2.6 Pumped storage power plants

[W. Bogenrieder]

2.6.1 Basic aspects

The constant uninterrupted supply of electrical power is a precondition for the functioning and further development of modern industrial countries. Any electric power supply system will have to meet the requirements on demand by securing an available capacity to cover the expected peak demand, plus an operating reserve, to supply the total energy demand and to meet the dynamic needs of the system. Both daily and seasonal variations occur on the demand side, and since electricity can not be stored economically in larger quantities, the supply side has to make power available at the instant of demand.

In thermal power systems various concepts have been considered for “indirect” storage of electric energy to convert the normally available energy production capability during low load periods into power capacity supply during peak demand. Among all energy storage concepts (compressed air storage, magnetic energy with superconductors, high power density batteries, hydrogen production) which are either still at a laboratory size stage, have not been further developed or use is limited by economical feasibility, the only concept so far applied world wide is the one based on pumped water storage.

The basic principle of a pumped storage power plant (PSP) is to store electric energy available in off-peak periods in the form of hydraulic potential energy by pumping water from a reservoir at a low elevation into a reservoir at a higher level. During peak periods this potential energy can be recovered and converted into electricity in a hydro turbine by a draw-down of the upper reservoir to meet the power system demand (see Fig. 2.6.1). Pumping takes place during off-peak periods, when electricity demand is low and there is surplus capacity from base-load plants (nuclear, lignite) to provide low cost energy. Generation takes place during on-peak periods, when the electricity system demand is high and pumped storage is needed to meet part of the demand or replace high-cost energy that would otherwise have to be produced with power plants fuelled by oil or natural gas.

Pumped storage is ideally suited for utility systems with a significant difference in power demand between on-peak and off-peak periods as well as in the cost of producing energy in these periods. The cycle of pumping and generating can be repeated on a daily, weekly or even seasonal basis. In the daily cycle the reservoirs can be filled and emptied within a 24 hour period while in the weekly cycle the upper reservoir is partially drawn down and partially refilled during weekdays and completely refilled during weekends when the system load is normally low. Seasonal pumping is applied in hydropower systems with a large annual variation in inflow of water to the reservoirs. Pumping of water from a lower level to a higher level reservoir is applied in situations when the inflow exceeds the demand, and power is produced by a draw-down of the upper reservoir when the inflow is below the demand.

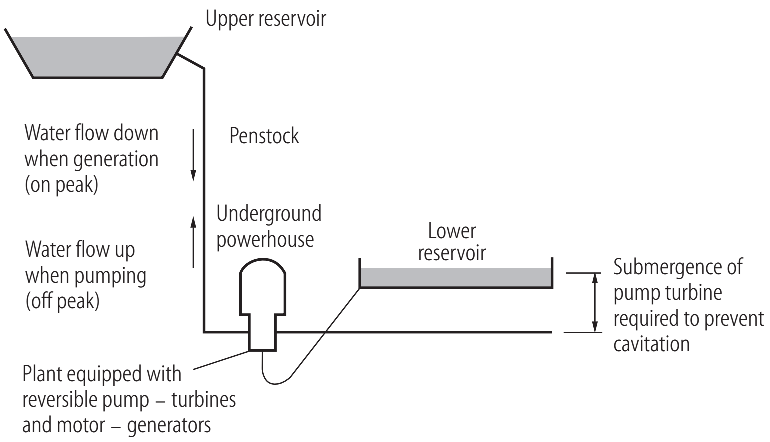


Fig. 2.6.1. Schematic diagram of a modern pumped storage plant [92Hag].

Due to the fluctuations in consumption, there is a need for controllable power stations not only to cover peak loads but also to allow fine tuning within the entire grid system. Although other power station types are controllable to a certain extend as well, PSPs offer the more economical solution to provide a wide range of services due to their superior operating characteristics and are therefore of considerable importance within power supply systems. Even though they do not produce any additional electricity, they offer the only means for large-scale energy storage in regional or trans-regional grids and can balance load fluctuations with optimum efficiency. In all, they are important tools for regulating the supply of electrical energy. The objectives of hydraulic pumped storage can be described in terms of the following technical and economic aspects:

- Conversion of low-load energy into peak-load energy (energy upgrading by recirculating operation);
- Utilization of surplus electricity from the base-load output (supplementing of supplies from thermal power stations and run-of-river plants);
- Direct contribution to the peak-load capacity of the interconnected grid (peak-load control);
- Optimization of the operation of thermal power stations by limiting their operation for the purpose of capacity regulation (extension of operating times in combination with constant energy output of thermal power stations);
- Immediate availability of reserve capacities (increased operational reliability within the interconnected grid);
- Quick utilization of surplus electricity in the event of sudden disconnection of large consumers;
- Filling of residual storage space by pumping if the natural inflow is insufficient (optimization of storage space management);
- Utilization for load frequency stability;
- Phase-compensating operation or phase shifting operation (voltage regulation).

The above details also indicate the different operating requirements, i.e. the multipurpose use of pumped storage plants. The tasks relating to the interconnected grid system comprise in particular:

- Provision of balancing means (daily, weekly or annually) between energy surplus and energy demand within the regional, transregional and international interconnected grid, i.e. primary control (recirculating operation, electricity upgrading);
- *Frequency stability*
  Keeping the small but sudden demand-related fluctuations in the system frequency within a permissible minimum range requires regulating facilities that are able to react sensitively. Pumped storage plants are particularly suitable for this purpose, since they can compensate for these fluctuations by the corresponding fine tuning of the water release to the hydraulic machinery during both the turbine and the pump operation mode. Therefore they are able to perform the secondary control (grid service).
- *Reactive-power or phase-shifting operation (phase compensation)*
  Self induction by transmission units (motors, transformers etc.) causes phase shifts in the network, so that the phase of the current is delayed as against the voltage with a resulting decrease in the power factor cos φ. Due to the overexcited no-load operation of the synchronous pumped storage machines coupled to the network, the phase shifts in the network can be reduced and the power factor can thus be improved.
- Quick compensation of extreme power fluctuations (e.g. in the mornings, at the start of the working week, at the end of the day, at weekends or at times of unusual electricity demand such as exceptional climate situations, special sport events etc.).
- Bridging of supply gaps resulting from a failure of power stations within the interconnected grid (provision of reserve/emergency capacity).
- Support for current and voltage tests prior to the final commissioning of large transformers, overhead lines and supply networks.
- Support for the interconnection of individual network units and for the reconnection of supply networks after network failure (blackout).

The concept of hydraulic energy storage using pumps to allow the economic upgrading of electrical energy was first implemented on a small scale basis at the end of the nineteenth century. With increasing electricity demand already during the nineteen twenties and -thirties, pumped storage plants with capacities of more than 100 MW were developed and implemented, by then with efficiencies of around 50%. During the following decades until today, pumped storage capacities have steadily increased, going along with rapid technical and economical development of plants and plant equipment. Today, plant efficiencies of up to 80% are reached or even exceeded.

The efficiency of a pumped storage plant is normally expressed as the efficiency of a complete pumping and generating cycle, i.e. the ratio of energy output to energy input. In new plants, this efficiency is expected to reach in excess of 75%, depending on unit size, length of water ways relative to the head, design refinements and how the plant is operated. The estimated losses or efficiency values of the individual plant components contributing to the overall plant efficiency are shown in Fig. 2.6.2.

Besides improvements in construction technologies (underground, reservoir sealing etc.), especially the development of reversible pump-turbines had a lasting effect on pumped storage activities, reducing the specific construction cost of these plants by approximately up to 30%. Today, radial single stage pump-turbines represent the most economical equipment for modern pumped storage schemes. This type of machine can be used at sites with available heads from 60 up to 800 m or more with unit capacities ranging from 50 up to 500 MW. By using variable speed machines, the operating flexibility and plant efficiency can be further improved by covering a wider operation range.

Today more than 300 pumped storage plants are in operation world wide, and the number is still increasing. In some countries the pumped storage capacity exceeds 10% of the total installed capacity. Table 2.6.1 shows to what extraordinary extend pumped storage plants – compared to other generating plants – are capable to meet the dynamic system requirements. It appears that a pumped storage plant is capable of meeting all the system dynamic requirements. Pumped storage has thus evolved into a sophisticated system management resource with many functions contributing to system reliability and quality of service provided. Moreover these superior qualities are accompanied by unattainable short start up and transition times (see Fig. 2.6.3) and extraordinary reliability and availability. Annual availability in excess of 95% and a reliability of more than 98% are typical for modern pumped storage plants.

The liberalization of electricity markets proceeding in the last years and the enormous increase in capacity of strongly fluctuating renewable energy sources such as wind and solar power will further strengthen the important role of pumped storage plants in interconnected grid systems due their outstanding suitability for shifting power to periods of higher demand and maintaining the stability of the electric power system.

Table 2.6.1. Capabilities of power plants to provide dynamic services [90EPR].

Normal operating cycle	Nuclear power plant Base load	Coal fired power plant Base/Intermed.	Oil fired power plant Base/Interm.	Gas turbine Peak load	Pumped storage Peak/Interm.
Unit start-up					
- Daily	No	No	Yes, hot	Yes	Yes
- Weekends	No	Yes, cold	Yes, cold	Yes	Yes
Cycling	No	Yes	Yes	No	Yes
Load following	No	Yes	Yes	Yes	Yes
Quick start (10 min.)	No	No	No	Yes	Yes
Spinning reserve	No	Yes	Yes	No	Yes
Frequency regulation	No	Yes	Yes	No	Yes
Load management	No	No	No	No	Yes
Black start	No	No	No	Yes	Yes

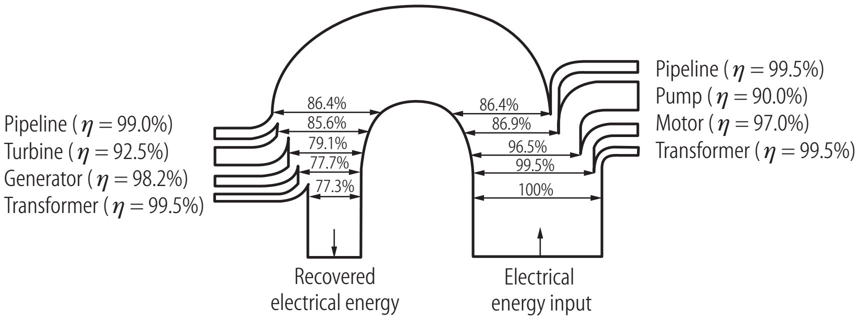


Fig. 2.6.2. Estimated losses and efficiency values of a pumped storage plant [98Gie].

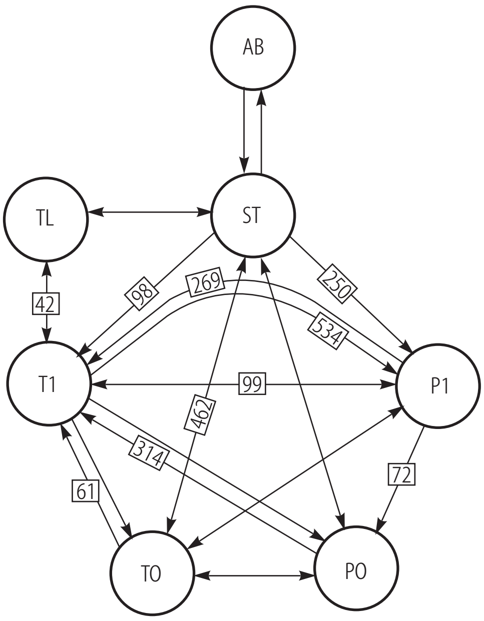


Fig. 2.6.3. Typical transition times in [s] of a modern pumped storage plant. AB - out of operation; ST - standstill, ready for operation, valve closed; T1 - turbine operation at full load; P1 - pump operation at full load; T0 - phase shifting operation direction of turbine rotation; P0 - phase shifting operation direction of pump rotation; TL - no-load operation of turbine, not connected to network.

2.6.2 Upper and lower reservoirs

The active storage of the reservoirs and the available head determine the work capacity of a PSP. The gross work capacity E in [kWh] without considering any efficiency losses or hydraulic losses is

$$E = V \cdot h_{\mathrm{m}} \cdot g \cdot \rho_{\mathrm{w}} \cdot \frac{1}{60 \cdot 60 \cdot 1000} ,$$

with V active storage [m^3],
h_{m} mean head [m] (level difference between gravity centers of the active storage bodies),
g acceleration due to gravity [m/s^2],
ρ_{w} density of water [kg/m^3].

An important criterion for the site selection of a pumped storage plant is the relative position of upper and lower reservoir. In general high heads going along with shortest possible waterways between the reservoirs should be aimed for in order to minimize investment costs. Furthermore short waterways allow for shorter switching times between the different operating modes of the machine unit (i.e. from turbine mode to pump mode).

Reservoirs for pumped storage purposes can be grouped according to the following different criteria [04EDI]:

- *According to inflow conditions*
  - without natural inflow,
  - with natural inflow;
- *According to their position in a river/lake system*
  - without natural connection to running waters,
  - in running waters, water level rising by dams,
  - as natural lakes (special case: sea);
- *According to position and operation mode*
  - upper reservoirs filled during pumping mode and emptied in turbine mode,
  - lower reservoirs filled in turbine mode and emptied in pump mode,
  - intermediate reservoir being used as lower and as upper reservoir;
- *According to storage cycle*
  - daily storage,
  - weekly storage,
  - seasonal storage,
  - yearly storage.

Depending on the topographical, geological and hydrological conditions there is a great variety of construction designs for the reservoirs. In particular for reservoirs operated in a daily or weekly cycle, the characteristic loads due to frequent fast rising or falling water levels are especially pronounced.

2.6.2.1 Natural reservoirs

The use of existing natural reservoirs (lakes) is the most economical possibility for a pumped storage reservoir. A special case is the use of the sea as a lower reservoir (e.g. Okinawa Seawater Pumped Storage Plant). However, the use of seawater leads to a number of specific problems particularly in relation to materials (corrosion protection), operating method and environmental protection (seepage losses, groundwater infiltration prevention) to be considered.

2.6.2.2 Artificial reservoirs

- *Reservoirs with natural inflow*
  Reservoirs with natural inflow created by barring valleys are often used as lower reservoirs due to topographical reasons. Depending on the individual conditions of the project and the construction site, all types of dams like earth or rockfill dams, concrete or Roller Compacted Concrete (RCC) gravity dams, arch dams etc. can be appropriate. In general these barrages are subject to the rules of dam construction. They must be provided with all the auxiliary structures for a safe operation of the dam and for flood control. However, in case of floods that are relatively low compared to the reservoir volume and capacity of the pump-turbine units, the flood flow can also be controlled by pumping into the upper reservoir, which then serves as additional safety in cases of extreme flood events (probable maximum flood).
  As fast high water level fluctuations occur very often in the reservoirs during operation, special attention has to be paid to the stability of the natural slopes of the reservoirs. To avoid water level fluctuations at the upstream end of the reservoir and hence to maintain a constant water level during operation, secondary dams are very often constructed, creating a subsidiary upstream reservoir that is not influenced by the operation. Additionally, sediments and debris is prevented from entering the main reservoir.

- *Reservoirs without natural inflow*
  Upper and lower reservoir can be constructed as artificial reservoirs without natural inflow. If both reservoirs of a pumped storage reservoir do not have natural inflow, the water for the first impoundment of the reservoirs and for compensation of evaporation and seepage losses has to be provided for example by ground water wells.
  Due to topographical reasons, reservoirs without natural inflow are mostly upper reservoirs located on top of a hill, mountain or plateau. The reservoirs are formed by ring-shaped barrages or embankments. As barrages either concrete or RCC gravity dams or earth or rockfill dams can be chosen. Sometimes also different dam types are combined as it is the case for the upper reservoir of the Hohenwarte II pumped storage plant (see Fig. 2.6.4) which is formed by three different dam types: Two hills functioning as a natural barrage are connected by an earth dam with internal clay core. Starting at the other side of each hill, a concrete gravity dam is encircling the rest of the reservoir.

However, artificial reservoirs are predominantly constructed in a cut and fill procedure (balanced earth works). The soil layers are excavated down to the bottom level of the designated basin and are favorably used as filling material for the embankment dam. A precondition for this construction method is the suitability of the excavated soil material for dam construction. The characteristics of the fill material determine the type of dam to be erected (rockfill dam, homogeneous earthfill dam or zoned earthfill dam). The maximum dam slope is defined by the angle of internal friction of the dam fill with an adequate safety factor. In order to minimize both the dam volume and the costs, the steepest possible embankment slopes are chosen which at the same time fulfill all requirements for the stability of the dam body.

Fig. 2.6.4. Upper and lower reservoir (Hohenwarte II, Germany).

Fig. 2.6.5. Asphaltic sealing applied on a dam-slope.

Artificial upper reservoirs are generally completely sealed in order to avoid seepage losses, which would affect the economical performance of the pumped storage plant due to the energy content of the pumped water. Furthermore, seepage has to be prevented or to be controlled safely in order to minimize the risk potential of the reservoirs. An unsealed reservoir bottom may only be considered in case of sufficiently impervious subsoil and detailed knowledge of the geological conditions.

The choice of the sealing system depends on the reservoir and dam construction. For upper reservoirs of pumped storage plants most frequently an external asphaltic concrete facing is applied [96STR], [99Sch]. Besides water tightness, asphaltic concrete facings provide further advantages. They react flexibly against external loads such as settlements or changing movements of the subsoil and the adjoining structures caused by frequent water level fluctuations. Furthermore, they have the required stability to be applied on steep slopes (up to 1:1.3) and are neither sensible to changes of climate nor are they damaged by ice formation.

In general, an asphaltic sealing consists of a drainage layer, a bituminous binder course and the final sealing layer. For protection against ultraviolet sun radiation it is common to apply a thin mastic layer as a surface finish. In case of higher safety requirements, i.e. in earthquake endangered areas or a subsoil that is sensible to erosion, a second sealing layer and a controlled drainage layer may be additionally applied. The drainage layer has to perform several functions:

- Collection and diversion of ground water or excess pore water to assure safety against uplift;
- Control of the sealing and diversion of possible leakage water;
- Compensation of air pressure differences, especially below extensive sealings.

The drainage layer is favorably divided into separate sectors in order to facilitate the detection of potential leakages. This can be achieved by systematically arranged drainage pipes directed to collecting drains that can be accesses on foot and that are an important element for the control of the reservoir sealing. Furthermore, artificial reservoirs certainly have to be equipped with all the other measurement and monitoring devices usually applied in dam construction.

2.6.3 Intake and outlet structures

The change of flow direction depending on the operation mode of the machine units is characteristical for the intake and outlet structures of pumped storage schemes. The terms “intake” and “outlet” apply to the direction of water flow at turbine operation.

Intake and outlet structures form the transition from the reservoirs to pressure conduits. For safety reasons and in order to protect the machine units from floating debris, the intake and outlet structures are provided with trash racks. Furthermore, they are equipped with shut-off devices. In order to reduce hydraulic losses to a minimum, sidewalls, sealing and as the case may be pillars should be designed in a hydraulically favorable way. Mostly a bell mouth type reduction of cross sections towards the pressure conduits is chosen. Along with an acceptable construction effort, a uniform, undisturbed and symmetrical acceleration should be aimed at. As a guideline, the flow velocity at the trash rack section should not exceed 1 m/s.

The depth of the water above the intake opening should be large enough to prevent air (vortices) from entering the pressure conduits even at the lowest operating level. In order to achieve the most favorable conditions, model tests are strongly recommended. Depending on their location in the reservoirs there are two different types of intake and outlet structures, lateral intakes and intake towers.

2.6.3.1 Lateral intakes

Lateral intakes are regularly used in reservoirs formed by barraging natural water courses. In this case the intake and outlet structures are preferably arranged in the valley flank with a certain distance to the dam. For pumped storage plants where the powerhouse is arranged peripheral to the reservoir, a special outlet structure is not required, as the powerhouse and outlet structure form a structural unit. Also for artificial reservoirs connected to the powerhouse by exposed pipes, a lateral intake integrated in the dam is a favorable solution. In the case of underground penstocks, lateral intakes might be favorable to minimize the required length of the penstock.

When lateral intakes are arranged in dams, special attention has to be paid to the connection between dam and intake structure. The construction must allow for movements between the rigid structure and the moving dam body (due to water level fluctuations), while at the same time water tightness has to be assured. Special control facilities for monitoring the construction should be arranged.

Fig. 2.6.6. Lateral intake structure arrangement in the dam (Goldisthal, Germany).

Fig. 2.6.7. Intake and access tower connected via catwalk (Rabenleite, Germany).

2.6.3.2 Intake towers

Free-standing intake towers (see Fig. 2.6.7) are preferably applied in artificial, completely sealed reservoirs that are connected to the powerhouse by pressure shafts. The dam can then be raised and compacted homogeneously without interference from the intake structure. Also, the connection of the sealing to the intake tower on the reservoir bottom is generally less problematic compared to the lateral intake.

The intake tower can be accessed either via a catwalk from the dam crest or via an access tunnel below the dam structure. However, a catwalk should only be chosen if it can be spanned from the dam crest to the intake tower without additional supports piercing the reservoir sealing.

2.6.4 Power stations

2.6.4.1 Basics

Pumped storage plants are built with aboveground or underground (cavern) powerhouses. The design for both types is essentially oriented on the equipment to be housed. Especially for cavern powerhouses the design also depends on the geological conditions. It can be assumed that the differences in manufacturing cost for aboveground and cavern powerhouses are small compared with the equipment costs. A decision in favor of one of them has therefore to be based on other reasons. Advantages of cavern powerhouses are [94Hoe], [63Mos]:

- Shortening of the headrace pipelines (also arranged underground), which helps avoiding expensive constructions (hinged supports etc.);
- Bigger variety for the choice of the optimum location;
- No risk of avalanches, landslides etc.;
- Avoidance of the cutting of slopes and thus of specific problems such as the initialization or acceleration of slope movements;
- Avoidance of flood/uplift case for the calculation of the size of the structures;
- More favorable supply levels during pump operation (avoidance of cavitation);
- Earthquake protection;
- Lower consumption of environmental resources, lower impact on the environment;
- Better operational conditions in winter (depending on the region);
- Better protection against the effects of war and terrorism.

Disadvantages of the underground arrangement are [94Hoe]:

- More difficult logistics, less space;
- More expensive rock excavation with possibly extensive securing and control;
- Existing high initial rock stresses;
- More exploration work, longer planning phase;
- Remaining insecurity in the prediction of the geological conditions.

A list of the various powerhouse types is contained in [98Gie]. Since caverns are often preferred for modern pumped storage plants, it makes sense to have a closer look at them. There are four types of cross-sections for caverns:

1) Mushroom shape (formation of an abutment for a concrete shell in the cavern roof, used in more than 50% of all caverns);
2) Cartridge shape (straight walls and flat cavern roof, approx. 30% of all caverns);
3) Horse-shoe shape (approx. 10% of all caverns);
4) Semi-circle shape (approx. 5% of all caverns);

2.6.4.2 Preliminary exploration [92Reu], [94Hoe]

The object of a preliminary exploration in which all important geomorphological, geological and hydrological factors are taken into consideration, is the general assessment and interpretation of the geological situation of the construction site. An examination of the various options for construction only makes sense after having completed this exploration work. It is based on geotechnical mapping, which allows a sufficiently exact assessment of the geological conditions as well as the examination of alternative locations and surrounding cavities. The investigation of the ground water and mountain water has to include the entire hydrogeological catchment area. Potential entrance points of water into the planned underground structures are of special interest. For an intensive investigation of the rock and soil conditions, it is often necessary to drive shafts and reconnaissance tunnels which can also be used to perform pilot tests and exact map plotting.

The extent of these investigations needed during the preliminary exploration phase for the construction of caverns particularly depends on the complexity of the geological conditions, on the amount and quality of existing geological information on the construction site and on the type of cavern to be used. In this respect, a powerhouse cavern can without a doubt be considered an extraordinary structure.

2.6.4.3 Preliminary design

2.6.4.3.1 Cavern geometry

The limitation imposed by the allowable width between supports and – in case of considerable side thrust – the height limitation are of utmost importance. Lateral space can be saved by placing components into parallel cavities (gate chambers and transformer caverns), which is also favorable from a safety point of view.

A semi-circle-shaped or steep roof is best suited for cases where the side thrust is very low, a more flat one for cases where medium and high side thrusts exist. For low side thrusts rounded walls can be used in exceptional cases, while straight walls are always advantageous with medium and high side thrusts, if only considering the construction work.

It is also important to avoid concrete vaults with the required arch abutments and crane way supports based on rock in order to avoid unfavorable tension concentrations. These will then only exist in the floor level area, where rounding out might be possible and where the internal concrete construction will later provide additional security.

2.6.4.3.2 Location of the cavern

Criteria for the choice of cavern axis direction are as follows:

- Major structural failure;
- Highest horizontal primary tension;
- Joint face system;
- Position of the slope.

Excavation should always be performed vertically to the main joint face.

2.6.4.3.3 Layout of the parallel and auxiliary structures

The dimensions of required rock columns between parallel caverns depend on the dimensions of the caverns, the rock quality, the interference, the side thrust factor and the pressure resistance of the roof. A conservative design is recommended because the savings achieved by using shorter connection tunnels are small in proportion to the additional cost of protective measures in the caverns, which are needed when the smaller columns threaten to deform plastically.

Drifts in the abutment and roof area as well as shafts in the roof area disturb the tensional contours and can hence not be permitted. In order to enable an even distribution of compression loads and a controlled rearrangement of tensional stresses, openings in walls and especially near the floor level need to be limited to a minimum. This needs to be kept in mind when constructing any additional auxiliary tunnels.

2.6.4.3.4 Stability calculations

Quite a number of effects such as block deformations, crack rigidity, long-term deformations, changes in rock parameters under load and even the behavior of visco-plastic layered material can nowadays be simulated. Geotechnical risks such as faults zones, dynamic load, seepage, temperature and splitting effects can be analyzed. Geometrical and physical boundary conditions can be varied more and more easily. Calculation time has been drastically reduced. A prediction of measurable deformations which are close to reality has favorable effects on the security and speed of the construction process.

2.6.4.3.4.1 Determination of geotechnical design parameters [94Hoe]

In order to achieve accurate and economic calculation results, the determination of geotechnical design parameters has to be assigned a high value.

- *Required mechanical rock parameters*
  One has to differentiate between stone, rock and joint face parameters. When using rock parameters, joint face parameters must also be considered.
- *Calculation parameters and parameter variations*
  In normal cases, and especially for simple preliminary calculations, conservative values, i.e. unfavorable divergences of the probable values, are required. These are usually the lower values of deformability and strength, but e.g. also the higher values of permeability, transverse expansion, anisotropy, differences in rigidity with sequences of strata, volumetric weight, crack volume or ground water level. In some exceptional cases the most probable geotechnical parameters can be used for stability calculations, e.g. for
  - reference cases for sensitivity analyses,
  - probabilistic analyses with divergences,
  - prediction of probable and
  - retrospective calculation of measured deformations.

2.6.4.3.4.2 Calculation methods [94Hoe]

The calculation methods of rock mechanics can be divided into calculations of a continuous and discontinuous spectrum, calculations of the service condition and boundary condition, deterministic and probabilistic approaches. Due to research and wide-spread use, suitable procedures and commercially available calculation programs exist for every design stage and the respective performance period.

2.6.4.3.5 Safety measures

Flexible (adaptable) safety concepts are becoming ever more important. Inner shells of steel reinforced concrete are mostly avoided. There is a tendency towards a slightly lower roof construction for caverns. Moreover one attempts to reduce the lengths of pre-stressing anchors. This latter attempt is limited by the rock's rigidity, which also limits the attempt to install less but heavier pre-stressing anchors. The lengths of loose and lightly stressed roof bolts have considerably increased. This is said to be due to the large spread avoidance of long pre-stressing anchors.

2.6.4.3.6 Dimensions of steel reinforced concrete

The well-known basics for concrete and steel reinforced concrete constructions apply. The static, dynamic and hydraulic loads need to be determined as exactly as possible. In the process, all operating conditions and special events, such as the effects of accidental electrical arcs, need to be considered.

2.6.4.3.7 Supervision of structures

A system of control measurements with unequivocal measuring results, which can be interpreted immediately, is the only possibility to verify the often very complicated geotechnical model. Although no stringent rule, it is recommended to measure direct variables such as deformations and tensions that can be evaluated without detailed knowledge of the mechanical rock parameters. These deformations have to be measured continuously at short frequencies in order to quickly verify the standstill position.

The measurements can be roughly divided into surface and deep below surface measurements, with the first ones occurring more frequently. The number of measuring points should linearly depend on the dimensions of the building and the rock quality regarding the geotechnical risk. To verify the model, mainly systematic measuring cross-sections, which also cover parallel caverns, shall be installed. In addition, some instruments shall be installed as early as possible (even in advance of construction). These are extensometers which are installed from a side tunnel before excavation of the cavern.

2.6.4.4 Hints on construction performance

The excavation of big cavities usually starts – for reasons of geo-mechanics, safety and construction sequence – in the roof, i.e. the calotte is driven first. Depending on the size and rock conditions, the calotte's cross section is frequently separated into two or three partial cross sections, which are then driven one after the other and, where necessary, secured temporarily and also permanently in the end areas. Often it is advantageous to integrate an existing auxiliary tunnel into the process. The calotte drive is followed by the removal of the bench. Like the complete process, this work is optimally adjusted to the condition of the existing rock and the construction technique (mesh size for shotcrete, anchor spacing etc.).

The choice of a suitable excavation technique is of special importance. Therefore part-section machines will hardly be profitable with highly abrasive rock material. In case of conventional excavation by means of drilling and blasting, it has to be ensured that the work is performed while conserving the contour lines (e.g. by pre-splitting with a blasting string) in order to minimize the additional excavation in joint face areas striking in parallel or at an acute angle. It is always important that non-permissible deformations and the resulting unfavorable disintegration of the rock are avoided.

The measuring instruments need to be installed early as well as be constantly controlled and read in order to be able to quickly react in case of upcoming problems (e.g. by reduction of the anchor spacing). Due to the confined space a carefully thought out logistics concept is required in all cases.

2.6.5 Penstocks and tailrace

2.6.5.1 Headrace pipelines

In pumped storage plants the headrace pipelines connect the upper reservoir and the machine units in the powerhouse. Generally, one can distinguish between aboveground and underground penstocks (pressure shafts). The decision whether to adopt an aboveground penstock or a pressure shaft largely depends on the choice between a surface and an underground powerhouse.

If the power station is built above ground, a penstock (usually built as a steel pipeline) may be considered. This solution, of course, will only be chosen if morphological and geological conditions permit and if the turbine flow is low enough to keep the number and dimensions of the pipes within economical limits. For dimensioning, the whole structural system with the bearing points and the stress of the internal pressure has to be considered. In case of underground power stations (as preferred for modern pumped storage plants), pressure shafts, which are also the more economical solution for larger discharges, always apply. Under fairly reasonable geological conditions it is possible to construct tunnels of approximately 5 to 8 m with flow velocities varying between 5 and 7 m/s, depending on the water volumes. In any case the pressure shaft diameter has to be optimized in order to minimize the annual costs caused by both friction losses and necessary investment.

The horizontal layout of an underground headrace pipeline depends on the excavation cross section which again depends on the demands of geology, topography (rock cover), hydrology and of course the bottlenecks. For vertical layouts, additional aspects to be considered are the drainage during the construction time as well as the system's ventilation possibilities during filling and draining and, as an essential influence, the powerhouse's type of construction (cavern, shaft powerhouse or aboveground powerhouse).

For conventional excavation of tunnels a horse-shoe cross profile facilitates the excavation work due to its horizontal floor level. Otherwise the statically, hydraulically and therefore also economically ideal circle profile has proven to be the ideal cross section profile for the excavation of cavities. This is why excavation by means of tunnel boring machines with their circular cross section is of great importance, especially as they provide the necessary careful treatment of the rock. This, too, requires preliminary economical investigations as far as the machine cost, length of excavation, potential relocation and rock type are concerned. Under certain conditions the second hand use of an existing machine can prove favorable.

Economical but also safety and technological aspects have to be considered in the choice of the excavation direction (rising or falling). The main disadvantages of a falling excavation direction occur during operation in winter and in pit work, while the rising excavation direction faces problems such as rock fall, ventilation during construction work and of personnel and material transport. A decisive advantage of the falling excavation direction can be the comparably small interdependence with other drives (independence in space and time).

Moreover, during conventional excavation the profile has to be precisely controlled in order to keep down the additional consumption of e.g. backfill concrete. The influence of the normal temporary security measures (shotcrete, anchors) on the construction process must not be underestimated. Here the use of steel-fiber shotcrete can prove to be advantageous.

For pressure shafts there are various types of construction, depending on the geological conditions and the stress of the internal pressure. These types are further described in the following sections.

2.6.5.1.1 Non-lined pressure shafts

Non-lined pressure shafts are used in stable and durable rock and are of special interest for shafts with little roughness (friction losses) excavated by boring machines. The solid rock has to be permanently abrasion-proof but does not necessarily need to be waterproof. To avoid losses of water it suffices that the ground water level is higher than the level of the operational water, bearing in mind the dangers of seepage flow between rock and tunnel. A criterion for the necessary depth of rock cover is the minimum primary rock pressure.

2.6.5.1.2 Simple concrete lining

Simple concrete lining may be applied in case of low internal water pressures. This lining is not 100% waterproof, but can be constructed more impermeable than the surrounding rock. Sub-types are

- cast-in-place concrete with lining of the base with tubbing elements,
- concrete lining without a waterproofing function,
- shotcrete lining and
- lining with tubbing elements.

2.6.5.1.3 Reinforced concrete lining

Reinforced concrete lining can ensure the stability of the shaft and efficiently reduce friction losses. However, since cracks in the concrete lining occur due to high internal pressure, water tightness cannot be achieved. To ensure water tightness the concrete lining can be pre-stressed, which can be done in various ways:

- *Pre-stressing with rock support*
  The concrete lining needs to be evenly stressed when injecting the gap between concrete lining and rock in order to achieve a compressive pre-loading and thus avoid tensile stresses in the concrete lining due to internal pressure. Two methods to be mentioned here are the core-ring lining according to KIESER and the TIWAG-method.
- *Pre-stressing without rock support*
  Pre-stressing without rock support is applied in case the surrounding rock can't bear any load. Three methods to be mentioned here are pre-stressed prefabricated pipelines, pre-stressed and cast-in-place concrete and the VSL-pre-stressing system (from the company Losinger).

2.6.5.1.4 Concrete lining with sealing foil

Concrete lining with sealing foil between lining and rock is applied to achieve water tightness. The foil must be flexible enough to bridge the cracks in the concrete due to tensile stresses caused by internal pressure.

2.6.5.1.5 Thin-walled steel liner with concrete inner ring

An approximately 5 mm thick steel lining is placed between rock and concrete lining. In addition to the sealing function, the steel lining also has a static function, partly taking over the internal pressure.

2.6.5.1.6 Thick-walled steel liner

The most widespread variant is the steel liner with concrete back-filling. Dimensioning of the pressure shaft steel lining is determined by both the existing external pressure on an empty pressure shaft and the existing internal pressure. For the latter, pressure surges which occur during the opening and closing procedures of the unit's closing and regulating devices have to be considered.

Depending on rock conditions the support of the surrounding rock can be exploited when dimensioning the lining for internal pressure. The layout can be performed e.g. according to [77Jac]. It is assumed that the concrete/rock surrounding of the steel lining will take over part of the internal pressure, which will lead to a reduction of the required wall thickness. Furthermore, a steel lining placed in rock needs to be dimensioned to withstand the external pressure caused by ground water in order to prevent bulging. There are various construction possibilities. First, there is the construction as smooth steel lining which is dimensioned for the full external water pressure; a second alternative is the construction with radial bracing rings in order to reduce the requirements for steel. A basis for the dimensioning can be found in [60Mon], [69Arm] and [74Jac]. Furthermore, there is the possibility to dimension the lining not for the full external pressure and to use relief valves which, however, always have to function safely in order to prevent bulging. Nowadays weldable fine-grained structural steels that are resistant to ageing (e.g. according to DIN EN 10113-2) as well as high-tension fine-grained structural steels are generally used for the construction of steel penstocks [83Jac], [84Wie], [65Kol], [79EUR], [71Fed], [75Seb], [85Sch], [86Sch].

2.6.5.2 Tailrace tunnel

Tailrace tunnels, bigger in diameter but with lower internal water pressure compared to pressure shafts, form the connection from an underground powerhouse (units' suction tubes) to the lower reservoir. In case of pumped storage plants they are not free surface flow tunnels due to the water levels required for pump supply. In case of long tailrace tunnels a surge tank must be provided. In medium-length tunnels the water velocity ranges between 2 and 3 m/s. When a surge tank is provided this can be increased up to 4 to 5 m/s.

Because of the low internal water pressure, the tunnels are usually lined with a steel reinforced concrete inner shell which can be produced in a high quality by means of Full-Round formwork transport wagons. When dimensioning a tailrace tunnel, a potentially higher external water pressure caused by the later impounded lower reservoir as well as the rock's permeability along the tunnel alignment needs to be considered.

For the excavation of a tailrace tunnel, basically the same applies as described in Sect. 2.6.5.1 for the headrace tunnel. It makes sense to excavate at least one tailrace tunnel, possibly only in partial cross section, as early as possible in order to drive the excavation through the later site of the powerhouse cavern even before the latter is fully excavated (transport possibility of cavern spoil, early manufacturing of headrace and tailrace manifold tunnels, favorable starting conditions for the use of a tunnel boring machine to drive the headrace tunnels).

For a conventional excavation, large excavation cross sections should always be subdivided for stability reasons, e.g. first the calotte drive and then the removal of benches. Otherwise, the division depends on the existing rock conditions.

2.6.6 Surge tanks

The frequent and sometimes very quick changes between turbine and pump operation in a pumped storage scheme and the resultant pressure fluctuations in the tunnels require thorough investigations of the necessity of appropriate remedial measures. Depending on flow velocities in the tunnels as well as governing and switch-over times of the hydraulic machines, there is a maximum length of waterways up to which governing of the machines is possible without surge tank.

As one always seeks to make the highly stressed pressure shaft as short as possible, an upstream surge tank will not be necessary in most cases. A short pressure shaft generally involves a long tailrace tunnel, so a surge tank frequently needs to be provided on the downstream side in order to ensure the desired short governing and switch-over times of the hydraulic machines. The most favorable solution with a minimum excavation volume has proved to be the provision of surge tanks with chambers arranged in such a way that the maximum and minimum water levels will remain within them. A further reduction in excavation volume can be achieved by arranging a throttle in the shaft connecting the tank to the tailrace tunnel, as this will substantially curb the influence of the initial oscillation. Care should be taken, however, that the throttling effect does not cause an unduly high pressure drop or restrict the reflection of the water hammers.

The loading case governing the design is largely dependent upon the power grid conditions. Formerly, a rhythmical loading and unloading was used as a basis on many occasions as it leads to the strongest provocation of oscillations. More recent calculation methods, however, make it possible to investigate a variety of loading cases and to find out the most unfavorable one without too much expense.

2.6.7 Shut-off devices [98DVW], [98DIN], [55Kol]

Shut-off devices in pumped storage plants serve as closing devices installed upstream and downstream of the machine units and in the intake and outlet structures. When considering criteria for the choice of the high-pressure and low-pressure shut-off devices at the machines of the pumped storage sets, two points are of particular importance:

- The development of pumped storage schemes towards ever-increasing capacities and correspondingly higher flow rates per unit as well as higher pressures in the tail water in order to obtain higher submerge and to allow for units with higher speed;
- The technical advance in design of the shut-off devices since the beginning of pumped storage scheme construction some 80 years ago.

The arrangement generally adapted on the high pressure side is the hydraulically driven spherical valve that is installed right in front of the machine (see Fig. 2.6.8). If it is closed, sealing is provided by a slide ring or a pressure plate. Hydraulically this is the most favorable solution since it does not offer any resistance to the water flow when the valve is in open position. Smaller or older plants are also operated with butterfly valves.

On the low pressure side of reversible pump-turbines flap gates which are hydraulically opened are usually installed. Closure is done by its own load, but only in case of service with the machine not operating and without flow.

The intake structures of modern pumped storage schemes are, without exception, equipped with remote-controlled, automatically closing shut-off devices. Intake towers are fitted with hydraulically driven cylinder gates which may also be designed as rapid-closing gates. Under normal operating conditions the cylinder gate is in ambush position right above the cross section to be shut off. It can be raised inside the intake tower for inspection. Lateral intakes mostly have hydraulically operated gates which, however, are not designed as operating gates. Besides serving as service gates they are also used as emergency gates in case of general damage.

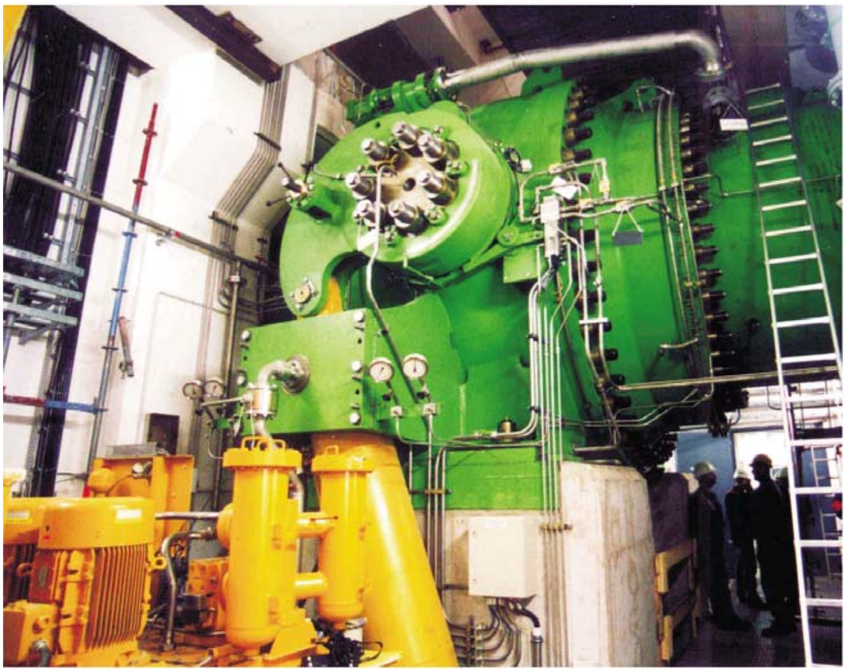


Fig. 2.6.8. Spherical valve.

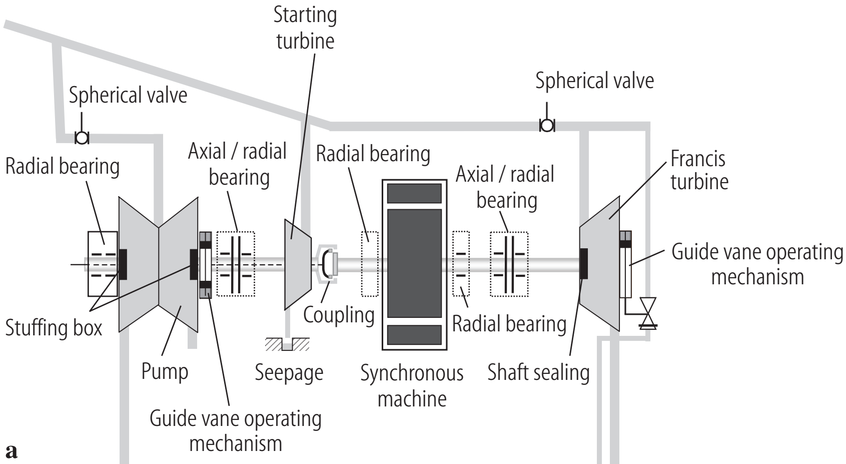
2.6.8 Mechanical equipment

2.6.8.1 Conventional construction

The main characteristic of the conventional construction is that every operation mode has its own hydraulic unit. The pumped storage unit therefore consists of a motor generator, a pump and a turbine. Depending on the installation configuration one differentiates between horizontal and vertical pumped storage units. The horizontal layout (see Fig. 2.6.9a) offers advantages mainly regarding the easy assembly and disassembly because of direct accessibility of all machine parts with the powerhouse crane. Disadvantages are, among others, the alternating loads of the shaft by the rotor's own weight, the non rotation-symmetrical load on the bearings and, in case of higher necessary supply levels for the pump, more construction work (depending on the local situation). This is where the vertical layout, which occurs more frequently in the case of bigger machine units (see Fig. 2.6.9b), has its main advantages. In this case the pump is always installed below the turbine and the motor generator in order to achieve a supply pressure for the pump which is as high as possible (to avoid cavitation).

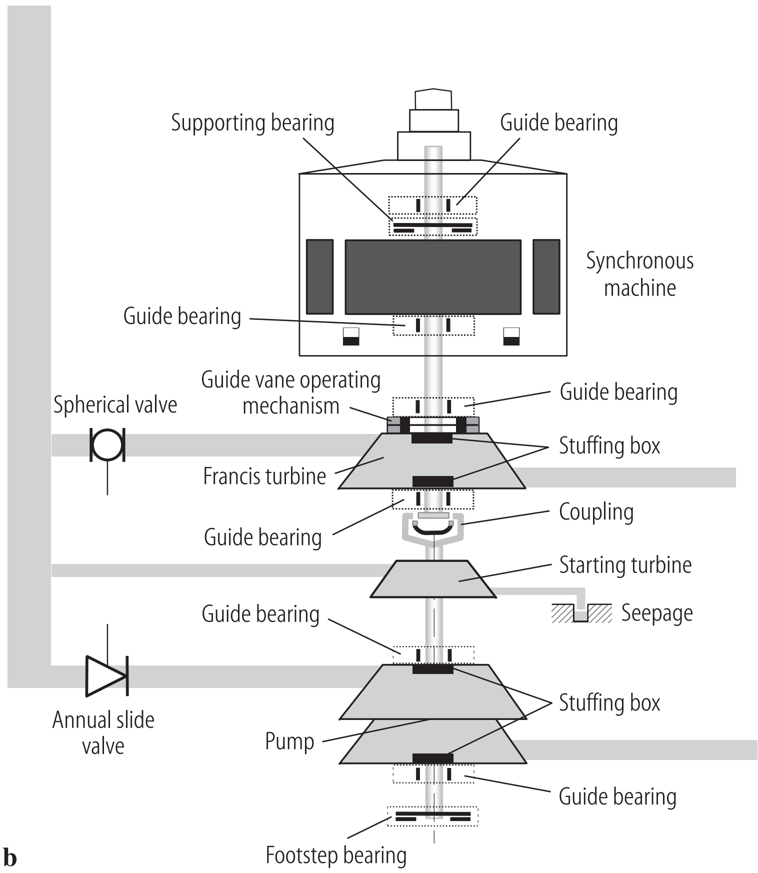
Over the last few decades conventional construction has become less important because of the greater amount of plant and construction work and because of the further development of hydraulics for reversible units. It is only still used for very high heads (> 800 m), when Pelton turbines and multi-stage centrifugal pumps are applied.

The functioning of the conventional pumped storage unit is as follows: During turbine operation the pump is separated from the generator shaft by a shift-coupling (e.g. gear coupling/clutch) and remains in standstill position. The turbine is rigidly coupled to the generator. Start-up of the plant in turbine operation is carried out hydraulically by the turbine. In pump operation residual water in the turbine is evacuated by means of pressurized air, the turbine runner is thus running in air. The low ventilation and clearance losses (<1% of rated output) are frequently tolerated because of the simplification of the plant and, moreover, because this process takes place in the off-peak or low-cost energy period of the day. Plants with an additional coupling between turbine and generator have been built (e.g. Säckingen). However, they are rather an exception. In pump operation mode, the start-up is usually initiated by a smaller starting-turbine, which brings the pump runner up to a synchronous speed before the shifting coupling connects generator and pump. This is mostly done with an evacuated pump which is flooded afterwards.



a

Fig. 2.6.9. (a) Basic-circuit diagram of the PSP Niederwartha with horizontal layout of the units.



b

Fig. 2.6.9. (b) Basic-circuit diagram of the PSP Hohenwarte II with vertical layout of the units.

2.6.8.2 Reversible pump turbines

The reversible pump turbine is a hydraulic machine which works as both a pump and a turbine. The direction of flow and the sense of rotation of the runner are reversed from pump mode to turbine mode, i.e. the same waterways can be used, while the machine needs to change its sense of rotation. The advantages of the reversible pump turbine are

- lower plant costs for the hydraulic machine, closing devices and waterways,
- lower construction costs by reduction of the plant size and
- simplification of the plant (elimination of shift-coupling).

The disadvantages compared with conventional construction are

- a slightly lower total efficiency (especially with pump turbine with fixed speed) and
- longer change-over times between pump and turbine operation because of the necessary braking process and re-starting in a different sense of rotation.

Since, however, the advantages outweigh the disadvantages by far, reversible pump turbines have prevailed in the most suitable head range (< 800 m). More recent developments in machines with variable speed even compensate for the efficiency disadvantage, which will be elaborated in Sect. 2.6.8.2.4.

2.6.8.2.1 Design

Principally, the design of a reversible pump turbine is comparable to that of a Francis turbine: A spiral with stay vanes, an adjustable guide vane operating mechanism, a runner with fixed runner blades, a draft tube, a casing and bearings. For hydraulic and stability reasons, however, the components have to be adapted to the requirements on pump turbines. Particularly through the loading in both directions of rotation, frequent starting and change-over processes as well as constant regulating processes, the static and dynamic requirements on almost all machine parts, especially on the bearings, are higher.

The hydraulic dimensioning of the runner also differs essentially. The design process normally commences with the pump runner followed by an optimization of the turbine runner, because the retarded flow in the pump runner canal is more difficult to control than the accelerated flow in the turbine runner (cavitation). With pump turbines this requires longer flow canals than with pure Francis turbines. Since in pump direction the angle of the vane at the outlet is restricted in order to achieve a stable characteristic curve, the pump turbine runner’s diameter will be greater than that of a Francis turbine.

2.6.8.2.2 Efficiency

As the layout of the plant favors pump operation mode, the efficiency can almost be compared to typical pump efficiencies (>93% maximum mechanical efficiency). However, due to the longer vane canals and the higher speed at the runner outlet, the turbine efficiency is below the optimum (by approx. 1-2%). Larger head fluctuations also have a stronger effect than on the Francis turbine, as the turbine operation with synchronous speed below the rather flat efficiency optimum is within the declining range (see Fig. 2.6.10). The gradient fluctuations H_{max}/H_{min} should be smaller than 1.3. The efficiency in part-load also declines more steeply.

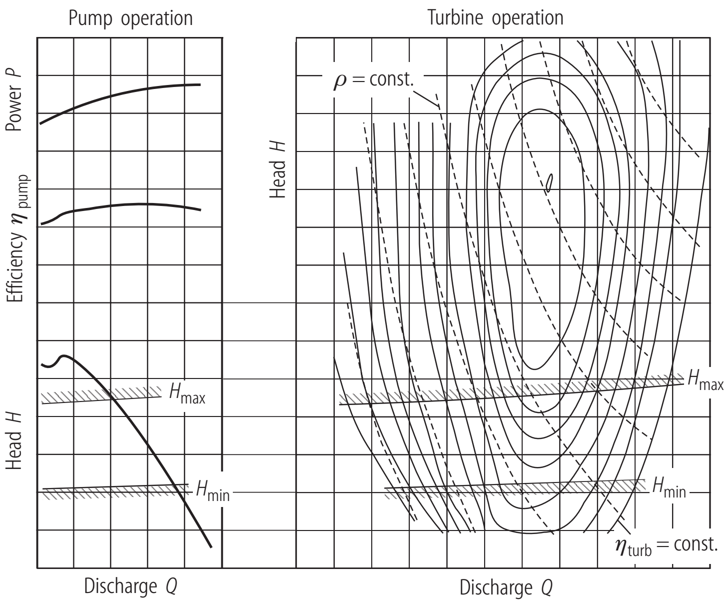


Fig. 2.6.10. Operation performance graph of a pump turbine with fixed speed [94Voi].

2.6.8.2.3 Controllability

Pump turbines in turbine operation can normally be controlled within a range of 0 to 100% of rated output. However, due to the low efficiency at extreme partial load and due to increased wear (cavitation, turbulence in the discharge, pressure pulsations) the range below 30% should be avoided during permanent operation mode. During partial load the injection of pressured air might be required for stabilization.

In pump operation, pump turbines with fixed speed cannot be adjusted. The power input is determined by the head. The adjusting of the guide vane operating mechanism (regulating device in turbine operation) is carried out only for optimizing the efficiency which depends on the head. The operation can only be regulated by the number of operating turbines (and thus the step-wise switching on and off of pump capacity) and the so-called "hydraulic short circuit". For this purpose pump and turbine are run simultaneously, the pump capacity is fixed and the turbine capacity can be adjusted. The balance of both is therefore also adjustable in the case of power input. The hydraulic short circuit, however, causes bigger losses and is therefore only used in exceptional cases.

2.6.8.2.4 Pump turbines with variable speed

The use of units with variable speed is a good way of improving the turbine efficiency as well as the controllability in pump operation. The construction of the pump turbine does not have to be essentially changed. The changes are limited to the electrical machinery.

2.6.8.2.4.1 Turbine operation

In turbine operation it is possible, by adaptation of the speed, to run exactly on the optimum efficiency curve in all load ranges (see Fig. 2.6.11). This can lead to efficiency improvements by up to 20%, especially in the partial load range. In practice this is not yet possible for bigger machines without limitation due to the higher required input of electrical components, which steeply increases with the size of the speed range. At the pumped storage plant Goldisthal efficiency improvements of up to 10% at partial load are achieved (see Fig. 2.6.12). At a synchronous speed of 333 rpm, the speed varies from 300 to 346 rpm.

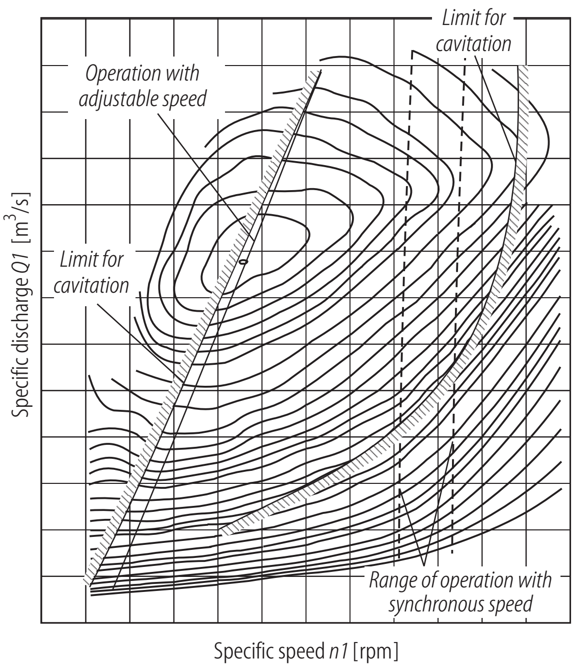


Fig. 2.6.11. Operation performance graph of a pump turbine with variable speed [94Voi].

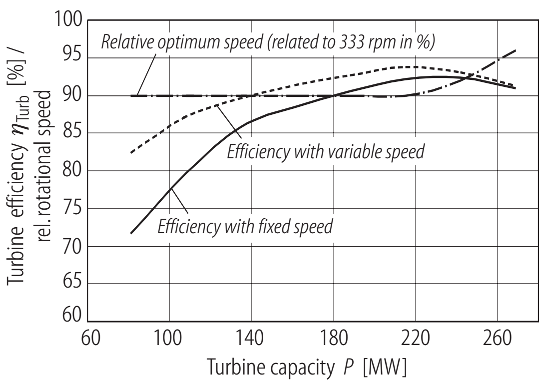


Fig. 2.6.12. Comparison of turbine efficiency curves at fixed/variable speed for the PSP Goldisthal.

2.6.8.2.4.2 Pump operation

As is nowadays quite common for smaller pumps, the capacity, and with it the output, are adjustable by adjusting the speed. For pump turbines the possibilities are still limited due to the high amount of work involved (see Sect. 2.6.8.2.4.1). For the PSP Goldisthal an adjustable range of 100 to 120 MW is available through speed variation of between 300 and 346 rpm, depending on the respective total head.

2.6.9 Electrical equipment

The basic electrical components of PSPs are virtually identical to those of bigger run-of-river or pumped storage plants. Since PSPs are essentially built to supply peak and reserve load and since their construction only pays off if correspondingly large reservoir-storage capacities are provided, the rated capacities of the units are at least in the two-digit MW range and their daily realizable operation times are several hours. Particularly because of these dimensions the size and complexity of the electrical components differ strongly from those of smaller hydropower plants. Another strong influential aspect on the design of the I&C and the electrical equipment are the requirements on the PSP regarding cold start and isolated operation capability, voltage control, frequency control and remote start or remote control possibility.

2.6.9.1 Motor-generator

As the units of a PSP are usually laid out as pumped storage units, the connecting link for the transformation of electric power into mechanical power and vice versa is effected through a motor-generator. In most cases synchronous units will be provided, but especially for the increased requirements on voltage regulating characteristics single speed-regulated pumped storage units are used, which, from a certain capacity size onwards, are only built in the form of double-fed asynchronous units.

Depending on the layout of the hydraulic machines the motor-generator is designed with horizontal or with vertical shaft. What is special about the horizontal layout (see Fig. 2.6.13) is that both sides of the motor-generator can be provided with shaft flanges, and thus the hydraulic components of a classical pumped storage unit (turbine and storage pump) can be coupled onto either side. This facilitates the use of shorter shafts and the installation of couplings which in turn minimize losses in the rotating component units. However, this centered layout of the motor-generator is also possible with a vertical shaft, but at the expense of increased construction works and less accessibility for operation and maintenance.

The constructive layout of the synchronous units of PSPs is virtually identical to those of other big hydropower plants. The units' rated voltage is, depending on the rated capacity, between 10 and 27 kV. However, the short daily operation times with their enormous load change speeds (e.g. from idling to turbine full load of 285 MW within 12 seconds at the PSP Dinorwig, GB) need to be considered during detailed design. These loads lead to large differences in temperature within the active parts of the stator (winding, metal laminations) and of the rotor and therefore cause different rates of expansion.

Compared with the asphalt- or shellac-saturated windings used in former times, the epoxy resin-saturated mica insulation of the stator windings, which are exclusively used at present, tend to shrink. Furthermore, for classical pumped storage units the respective contact pressure of the stator winding bars to the lateral sides of the metal lamination grooves, positioned opposite to each other, has to be considered. Therefore, when placing the winding bars in the lamination, special measures have to be provided against later possible loosening (corrugated springs, permanently elastic embedding materials). Otherwise the mica protection applied on the winding (semi-conducting lacquer or tapes) is destroyed by vibrations and movements, and the resulting partial discharges will cause erosion of the high voltage insulation.

The stator lamination packs, packed from single metal segments, also experience considerable stress by the frequent load changes. The pressing of the metal packet has therefore to be maintained by suitably designed equipment even after many years of operation until the necessary stability is ensured by re-tightening the metal lamination bolts.

In special cases PSPs are equipped with speed-adjustable pumped storage units. For a rated capacity up to approximately 50 MW, conventional synchronous units can be equipped with frequency converters incorporated into the generator output in order to influence the shaft speed through frequency change of the stator's rotating field. The re-usability of existing motor-generators represents a big advantage, which facilitates a potential upgrading. A disadvantage is the limited automatic control operation mode and a considerable increase of losses, because the entire unit capacity has to be frequency-converted. This requires a correspondingly sized and therefore expensive frequency converter.

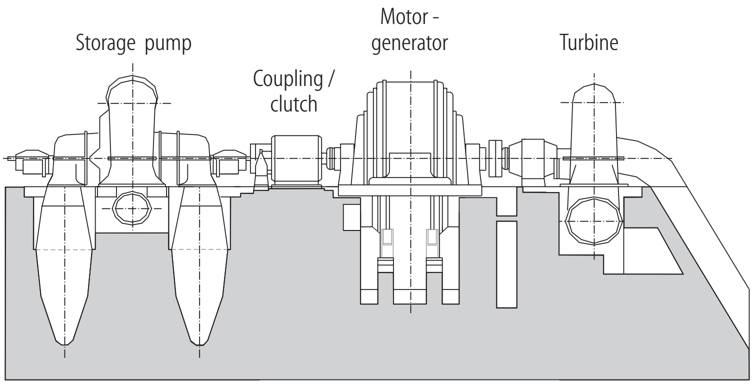


Fig. 2.6.13. Horizontal motor-generator between storage pump and turbine of a classical pumped storage unit.

For larger rated capacities asynchronous units whose rotors with slip rings are subject to changeable frequency serve as motor-generators (e.g. PSP Goldisthal). For these so-called double-fed asynchronous machines only a frequency converter with a capacity equal to the required slip capacity is used. The slip capacity is proportional to the desired speed deviation from the synchronous speed and usually amounts to a maximum of 10% of the pumped storage rated capacity. This is advantageous in as far as the resistance losses and the assembly costs for the converter are lower and the automatic control mode (synchronous condenser mode) of the motor-generator is not restricted. However, it is disadvantageous in terms of the enormous power needs to be transferred to the rotor via carbon brushes and of the rotor itself that has to be specially manufactured. In the concerned power ranges little experience is available for design, manufacture and operation of such equipment.

2.6.9.2 Exciters

A basic condition for the operability of synchronous units is their need for a magnetic field which rotates independently of induction. For this purpose the poles of the slowly running hydropower units are fed with direct current via slip rings. The current is produced in static thyristor converters following the latest technology. These converters, also called static exciters, are differentiated by their power supply. Most frequently the excitation input is received directly by tapping the generator outlet with a corresponding transformer for adaptation of the current. Furthermore, arrangements are common with an additional current transformer driven through the generator outlet (either in the region of the neutral point or between motor-generator and generator circuit breaker) or with a separate three-phase current generator on the shaft of the pumped storage unit (shaft generator). These additional devices ensure that the excitation is maintained in the case of a short circuit close to the generator (very low current of the motor-generator). This causes a sufficiently sized current to flow, which in turn causes the electric protection relays in the subordinate system to trip.

Depending on the additional requirements, modern exciters provide numerous underlying protection and regulating functions such as control of the boundary values for stator and exciter current, automatic control or cos φ control, rotor pendulum damping etc. For double-fed asynchronous units the converter basically also fulfills the tasks of an exciter for the rotor feed. Besides its task of determining the shaft speed, it thus guarantees all control, protection and regulation tasks just as a classical exciter for synchronous units does.

2.6.9.3 Starting device

Modern pumped storage units with pump turbines have to change their sense of direction between the turbine and the pump operation modes. In turbine operation the acceleration of the rotating parts up to synchronization is done via a corresponding regulation of the water flow through the turbine, which is influenced by the turbine governor through the guide vane operating mechanism. In order to achieve a speed that is synchronous to the power supply and in the pump's sense of direction, auxiliary devices are required. Presently, mainly so-called start-up converters are used for this purpose. They are mostly frequency converters (with a direct current intermediate circuit) which can produce a variable frequency between just a few and 50 Hz and have a sufficient capacity to accelerate a pumped storage unit from idling mode up to rated speed (air-filled pump turbine runner) within a short time (1 to 2 minutes). For this process, under conditions of a switched-off generator circuit breaker and an activated exciter, the start-up converter is connected to the generator stator and the rotor is accelerated by variable frequency up to synchronization (parallel circuit of the system by generator circuit breaker). In the reverse sequence, the same is possible for braking from both senses of direction down to standstill. Since the assembly costs for start-up exciters are considerable, such a start-up device is usually not provided for every pumped storage unit. Instead, each PSP is rather equipped with one or two exciters which can accelerate or brake every pumped storage unit via a start-up bus bar. However, a simultaneous start-up in pump mode is not possible under these circumstances.

Another common start-up device is the so-called start-up motor which is integrated into the pumped storage unit. Usually this is a high performance asynchronous motor with rotor and slip rings. Such devices, controlled by start-up resistors, can accelerate the rotating parts of a pumped storage unit up to synchronization within a short time. As a design condition the number of pairs of poles of the start-up motor must be lower by one than that of the motor-generator. Since in this case all pumped storage units of a PSP are equipped with start-up motors, the simultaneous start in pumping mode is possible.

Finally, another variety is the direct connection of the motor-generator to the system by means of a start-up choke, at standstill, with subsequent asynchronous starting. From a certain rated capacity onwards, however, this starting procedure leads to enormous reactions on the system and moreover requires extensive constructive measures, especially in the rotor. This is why it has not been realized very often.

2.6.9.4 Switching devices

The connection between motor-generator and unit transformer is realized by the so-called generator outlet. The switching devices in the generator outlet (generator circuit breaker, cut-off key, earthing switch, see Fig. 2.6.14) do not differ, in regard to construction and capacity, from those of other bigger hydropower plants. The specific characteristics of PSP require further switching devices, though.

For pumped storage units with pump turbines in turbine operation a different sense of rotation is required than for pumping mode. In order to reverse the rotary field in the stator of the motor-generator for these different mechanical senses of rotation, rotation cut-off devices are required. These are usually arranged between the generator circuit breaker and the motor-generator and consist of five one-pole cut-off keys. One cut-off pole (mostly the one for the middle phase) is closed for both senses of rotation, the remaining four cut-off poles are, depending on the sense of rotation, closed either identically (two cut-off keys) or crossed (two cut-off keys). Switching is done at standstill of the electrical unit (see Fig. 2.6.15).

In order to achieve short times for changes of operation mode, especially in the case when the sense of rotation of pumped storage units is changed, it is required to brake down to standstill as quickly as possible. In the past, mechanical brakes were arranged on the pole wheel of the motor-generator for this purpose. However, the resulting wear required constant replacement of their lining and led to considerable dirtying of the motor-generator. By the use of static exciters, and earlier also by using external exciter units, it is possible to produce an induction current for braking in short circuit operation that is independent of the present speed of the pumped storage unit's shaft. For this purpose the stator winding of the motor-generator is short-circuited with a three-pole cut-off key after power cut-off and de-energizing. A braking momentum is created by feeding an adequate induction current causing a near-to rated voltage flow in the short-circuited stator winding (see Fig. 2.6.16). The braking momentum increases with decreasing speed, so that the range of mixed friction, prevalent at very low rotational speed and being critical for the sleeve bearings, is passed especially rapidly. The short-circuit cut-off key is usually arranged between motor-generator and generator circuit breaker (see Fig. 2.6.16) or between generator circuit breaker and cut-off key.

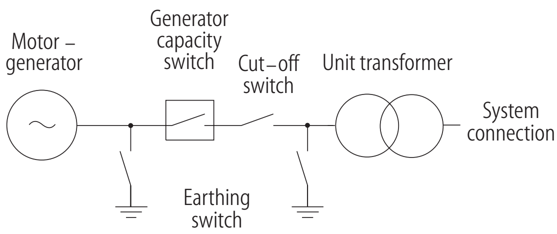


Fig. 2.6.14. Schematic layout of a generator outlet (one-pole).

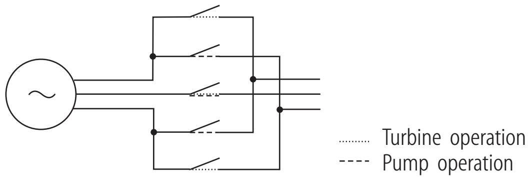


Fig. 2.6.15. Change of sense of rotation with cut-off switches (three-pole schema).

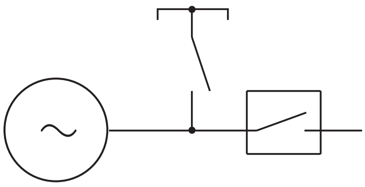


Fig. 2.6.16. Short-circuit braking with short-circuit cut-off key (one-pole).

2.6.9.5 Unit transformer

Due to efficiency reasons and construction problems with the insulators, the motor-generators of pumped storage units are only built for voltages between 10 and 27 kV. The unit transformer (also called block transformer) is therefore required for conversion of the unit voltage to a higher voltage that is suitable for power transmission. The longer the distances to overcome, the bigger the used voltage of the power system has to be chosen. Word wide, transformer systems with a rated voltage of up to 1200 kV are used.

Unit transformers for pumped storage units hardly differ from conventional large transformers. Presently they are almost exclusively built as oil-insulated transformers which are equipped with sequence switches for a corresponding influence on the idle power flow in the network and for regulation of the station service system's voltage. They have to be designed especially for the considerable load change speeds, which is done by controlled overflowing of the active part (core and windings) with insulation oil and by variable control of the amount of cooling air and cooling water, respectively.

2.6.9.6 Network connection

The network connection is the high-voltage side connection of the unit transformers to the transmission network. Usually a high voltage unit is required for this purpose, which should take over at least the following tasks:

- Protection of the transformer from excessive voltage by lightning and switching;
- Galvanic cut-off between network and unit transformer;
- Earthing of the transformer.

If the network connection is achieved by an auxiliary line to a close-by transformer sub-station (say less than 20 km), there is the possibility to shift the high voltage switch for this network connection to the connection point.

If the unit transformers of pumped storage plants as well as the pumped storage units are located in caverns, the network connection also has to fulfill special conditions. The high-voltage side connection to aboveground is done by cables (e.g. PSP Goldisthal) or gas-insulated lines (e.g. PSP Wehr, Germany). The appertaining underground high voltage switch plants and, depending on the space at disposition, those above ground are also gas-insulated.

2.6.9.7 Station service system

The numerous electrical drives (oil pumps, cooling water pumps, seepage water pumps etc.) and other consumers (converter for battery units, heating etc.) of a pumped storage plant have to be provided with electric power as reliably and economically as possible. Depending on the final delivered power this is mostly done on the low voltage level, but for bigger drives also directly on medium voltage level. The feeding of the station service system is best done via a branch from the generator outlet. This method has the advantages that no additional high voltage transformer is required for the connection to the transmission network and that the pumped storage unit can provide itself with the required station service system power after network failures. The regionally existing medium voltage networks do mostly not provide the required high reliability in supply and should therefore only serve as reserve feed.

2.6.9.8 I&C and protective system

The high complexity of PSPs requires comprehensive I&C equipment for an automatic control of mode changes (standstill – turbine mode – synchronous condenser mode – pumping mode), for their safety control (critical values of temperatures, flows, vibrations etc.) and the regulation of operation parameters (actual efficiency, idle power, voltage at net transmission point etc.). The control of all processes in the plant by dedicated personnel is usually done from a central switchboard gallery which, because of today's possibilities of data transfer, does not need to be located in the immediate vicinity of the pumped storage units. A basic component of the switchboard gallery is an instrumentation and control system which, because of the large dimensions of the plant components of a PSP, is based on interlaced automatic units and comprises central installations for operation, archiving and error messages. However, the multitude of high technology devices requires a certain manual control to be carried out directly by supervisory and maintenance staff that perform regular rounds of inspection at least on weekdays.

The protective system usually comprises electrical protective devices for the main components motor-generator, unit transformer, net connection and station service systems. According to modern technology these are digital protective relays which can be connected to switching error protection devices via central protective data devices and combinations. Their main task is the limitation of damage after unforeseen occurrences of electrical failures (short circuit, ground leak, overload etc.) by implementation of corresponding measures (warning, triggering of circuit breakers etc.).

2.6.10 Case study – Goldisthal PSP [00Bog], [01Bog]

A good example of the most recent technical state of the art pumped storage is the Goldisthal plant located in the German region of Thuringia. The history of this project dates back to the mid 1960s. Although preparatory works started ten years later, the project had to be postponed for financial reasons by the government of the former GDR in 1981. After restarting the project in the early 1990s, construction works started in late 1997. Commissioning finally took place in 2003/2004. The Goldisthal plant (see Fig. 2.6.17 for an aerial view) is one of the largest and most modern pumped storage plants in Europe. With a generating capacity of 1060 MW it is designed for eight hours of full turbine load operation. The main plant components are

- the upper reservoir with an intake structure,
- two headrace tunnels,
- the underground powerhouse with an access tunnel,
- the underground transformer station with an energy transmission gallery,
- two tailrace tunnels with an outlet structure,
- the lower reservoir with the main dam and (secondary) upstream dam and
- a control building, stores and a workshop.

The upper reservoir is formed by a 3370 m long rockfill ring dam, providing an active storage volume of $12 \cdot 10^6$ m³. Depending on the topographical conditions, the dam height varies between 10 and 40 m. The dam was constructed by the cut-and-fill method with slopes of 1:1.6, requiring a total fill volume of $5.8 \cdot 10^6$ m³. The reservoir is completely sealed with an asphaltic concrete facing. The intake structure is a double tower of reinforced concrete integrated in the ring dam, with bulkhead gates as emergency gates and two vertical lift gates as service gates.

Fig. 2.6.17. Aerial view on the PSP Goldisthal.

Two inclined 870 m long steel-lined pressure tunnels with a finished diameter of 6.20 m lead from the upper reservoir to the four machine sets accommodated in the 137 m long, 26 m wide and 48.5 m high underground machine hall, which can be reached via an 1.4 km long access tunnel. The machine sets are equipped with one spherical valve each on the high-pressure side as an operation, emergency and inspection valve and a draft tube flap gate on the low-pressure side as an inspection valve. A separate underground transformer cavern is located parallel to the power cavern, as close as is technically feasible. The electrical equipment, which is accommodated in the transformer cavern, primarily consists of four block-type current transformers, circuit switches and the associated equipment such as start-up converters and auxiliary transformers. The electricity is transmitted through a cable gallery to the transmission platform at the lower reservoir. From there an eight kilometer long 380 kV overhead line connects the plant to the existing high voltage grid.

Two concrete-lined tailrace tunnels with finished diameters of 8.2 m connect the power cavern to the outlet structure at the lower reservoir. The concrete construction primarily consists of two locking shafts with operating platforms and two bell mouth type outlet cones protected by trash racks. Stop logs serve as inspection gates. The lower reservoir is created by a 67 m high rockfill dam across the Schwarza rivulet with slopes 1:1.6 and a crest length of 220 m.

The upstream face of the dam is sealed with an asphaltic lining which is connected to the concrete control gallery below the upstream dam base. Seepage is reduced to an acceptable extent by a double row grout curtain. The bottom outlet and flood control structures are located opposite the outlet structure making use of the diversion tunnel operated during the dam construction. At the end of the diversion tunnel a small-scale hydropower plant equipped with a cross-flow turbine produces renewable energy, making use of the natural river flow which has to be maintained permanently. A subsidiary upstream reservoir maintains the water level in the main reservoir to ensure an adequate head during operational fluctuations of the water level. The operation buildings, workshops and stores are located in the immediate vicinity of the access tunnel entry. Besides other facilities the control and monitoring center is accommodated here.

The four machine units in the power cavern are the heart of the facility (see Fig. 2.6.18). The plant is equipped with identical pump-turbines of 265 MW each, two of them rated at a variable speed between 300 and 346 rpm. With a rated head of 301.65 m and a maximum flow of 101.6 m/s per turbine in the generating mode, the peak output of 269 MW can be reached within 75 s from standstill. In the pumping mode (max. 80 m^3/s per machine), a minimum control range of at least 100 MW is available for the speed adjustment to enable power regulation within the network. In the generating mode, speed adjustments between 300 and 320 rpm are sufficient for efficiency optimization. Lower speeds linked to a higher turbine efficiency or to the start-up in the pumping mode reduce the dynamic loading of the pump-turbine and the motor.

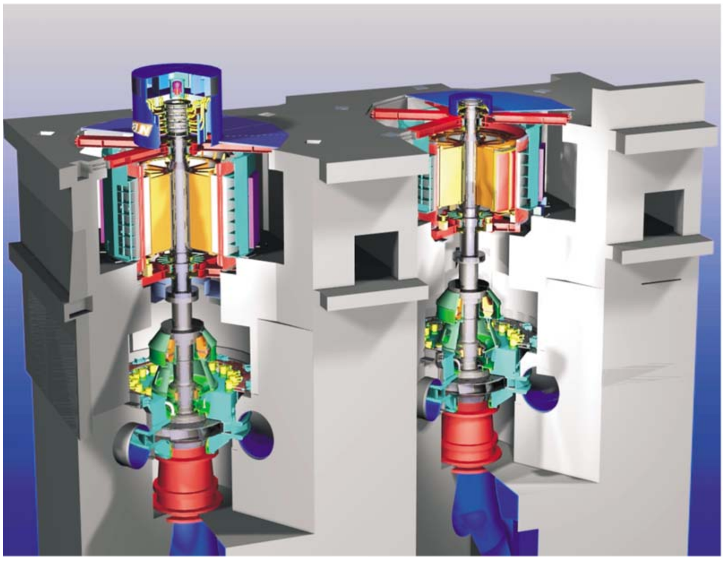


Fig. 2.6.18. Cut away view of adjustable (left) and fixed speed (right) units of the Goldisthal PSP.

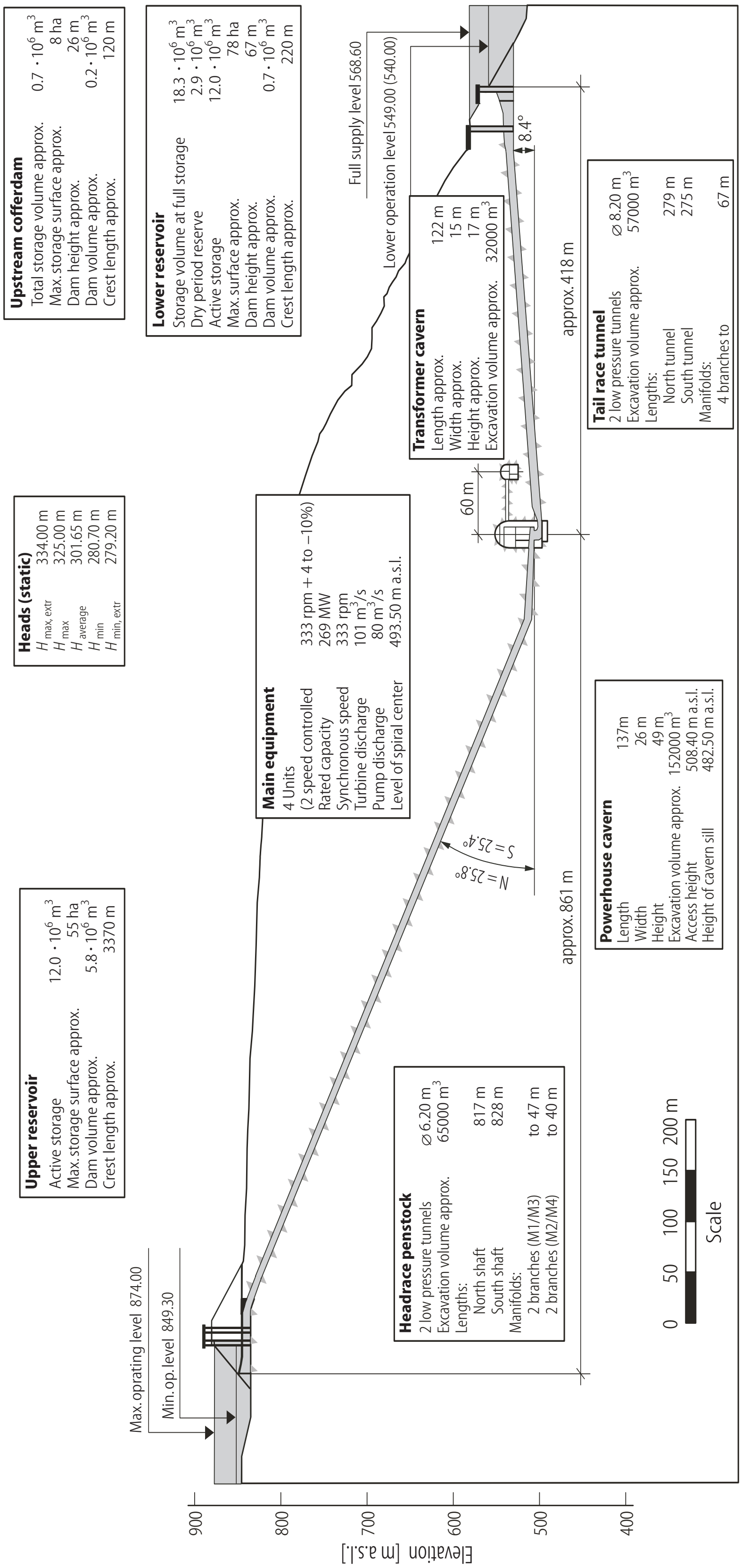


Fig. 2.6.19. Longitudinal section of the PSP Goldisthal.

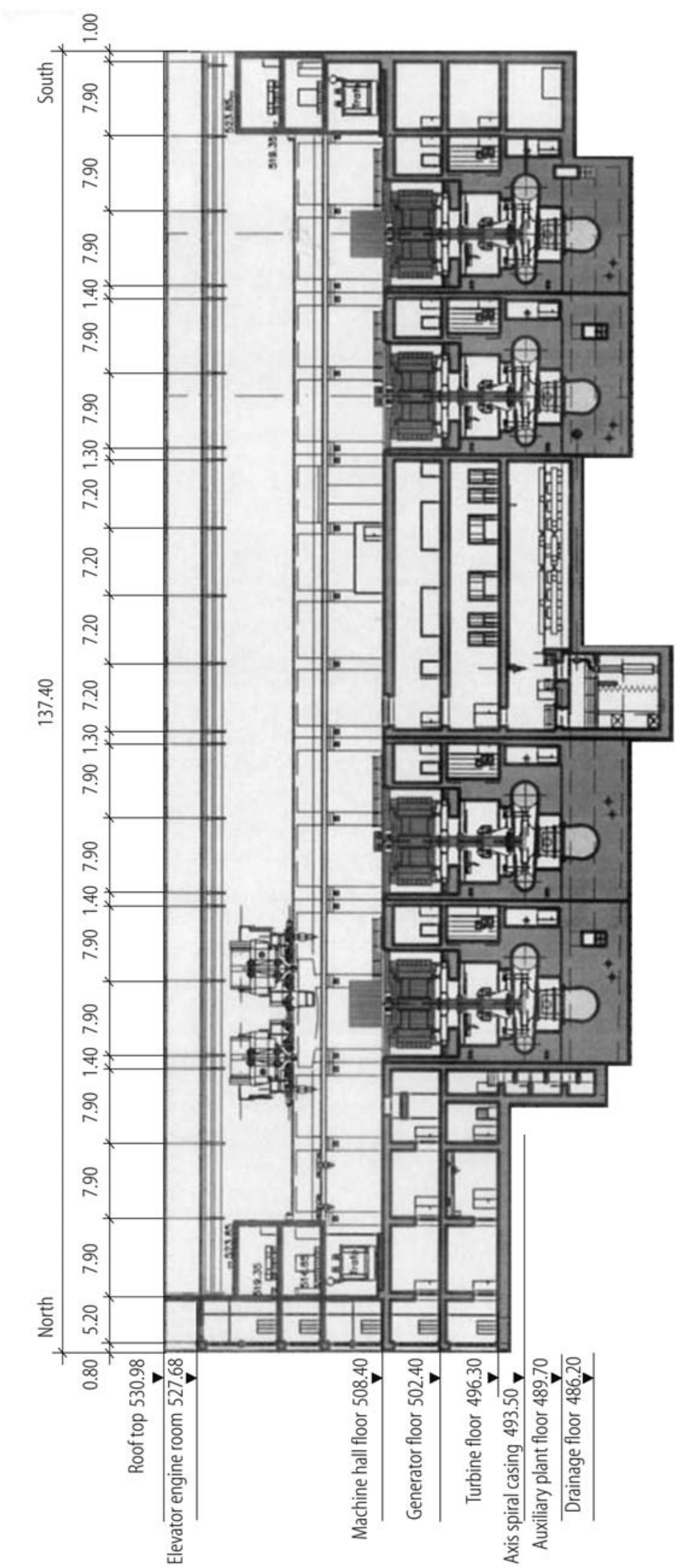
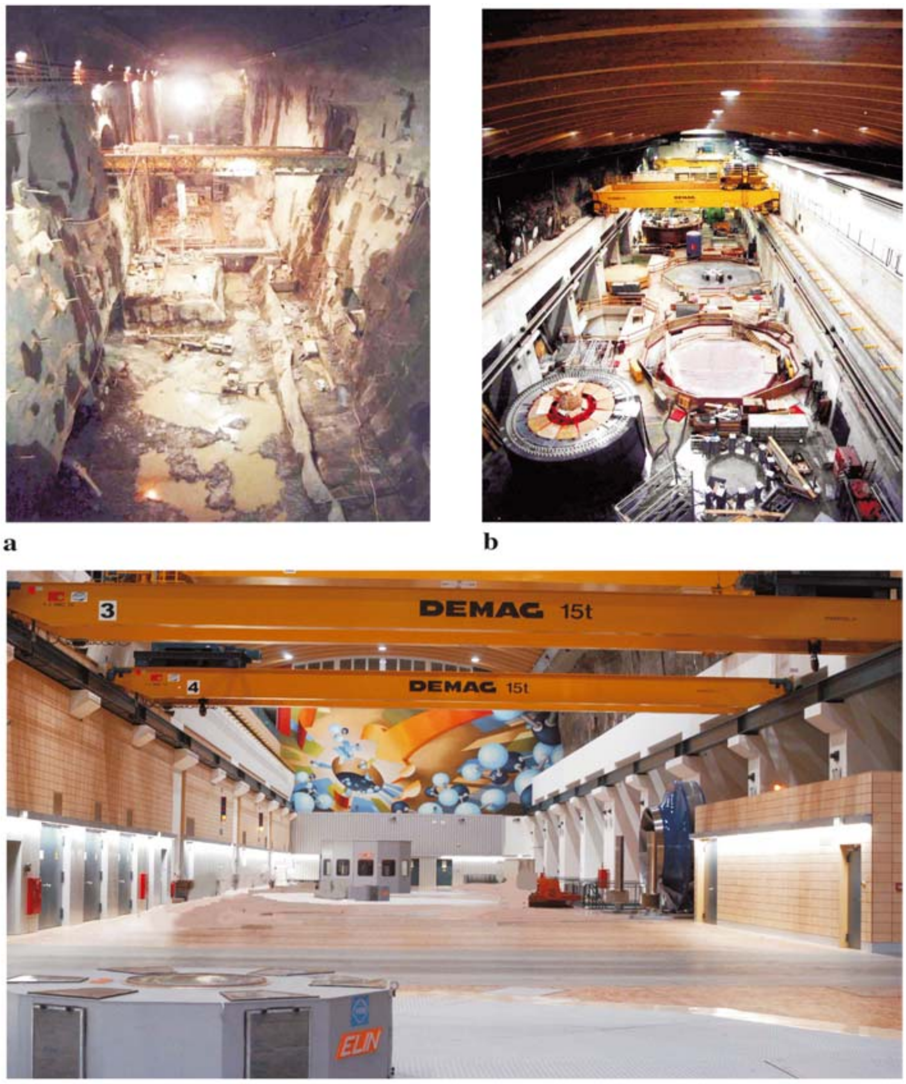


Fig. 2.6.20. Longitudinal section of powerhouse cavern of the PSP Goldisthal.

Considering the specific requirements of the owner's production system, two units are equipped with adjustable speed motor-generators. Since the owner's generating resources are mainly based on base-load plants and a relatively small proportion of medium-load plants, the Goldisthal pumped storage plant is intended for capacity regulation in the peak-load and, to some extend, in the medium load range. In addition to ensuring fast availability and allowing frequent changes of the operating mode, the machine sets must therefore also be able to perform network control functions over extended periods of time. Motor-generator units with adjustable speed are much more suitable for this task, but had not been installed so far on this scale in Europe. They were built as double-fed asynchronous machines requiring new solutions for various construction details concerning, for example, the fixing of end windings of the rotor, the transfer of high currents via the slip ring body or cooling/ventilation.

The advantage of improved part-load efficiency contributes to a high overall plant efficiency of more than 80%, which is another outstanding feature of the Goldisthal plant.



a b c

Fig. 2.6.21. Goldisthal PSP powerhouse during **(a)** excavation, **(b)** installation and **(c)** operation.

2.6.11 References for 2.6

55Kol Kollbrunner, C.F., Streuli, L.: Dichtungen im Stahlwasserbau, Mitteilungen über Forschung und Konstruktion im Stahl-Bau, Heft Nr. 18, 1955.
60Mon Montel, R.: Formule semi-empirique pour la détermination de la pression extérieure limite d'instabilité des conduites metalligues lisses noyées dans du beton, La Houille Blanche, 1960.
63Mos Mostkov, W.M.: Errichtung von Untertagebauwerken großer Querschnitte, Moskau: Staatlich-technischer-wissenschaftlicher Verlag für Bergbauliteratur, 1963.
65Kol Kollbrunner, C.F., Milosavljevic, S.: Neuer Beitrag zur Berechung von auf Außendruck beanspruchten kreiszylindrischen Rohren. Frei verlegtes Rohr und einbetoniertes Rohr, Heft Nr. 31, Conrad Zschokke AG, 1965.
69Arm Armstutz, E.: Das Einbeulen von Schacht- und Stollenpanzerungen, Schweizerische Bauzeitung, 1969.
71Fed Feder, G.: Zur Stabilität ringversteifter Rohre unter Außendruckbelastung, Schweizerische Bauzeitung, 1971.
74Jac Jacobsen, S.: Buckling of circular rings and cylindrical tubes restrained against radial displacement under external pressure, Water Power & Dam Construction, 1974.
75Seb Seeber, G.: Die Sicherheit von Druckschachtpanzerungen, Österr. Ing.-Zeitschrift, 1975.
77Jac Jacobsen, S.: Pressure distribution in steel-lined rock tunnels and shafts, Water Power & Dam Construction, December 1977.
79EUR European committee: Recommendations for the design manufacture and for boilermaking and erection of steel penstocks of welded construction for kindred steel structures hydro electric installations, C.E.C.T., 1979.
83Jac Jacobsen, S.: The proper design of steel linings for hydro power tunnels, Water Power & Dam Construction, June 1983.
84Wie Wieser, H.: Außendruck glatter Panzerrohre. Ein Vergleich der Formeln von Amstutz und Montel, ÖIAZ, 1984.
85Sch Schwarz, J.: Druckstollen und Druckschächte - Bemessung und Konstruktion, Bericht Nr. 54 des Institutes für Wasserbau und Wassermengenwirtschaft und Versuchsanstalt für Wasserbau, Oskar v. Miller-Institut in Obernach, Technische Universität München, 1985.
86Sch Schleiss, A.: Neuzeitliche Ausbildung von Druckstollen, in: Wasser, Energie, Luft - eau, ènergie, air, 78. Jahrgang, Heft 1/2, CH-5401, Baden, 1986.
90EPR EPRI: Pumped storage planning and evaluation guide, Electric Power Research Institute (EPRI); Chicago: HARZA Engineering Company, 1990.
92Hag Haga, I.: Coordinating hydropower and thermal power; Series: Hydropower development, Vol. 2, Trondheim: Norwegian University of Science and Technology, 1992.
92Reu Reuter/Klengel/Pašek: Ingenieurgeologie, Leipzig: Deutscher Verlag für Grundstoffindustrie, 1992.
94Hoe Hönisch, K.: Zur Strategie der Gestaltung großer Krafthauskavernen, Dissertation, Schriftenreihe Heft 20, Lehrstuhl für Prüfamt für Grundbau, Bodenmechanik u. Felsmechanik, TU München, 1994.
94Voi Voith: Konzeptionelle Aspekte bei der Planung und Modernisierung von Pumpspeicheranlagen / Conceptional aspects for the design and modernisation of pumped storage plants, 1994.
96STR STRABAG-Schriftenreihe, Nr. 51, Speicherbecken, 1996.
98DIN DIN 19704 Stahlwasserbauten, May 1998.
98DVW DVWK Merkblätter: Betrieb von Verschlüssen im Stahlwasserbau, Z49/1998.
98Gie Giesecke, J., Mosonyi, E.: Wasserkraftanlagen, 2. Auflage, Berlin: Springer-Verlag, 1998.
99Sch Schömau, Dr.-Ing. E.: The Shell Bitumen Hydraulic Engineering Handbook, 1999.
00Bog Bogenrieder, W., Groschke, L.: Design and construction of Germany´s Goldisthal pumped-storage scheme, Hydropower and Dams, Issue One, 2000.
01Bog Bogenrieder, W., Groschke, L.: Progress at the Goldisthal pumped-storage scheme, Hydropower and Dams, Issue Four, 2001.
04EDI E DIN 19700-14 Stauanlagen, Teil 14: Pumpspeicherbecken.