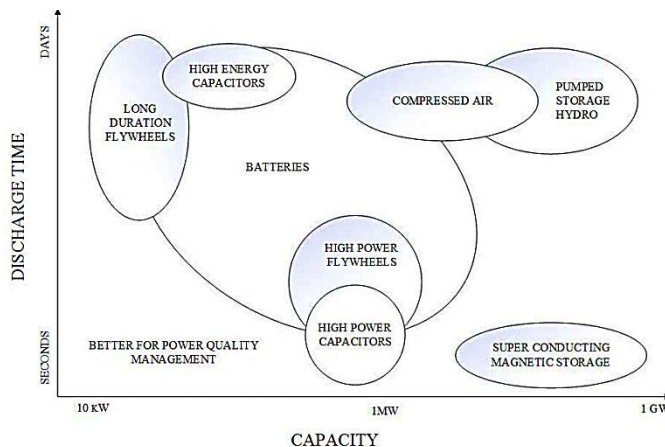


Figure.1 Capacity vs. Discharge Time for different technologies. [2]

The characteristics like grid reliability are considered because of the reason that the wind blow is seasonal and solar energy is available only during daytime [3]. There is more demand for the development of energy storage systems as essential components for using renewable energy systems more efficiently and in large amounts. The variable speed pumped storage technology provides quick response in adjusting frequency regulation in both the generation and pumping. PHS is not very expensive as it does not require any additional fossil fuels for generating electricity. It is an emission free energy storage mechanism. It is the best storage alternative while meeting the demand for bulk loads and is very quick in response. It is also having a high overall efficiency of about 70-80%. But these systems need lot of resources

such as proper terrains for installing the systems [4]. The main limitation of the PHS system is that it needs minimum one dam along the river streams or any water bodies that has a constant flow of water resources. So initiatives should be taken to implement the projects in sites where there will be minimal effects to the environment surrounding it. For that a feasibility study should be done in those areas where the plant implementation is proposed. New approaches like locating reservoirs that are physically separated from existing river systems must be encouraged. Priority must be given to reduce the evaporation and seepage losses. There should be regular treatment to the Pumped Hydro Systems for better performance. But these systems will need less investment compared to flywheel, SMES, and battery storage technologies [5], [6]. In these plants, the energy is stored in the form of potential energy of water pumped up from a lower elevation reservoir to a higher elevation [7]. During periods of high electrical demand, the stored water is released through turbines to produce electric power by running an electrical machine (like Synchronous or Induction) in generating mode and during the process of pumping water from lower elevation to higher elevation, the electrical machine is operated in motoring mode [8],[9]. The motoring mode and generating mode can be achieved by either fixed or variable speed operations. The generating set operates at constant speed and during this fixed speed operation, power input is directly dependent upon the pumping head and cannot be adjusted. In variable speed operation, pump mode enables operation with adjustable power input at each of the required pumping head [10], [11], [12], thus providing regulated pump operation.

The machines used for pumped hydro systems can be fixed or variable speed machines. The synchronous machine, cage rotor induction machine, squirrel cage induction machine and wound rotor induction machine are reviewed. In current developing systems, variable speed machines are being deployed as they have advantages in reducing the mechanical stress and they dynamically compensate for torque and power pulsations to improve power quality and system efficiency.

Overview of Pumped Hydro System

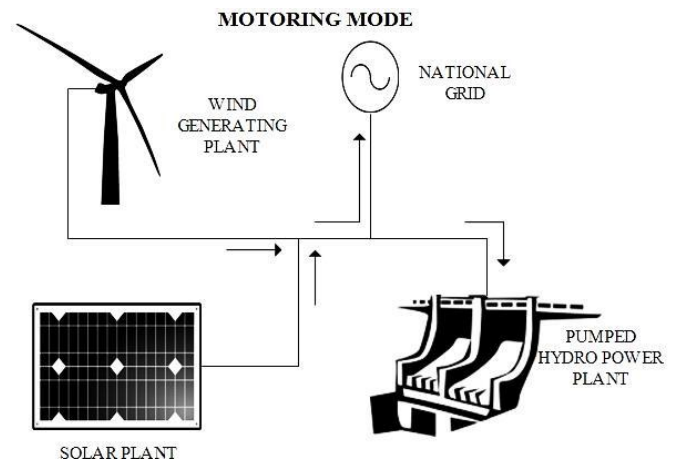


Figure.1 Motoring mode of Pumped Hydro System

An ideal example of a grid connected to pumped hydro system as well as a solar and wind plants is considered. If the load is low, then the excess power generated by wind and solar plants is taken by the pumped hydro system and water is pumped to a storage system located at a higher altitude as shown in Fig.1.

The most difficult situation arises when the wind and solar plants generate very low power at the same time when load reaches peak. In this case, the power generated by pumped hydro system should be enough to compensate the peak load.

If the load demand is high, then the additional power required to meet the demand is generated by pumped hydro system as shown in Fig.2. The pumped hydro system uses the mechanical energy generated by sending water downstream on turbines and generates power. The power generated by wind and solar plants is subject to fluctuations in the amount of wind energy and sunlight. In those cases where the power

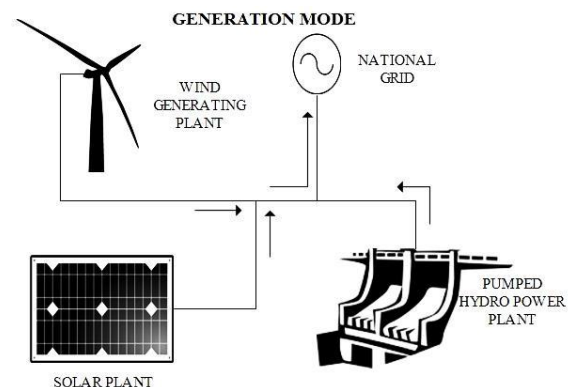


Figure.2 Generation mode of Pumped Hydro System

generated by wind or solar plants is very low, the additional power required is given to the grid by pumped hydro system. Thus load regulation is achieved by using a pumped hydro system. Systems with variable loads and constantly changing renewable inputs require pumped hydro systems.

Possible Machines for Fixed Speed Pumped Hydro

1. Synchronous Machine

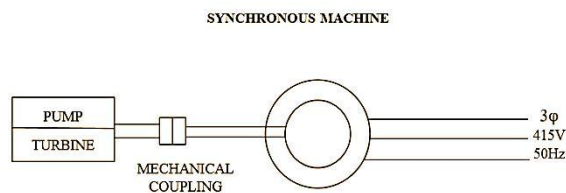


Figure.3 3-Phase Synchronous Machine Pump-Turbine System

A synchronous machine is a fixed speed machine. The field excitation given here will be a DC supply. They have special starting characteristics and constant speed under load variation. In fixed speed systems, synchronous machine will be made to run as Induction machine for motoring applications and for generating applications it is made to run as synchronous machine itself. DC excitation of a synchronous generator should not only ensure stable AC voltage on the stator but also should take care of the sudden changes in the load.

There are 3 ways of exciting the rotor.

1. Slip ring's link the rotor through an external DC source.
2. A dc source is placed on the rotor shaft of the machine. Rectifying the current sent to the rotor through commutators [13].
3. With the help of brushless exciter.

Hydro electric generators are machines which are run by water turbines. These machines are basically synchronous generators with their rotor connected to hydraulic turbine. They are usually made to run at a power factor range of 0.9 to 0.95[14]. High capacity, low speed generators are very large in size [15]. While designing hydro generators, priority is given to the rotating units, cooling system for the windings and the rotor. The machine below 100rpm is considered as a

low speed machine and if the speed is above 100rpm, it is high speed machine [16], [17].

When used for pump turbine application they operate as both motor and generator. The synchronous machines are widely used as generators in A.C. transmission. But the range of variation in load angle is limited and the system can go out of synchronization when there is a large sudden change in the load because the machine cannot sustain it. The rating of the equipment connected for operation should be same as the machine [18]. So high power rating power electronic devices are needed for excitation system. This makes the system expensive. The other factor that should be considered is that the DC supply for higher current rating is expensive. So for higher current rating, DC is obtained through rectification. For turbine application, it runs as synchronous generator. The supplied power varies depending on the power delivered by prime mover and at lower power ratings the machine runs at lower efficiencies. So for higher power ratings, systems are run with synchronous machines with permanent magnets [19]. The DC excitation system as well as the power electronic equipment is located on the rotor side. The number of poles and the frequency of the system decide the speed of the machine.

Synchronous machines and DFIG have the same type of stator but differ in the structure of rotor. Rotor of constant speed type generator-motor with DC-excitation is salient pole with solenoid type field coil. For variable speed type generator-motor with AC-excitation, rotor is cylindrical type with 3-phase windings. Compared to fixed speed systems, variable speed systems are good for extracting more power from prime mover and to run the prime mover for optimal efficiency by running it at variable speeds [20]. This is more advantageous and favorable with respect to the lifetime of the system and reduces the effort of maintenance.

4. Induction Machine

An induction machine is a self-starting machine and need a soft switch for smooth start. It is very robust, cheap and easy for mass production. The rotor can be made with bars short circuited at both ends. It's a low power factor run machine and complexity lies in providing reactive supply to the machine.

This system consists of Induction machine connected directly to grid without any converter [21]. It is basically connected to transformer and then to grid. It will run at constant speed as the slip is made constant. Some speed variation will be there and it is of narrow range. This is due to

the reason that the system is protected against over slip and overload. To compensate the lagging power a large capacitor bank is needed. The grid voltage is controlled by adding a capacitor bank. To

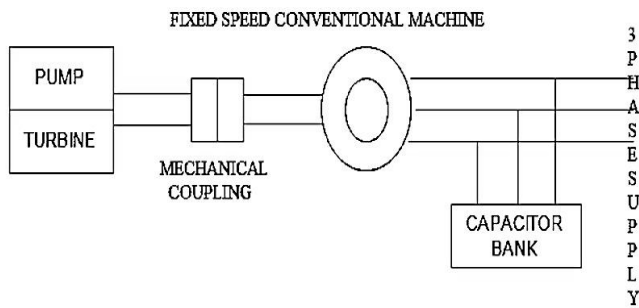


Figure.4 Fixed Speed Conventional Machine (Induction Machine)

stabilize the system the switching of capacitors is necessary and this leads to undesired transients. For the system to run at low power conditions it is to be provided with another set of stator windings by changing the number of poles. This reduces the synchronous speed of the machine and allows the operation at low power capacity for same torque. When operated as generator and it also operates at less power rating for same speed when operated as motor. So, this considerably effects the construction of the machine and makes it more expensive. Compromises are to be made in consideration of the extra added winding on the stator side.

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Possible Machines for Variable Speed Pumped Hydro

1. Variable Speed Induction Machine

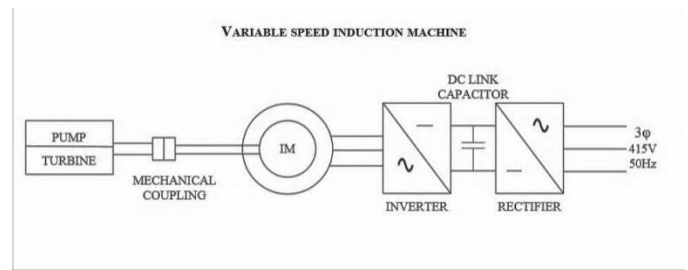


Figure.5 Variable Speed Induction Machine (Squirrel Cage)

In recent applications, due to the advancement of power electronics, the machine is being controlled by VFD (Variable Frequency Drives) or v/f drives. Its speed can be controlled by Stator Voltage Control, V/f control and also by changing the number of poles in the stator.

A variable speed system improves the power generation and consumption compared to other fixed speed systems [22]. This system will run at higher efficiencies compared to conventional fixed speed machines [23], [21]. For variable speed control a back to back PWM control converter configuration should be placed on the stator side. The main advantage of this system is that the selection of the system for generating or motoring in the PHS can be done based on the requirement as it can run efficiently at any rating. The power electronics equipment needed for the system to run should have higher rating than the machine rating. When made to run as a pump and turbine system, the firing angle can be adjusted to make it to run either as generator or as a motor. When made to run as a motor, the speed given can be controlled by PWM converter. The speed determines the torque characteristics of the pump load. So the speed is adjusted based on the power available on the grid. When at times of high demand the machine is made to run as generator and power needed is delivered again based on the speed control. In this machine the speed can only be controlled up to certain limit. The reactive power required is supplied by placing a DC link capacitor in between the back to back inverter configuration. This system can be directly connected to the grid side and can be applied to any power rating. When the machine speed is controlled by changing the number of pole pairs then for higher number of poles the head will be low and machine runs at lower speed. And for high head the machine is made to run with stator having lower number of poles as the speed is high.

2. Doubly Fed Induction Machine

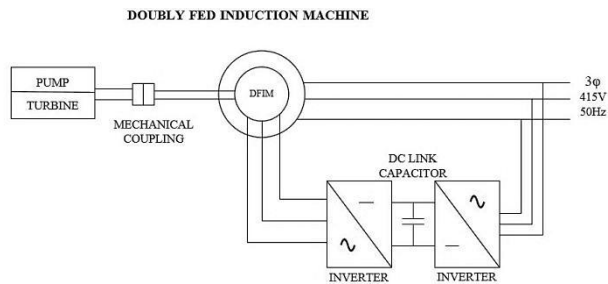


Figure.6 Doubly Fed Induction Machine

DFIM is a Wound Rotor Induction Machine with AC supply given to both stator and rotor. The PWM back to back inverter is connected to the rotor side. The main advantage of this system is the capability of rotor circuit in allowing the bidirectional flow of power in both sub-synchronous mode and super-synchronous mode [21]. The power rating of the converter is also reduced as it is connected to the rotor side. It is to note that the number of turns in stator should be more than the number of turns in the rotor [24]. With the voltage reduction in the rotor side, it is possible to operate at a lower DC bus voltage. Consequently the voltage ratings for the devices and the capacitor bank can be optimized [25]. So, for the same power rating, the power generated by this system is higher compared to other systems. Its speed range is very high. It can run both in sub synchronous mode and super synchronous mode based on the requirement [26], [27].

There are many control strategies developed for DFIM. Vector speed control, direct torque control, direct power control methods are some of the control strategies for controlling the DFIM. There are many predictive control methods along with sensor less control techniques [28], [29]. Variable speed operation is having more advantages than fixed speed for large scale turbine. The main advantage of the DFIM is that the power processed by the power converter is only the slip power, it is only a fraction of total power. If it is operated within a speed range preferably around the synchronous speed, then the power converter rating can be reduced drastically. This is more advantageous for centrifugal loads as pumps. The speed limit is set by the rating of the converter we deploy in the system. If it goes beyond this speed then the converter loses control. So it will have a little problem in starting. To solve this problem, starting resistors or autotransformers can be used. It is applicable to PHS as the system is having apparatus of high capacity. In a grid controlled DFIM system, the voltage and frequency are imposed by the grid. So, the active power and reactive

power control should be taken care of. If it is made to run as stand-alone, voltage and frequency should also be regulated. The active and reactive power flow control is the main concept behind the control methods. The active and reactive power oscillations of DFIM under voltage sag are very less and are only for fraction of seconds. If the reference reactive power is set then the reactive power suddenly increases and then reduces to the rated value. Even the DC link voltage will oscillate for some time and settles quickly. When the grid voltage reduces, the rotor flux also gets reduced. Under voltage swell i.e., when voltage is increased to more than rated value the active power again oscillates and settles at rated value. The reactive power suddenly reduces and comes to the rated value.

Compared to the Synchronous machine and Induction machine drives, DFIM has better efficiency. It does not require high rating power converters as they can be connected to the rotor side with half the power rating [30], [31]. They have better dynamic stability than the other machines under variable speed operation. The time taken for them to convert from motor to generator is less compared to other machines. The amount of power generated using the same size machine for DFIM will be more compared to other machines [32]. During motor condition in sub-synchronous mode, the rotor generates power and in super synchronous mode, it absorbs power. In generator condition the rotor absorbs power at sub synchronous mode and produces power in super synchronous mode.

When comparing the dynamic behavior the factors voltage drop test, testing for torque perturbations, behavior of the systems based on inter area oscillations are considered [33]. When compared the synchronous machine has less voltage drop and the variable speed machine DFIM has high voltage drop but the time taken to stabilize the active power and reactive power is less. In case of torque disturbances the variable speed has more advantage than the fixed speed as the change in torque is stabilized by the change in the speed which has to compensate by power flow control in synchronous machine [34]. In a variable speed system the torque disturbances will never be a problem. The synchronous machine provides good damping for active power oscillations only until certain frequency while the variable speed machine provides good damping for a better frequency range. With or without Power System Stabilizer, the behavior of reactive power and stator voltage are similar. If we consider reactive power, the behavior of synchronous and variable speed machines

fluctuates for different frequency ranges. For one frequency range, one machine behaves better than the other. For a lower frequency range, the variable speed machine has better behavior because it has constant amplitude. For a higher frequency range, the synchronous machine has better behavior. Compared to DFIG with same speed and power, a synchronous machine has smaller dimensions and inertia with a larger air gap. With lesser rotor current, DFIG can generate same active and reactive power as a synchronous machine. So, synchronous machine is not as cost effective as DFIG.

Conclusion

This paper provides an overview of possible different machines that can be used in pumped hydro applications. The possible configuration and basic characteristics of each machine are described with their advantages and disadvantages for pumped hydro application. The Fixed speed and variable speed machines with different power topologies for pumped hydro systems were discussed. A detailed analysis is made based on the machine rating and the converter-inverter configuration of the system. The dynamic stability of the system was also considered.

Fixed speed systems being reliable, have certain limit in their operation. These systems have to run at rated conditions for better efficiency. They have limitations when used in pumped hydro system.

It is preferable for PHS to be able to run at variable speeds because the power input varies and the system must run at a speed which is optimal for that power. This ensures maximum efficiency. So, variable speed systems are better suited for PHS. Among variable speed machines, DFIM takes precedence. The PWM inverter back-to-back configuration makes the DFIM to run at any operating condition optimally. This configuration has less power loss and more control on the machine compared to any other variable speed drive configuration.

It can be concluded from this comparative study that a variable speed system using Doubly Fed Induction Machine performs better for PHS than the conventional fixed speed machines and synchronous machines. The dynamic performance of the DFIM is more optimal for PHS. The DFIM has the capability to adjust power flow very easily compared to other machines. As there is a need of better dynamic performance and optimal

power generation with high efficiency, DFIM is best suited in PHS.

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