Reliable power delivery from a powerstation dedicated to a single user.

-The Kárahnjúkar Powerstation in Iceland. –

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Introduction.

The Kárahnjúkar powerstation is directly connected to a large aluminium smelter, with a weak connection to the main grid in Iceland. The reliability of power delivery from the powerstation is therefore of vital importance as the aluminium smelter can only withstand power loss for limited time without damage to the potline. The basic design of Kárahnjúkar powerstation placed special emphasis on the reliability of the power delivery.

The paper covers the design of the powerstation, considering specifically the reliability of the operation and energy delivery. The main aspects of the design related to reliability of power delivery are described and the experience from the first years of operation presented. The main items of the design criteria for reliability are the partition of the powerstation into two separated halves, division of the headrace into two separate pressure shafts with butterfly valves on top, the selected number of generating units, separation of the generating units, explosion proof transformer cells, design of the station service power system and redundancy of auxiliary equipment.

1 The project.

A Memorandum Of Understanding (MOU) was signed on 19th of July 2002 between the *Government of Iceland*, *Landsvirkjun* (the National Power Company), and *Alcoa Inc*. (Alcoa), USA, regarding the evaluation and potential implementation of an industrial project involving the development of an aluminium reduction plant in eastern Iceland. The plant was envisaged as having a production capacity of approximately 295,000 metric tons per year of primary aluminium, requiring approximately 4300 GWh/year or 500 MW supplied on a continuous basis under a long-term agreement. For meeting the power requirements of the plant, Landsvirkjun proposed to develop the Kárahnjúkar Hydroelectric Project to a rated capacity of approximately 630 MW.

On 18th of March 2003 a binding long-term contract was signed between Alcoa, the Icelandic government, Fjarðabyggð municipality and Landsvirkjun, for the project as a whole. The aluminium plant size was set to 320,000 metric tons per year, with an average load of 537 MW and short term peak demand of 575 MW. The capacity of the Kárahnjúkar Hydroelectric Project was set to 690 MW and 4800 GWh/year. During the contract negotiation period Landsvirkjun and Alcoa did extensive due diligence work on the Kárahnjúkar Project.

The Kárahnjúkar hydroelectric scheme is located in east of Iceland. Operation of the HEP started in November 2007. The construction period of the project was five years, from spring 2003 to autumn 2007 with additional pertinent schemes to be completed in 2009.

1.1 Project description

The Kárahnjúkar hydroelectric project in Iceland is one of the largest hydropower projects recently constructed in Europe. The project features include a 198 m high concrete faced rockfill dam, almost 70 km of tunnels and an underground powerstation with six high-head Francis turbines. The project harnesses the flow of two glacial rivers from Vatnajökull, Iceland’s largest glacier. The main reservoir, Hálslón, has an active volume of 2.100 Gl from the minimum level of 550 m a.s.l. to the full supply level of 625 m a.s.l. The turbine centreline is at 12 m a.s.l. and the tailrace water level is 26 m a.s.l. The gross head varies between 524 and 599 m.

The underground powerstation is defined as the section of the power project from the end of the headrace tunnel on one side, to the end of the tailrace tunnel, access tunnel and to the substation at the other side. This includes two pressure shafts, each with a valve, powerhouse in two sections with six generating units, transformer cavern in two sections with six step-up transformers, tailrace tunnel, access tunnel and cable tunnel to the substation. Two transmission lines connect the substation to the aluminium smelter.

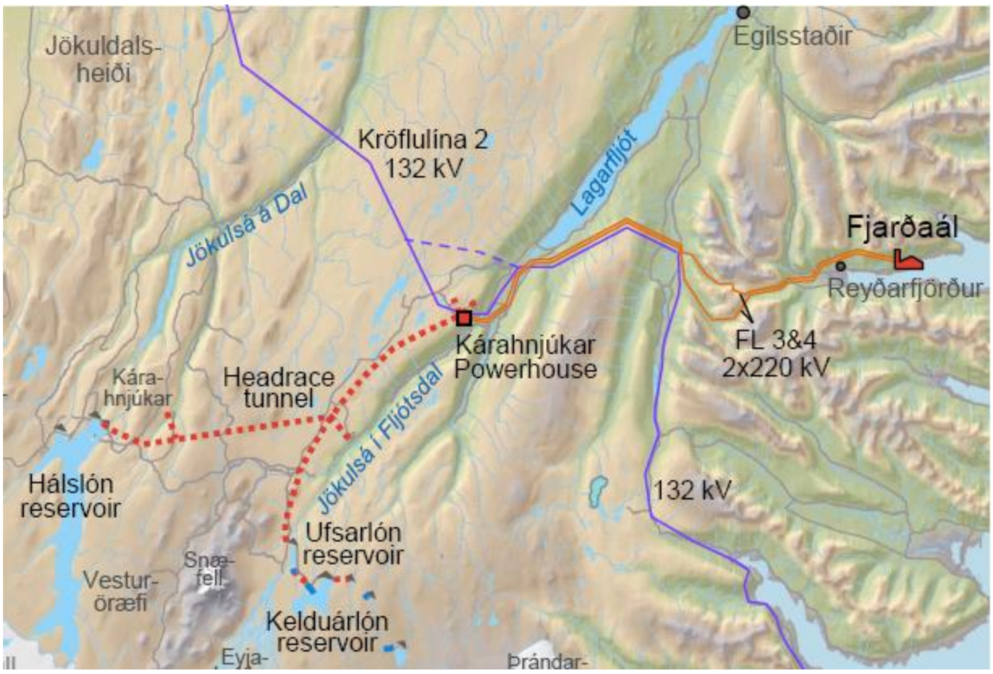

Figure 1. Kárahnjúkar HEP 690 MW.

The project is located on the East Cost of Iceland with a weak 132 kV connection to the main power system in South-Iceland. The maximum import to the Aluminium Plant from the 132 kV connection is calculated to be around 100 MW (stability limit).

Early on it was decided that the Kárahnjúkar Hydro Project together with the 132 kV connection should be able to cope with the Aluminium Plant using N-1 conditions, meaning full power delivery to the Aluminium Plant with outage of either one generating unit in the hydro station or the 132 kV connection.

1.2 Number and capacity of generating units

The requirement that the power station must satisfy the smelter's power requirement, with the limited assistance of the weak grid connection, after an unplanned outage of a generating unit, limited the possible size of the units significantly. Four 172,5 MW units were out of the question and five 138 MW units would also have been too large. Therefore the Kárahnjúkar Hydro Project was designed having 6 generating units, each with the capacity of 115 MW (130 MVA) with 10% overload capability.

The turbine units are designed for 24 m^3/s rated flow and a maximum overload flow limit of 26,4 m^3/s, valid throughout the expected range of net head. The waterways were designed for 6 x 24 = 144 m^3/s maximum flow, which means that the overload flow cannot be used when all six units are in operation. The significant pressure losses in the very long headrace mean that each unit of flow will produce more power at lower total flow through the headrace. This effect can be observed in the chart in figure 2, which shows the maximum station power as a function of the reservoir level. Separate lines show three, four, five and six units in operation. The effect of head losses in the waterways are accounted for.

The generators are limited to 125 MW power (130 MVA), and this limit can be seen in the chart where the lines representing the total station power become horizontal. The smelter power requirement is shown on the chart both for the above mentioned N-1 criterion, 553 MW, as well as for a less stringent N-2 criterion, 469 MW.

The significant effect of the reservoir level can be seen in the chart. Planned outages of units will be limited to the periods of high reservoir level.

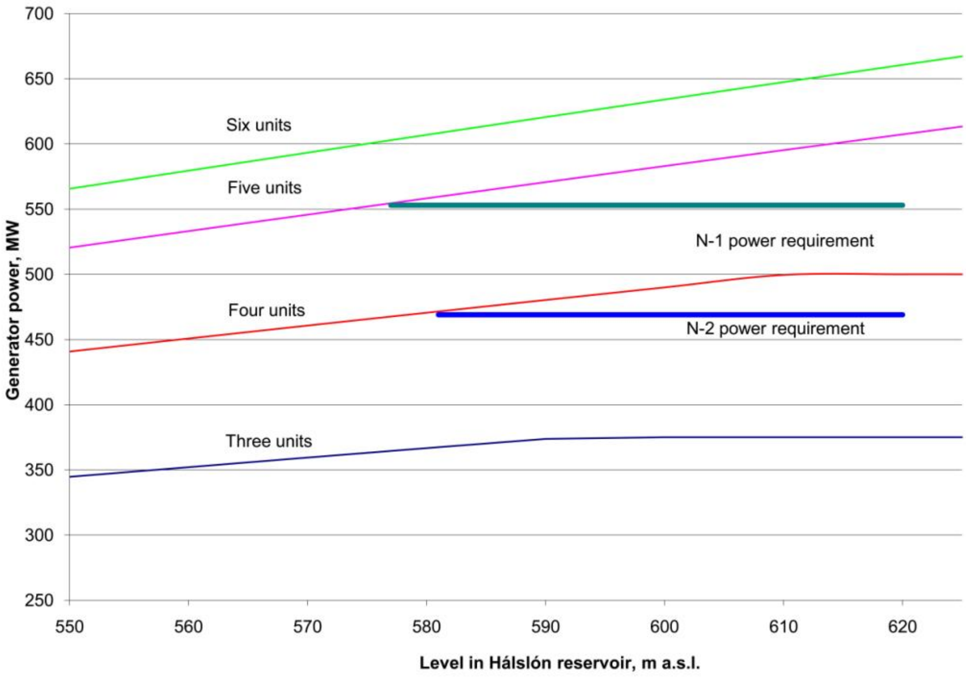

Figure 2. Station power at maximum unit flow.

2 Powerstation layout.

The water flow from the reservoir is conveyed to the power station area in Fljótsdalur valley via a 40 km long mostly unlined headrace tunnel. The headrace tunnel terminates in a valve chamber wherefrom two steel lined pressure shafts convey the flow, each to a group of three turbine units. The pressure shafts are vertical, connecting the valve chamber with the power station directly below. Each pressure shaft is preceded by a butterfly valve to enable closure and dewatering of one pressure shaft for maintenance with the other shaft operative. Ultrasonic flow meters in each pressure shaft initiate emergency closure of the butterfly valve in case of excess flow rate.

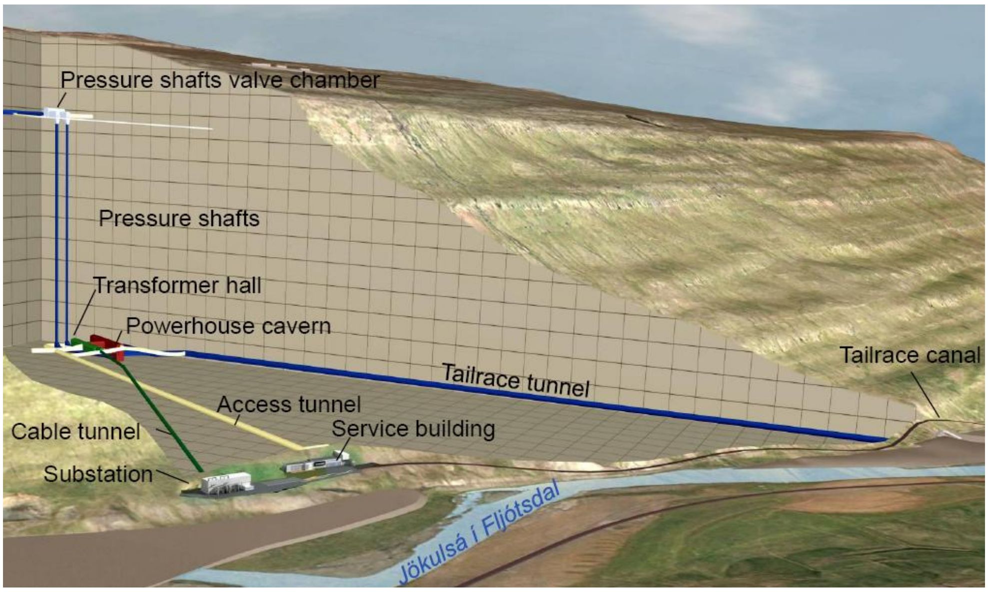

Figure 3. Powerstation complex.

The two caverns comprising the main part of the power station are the power cavern and the transformer cavern. The power cavern houses the turbine generator units and their auxiliary equipment. The transformer cavern however contains the unit transformers, each in their own individual closed cell.

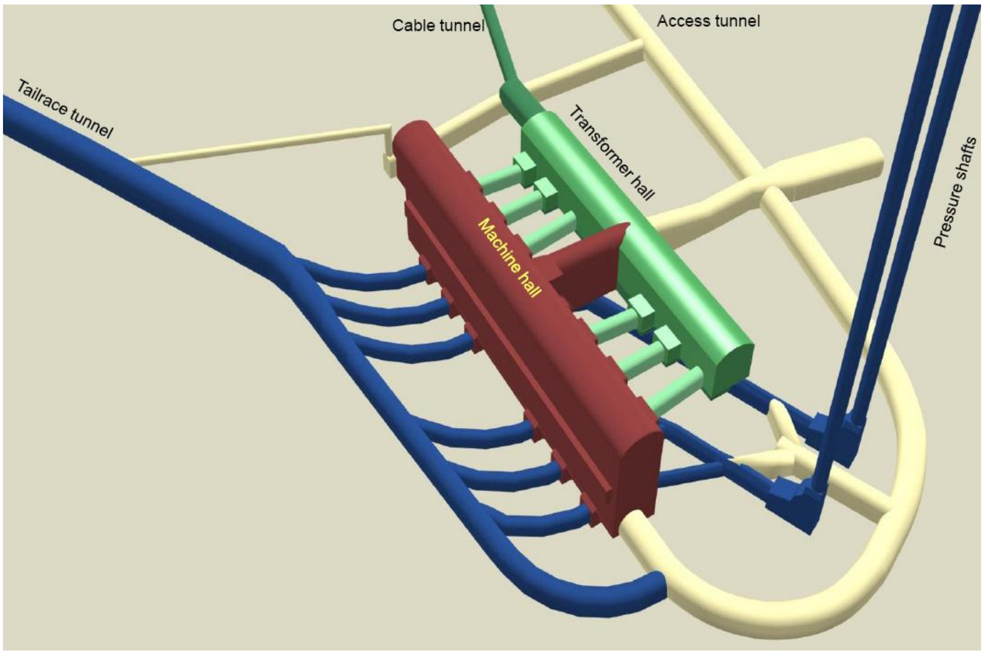

Figure 4. Powerstation perspective view.

The main cavern with the six generating units is designed with a central access onto an erection floor which is the roof of a central concrete structure dividing the power cavern into two sections, each housing three units. This arrangement was decided due to the high number of units, favouring a central erection floor to minimise hoisting of heavy equipment over units in operation, but also for safety reasons as the division of the powerhouse into two halves reduces the risk of one very serious accident or failure having catastrophic consequences for all six units.

The power cavern has three floors below the main floor elevation and these floors are split into two sections by the central structure. The two lower floors, the valve floor and the turbine floor comprise one fire section together, but the generator floor is separate and isolated from the lower floors. The upper part of cavern above the main floor comprises one fire section along the total length of the cavern. Each fire section can be individually cleared of smoke by a controlled smoke exhaust system. If fire or smoke is detected, large axial smoke exhaust fans can extract hot air and gases from the section, releasing the smoke into the tailrace tunnel which has a free water surface and adequate room above it to convey the smoke out into the open. In case of smoke exhaust, fresh air is drawn through the access tunnel and conveyed by ducts into the section being exhausted.

All rooms in the central structure are designed to prevent the spread of fire. Walls are made of thick reinforced concrete. All doors are certified fire doors, ventilation ducts are provided with automatic fire dampers in wall openings and all cable openings are closed after cabling with fire certified material. The 400 V main distribution rooms are provided with inert gas fire extinguishing systems and the oil room with a droplet sprinkler system.

The generator housing walls are made of reinforced concrete and each generator is equipped with an inert gas fire extinguishing system. Each unit is equipped with a generator breaker situated in a niche in the power cavern wall. A tunnel from each niche contains the IPB ducts connecting the breaker with the transformer. A thick concrete wall with an explosion certified pedestrian access door is in each IPB tunnel.

Each transformer is situated in a separate completely closed cell. The cell walls and ceiling are especially reinforced against a calculated pressure resulting from an unvented explosion of carefully estimated magnitude. Each transformer cell is equipped with a droplet sprinkler fire extinguishing system. The cell transport opening is closed with removable concrete elements and the pedestrian cell access door is certified for the expected explosion pressure.

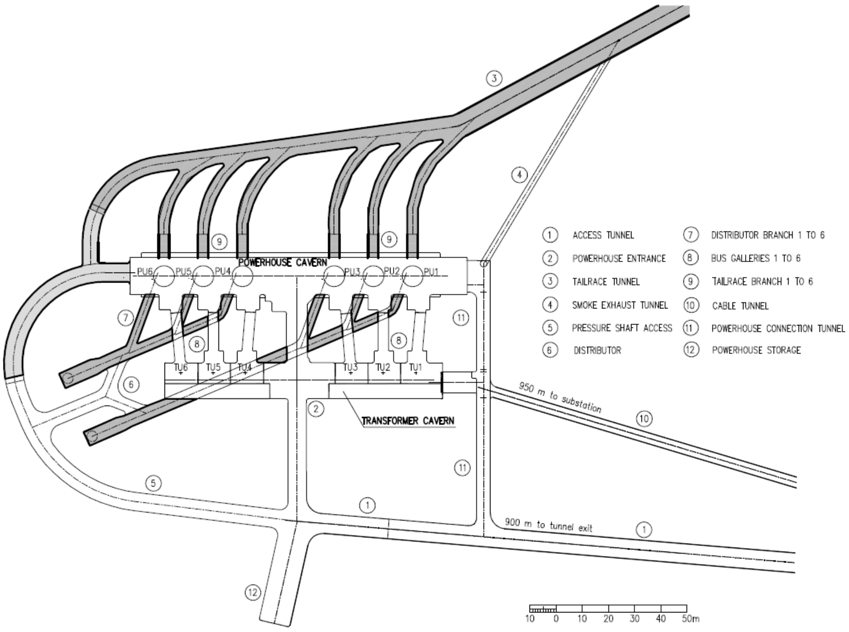

Figure 5. Powerstation plan view.

3 Powerstation equipment.

In the design of the powerstation strong emphasis was placed on reliable overall design of the station, and reliable design of each generating unit. Powerstation equipment and systems can be divided into two categories, i.e. equipment serving one unit only and common station equipment serving more than one unit. The third category is the equipment belonging to the transmission system. The following is an overview of features that were implemented to enhance reliability in each equipment category:

Equipment serving individual generating units:

Block design for the generating units, with redundant pumps for all auxiliary pumping systems. Stand alone control system for each unit with redundant CPU´s. Double Protection systems. Turbine runners can be replaced from below without dismantling the generator. Generator Circuit Breakers installed between each generator and unit transformer. Explosion reinforced transformer cells. Separate fire resistant HV (220 kV) cables from each unit transformer to the GIS switchgear. Unit transformers with point on wave energising from HV side.

Common station equipment:

Double (fully redundant) structure of station service systems including AC and DC distribution systems, with separate cable routes to each unit, to minimize possibility of a multi unit outage in case of cable damage due to fire or other local damage. Redundancy in sump pumping systems, with two separate sumps, one on each side of the powerhouse. Separate water level monitoring in each sump, and several water level monitors on the lower floors. Extensive fire alarm and fire extinguishing systems. One signal source cannot trip more than one generating unit.

Transmission system equipment:

The HV switchgear in the substation is of the double busbar type and has additionally busbar sectionalising. In normal operation the transmission system is divided in two sections. Double (fully redundant) structure of station service systems in substation, including AC and DC distribution systems.

3.1 Equipment serving individual generating units.

Each generating unit is equipped with all the auxiliary equipment necessary for the operation of the unit. Common equipment used for more than one unit is solely limited to condition monitoring equipment and fire extinguishing equipment, in addition to the common station AC and DC distribution equipment described below.

Turbine inlet valves of spherical type with counterweight closing facilitate the maintenance of individual turbines with other turbines, on the same penstock, in operation. The valves can close against full pressure and full flow. At the downstream side of the turbines draft tube gates are installed, facilitating dewatering of the turbine independent of the operation of other turbines. The draft tube gates can only close after the inlet valve and by-pass have been closed. In case of too high water level in the tailrace tunnel or on the powerhouse floor the generating units are stopped, inlet valves are closed, followed by automatic closing of the draft tube gates. Water level sensors for alarm and closure of units because of water on the powerhouse floor are installed close to each unit and are programmed to close only the adjacent unit to prevent false tripping of many units.

The turbines are designed for replacement of runners from below. This shortens the replacement time of runners as the opening of the generator and removal of the generator rotor is avoided.

Generator circuit breakers with high breaking capacity are installed between the generators and the step-up unit transformers. The generator circuit breakers increase the safety of the generating units and connected equipment as interruption of fault currents are faster compared to de-excitation and stopping of the generating unit. The safety of the step-up transformer is significantly increased as the fault current from the generator is interrupted instantly, thus reducing the risk of transformer explosion.

Each 220 kV unit step-up power transformer is housed in an explosion reinforced concrete transformer cell. Serious fault leading to explosion in one transformer should therefore not damage other generating unit blocks. SF_6 insulated bus-bars connect the High Voltage (HV) bushings of the transformers to the more than 1 km long HV cables to the substation. Surge arresters are part of this equipment, protecting the transformers for possible over-voltage surges at the transformer end of the long cables.

The HV cables are installed in a separate cable tunnel, with three cable sets at each side of the tunnel. The cables are XLPE insulated with fire resistant cable sheath according to class A of standard IEC 60332. The cable sheaths are also of the low smoke and halogen free type.

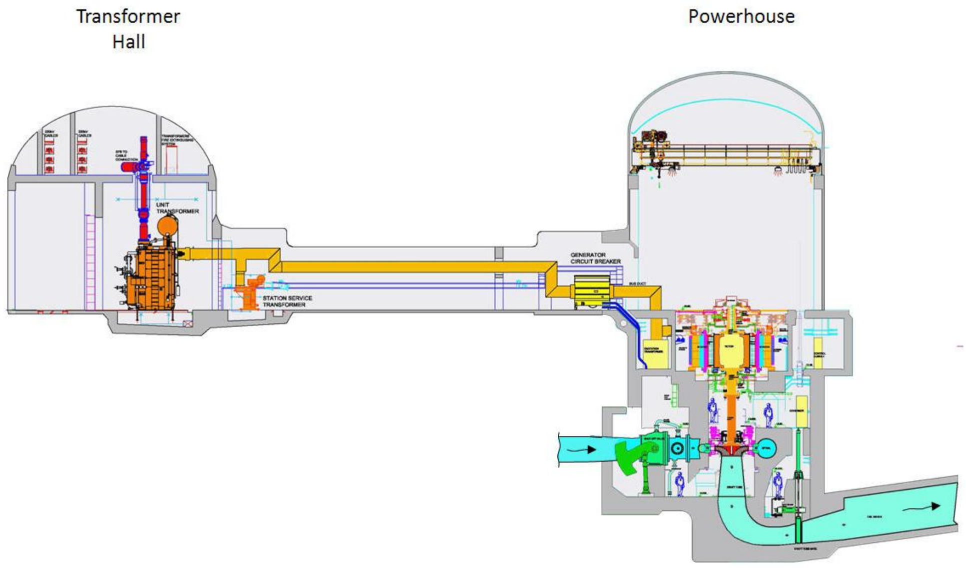

Figure 6. Section through generating unit block.

All mechanical auxiliary systems for each generating unit are equipped with two pumps whereof one is sufficient for operation of the unit. This includes raw water pumps and closed circuit water pumps in the cooling system, governor oil pumps and inlet valve oil pumps. Each cooling water pump is replaceable without disturbing the operation of the respective unit.

The control system for each generating unit is a separate system that can operate without connection to the higher level control system. The control system is of the distributed structure with the I/O's located close to the respective equipment. Each Programming Logic Controller (PLC) of the control system is equipped with a redundant CPU. The individual control systems are interconnected on a redundant Ethernet network according to IEC 60870-5-104.

The relay protections for each generating unit are fully redundant in separate cubicles, each section including a multifunctional protection relay. Each section of the protection relays and the associated trip relays have their power supplied from different parts of the double direct current system.

Energising large power transformers can cause shock on the transmission network, especially a weak network as in this case. Therefore soft energising equipment was installed for each HV circuit breaker for unit transformers and interconnection transformers. This equipment ensures that each phase of the circuit breaker is closed on the most favourable time in the cycle.

3.2 Common station equipment.

The powerstation is equipped with two 110 V Direct Current (DC) systems. All equipment necessary for operation of a generating unit and safety of the station have feeders from both DC systems. This includes electrical governors, voltage regulators, control and protection systems and fire extinguishing systems.

In the powerhouse there are two 400 V Main Distribution Centres (MDC), each with feeders to all Motor Control Centres (MCC) wherefrom the individual equipment is fed. There are four station service transformers, two connected to the generator side of a unit transformer, and two to interconnection transformers on the 132 kV network. The MDC´s are housed in separate rooms in the powerhouse.

There are two wet sumps in the powerhouse, one in each section of the powerhouse. Each wet sump is equipped with three sump pumps whereof one is normally sufficient to pump the leakage water to the tailrace. The two dedicated MCC´s for sump pumps and smoke exhaust fans have the third incoming feeder on 400 V from emergency diesel generating unit located in the service building above ground. High water level in the station sumps gives alarm indications to the station control system. On the inlet valve floor double water level sensors are located at each generating unit. These sensors have two levels, alarm level and trip level. To avoid false tripping of more than one unit the water level sensing at the individual units is independent. This is a general design philosophy in the station; no signal with single source should trip all generating units. Double water level sensors are also located in the tailrace at different levels. In case of too high water level in the tailrace three units are tripped, and then the other three if the level continues to rise.

For personal safety and station reliability the powerstation is equipped with a number of fire warning and extinguishing systems. Two inert gas fire extinguishing systems are installed for the generators, two foam systems for the governor and inlet valve oil units, and two water spray systems for the unit transformers. Each system is common for three generating units. In addition, an inert gas system is installed for the 400 V main distribution rooms and a droplet sprinkler system for the oil room.

3.3 Transmission equipment.

The 245 kV Gas Insulated Switchgear (GIS) switchgear in the substation is of the double bus-bar type and is in addition sectionalised in such a way that three units, one transmission line to the aluminium smelter and one interconnection transformer to the national grid are connected to each half of the bus-bars. The division of the switchgear is therefore similar to the division of the arrangement in the powerstation as illustrated on figure 7.

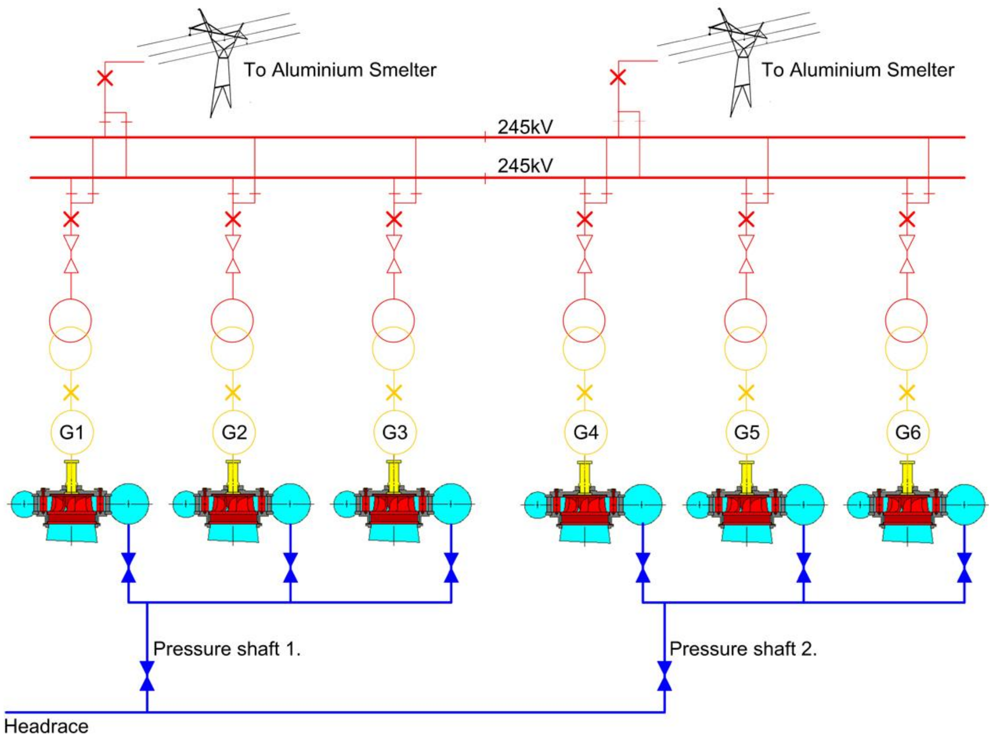

Figure 7. Division of generating units and transmission system.

Two approximately 50 km long transmission line connect the substation to the aluminium smelter. The lines are on separate towers and partly routed via different valleys, where there is a potential risk of snow avalanches. In all locations where there is a risk of avalanches, special towers designed to withstand snow avalanches are used.

In normal operation of the transmission system the configuration is as shown on figure 8. Both busbars in the two substations are used and bus coupler circuit breakers closed at both locations. Five generating units and one transmission line to the aluminium smelter are connected to busbar A in Substation Fljótsdalur. One generating unit, one transmission line and the interconnection transformers to the national grid are connected to busbar B. At the aluminium smelter the transformers serving the potline load are connected to busbar A and the transformers serving the auxiliary load in the factory are connected to busbar B. In case of trip from the potline control in the aluminium smelter the signal is transferred to the bus coupler circuit breakers in the substations via high speed communication links. The potline on no-load with five generating units spinning up in speed is thereby isolated from the network but keeping the supply to the auxiliary load in the factory via the other transmission line and limiting the influence of the load rejection on the grid.

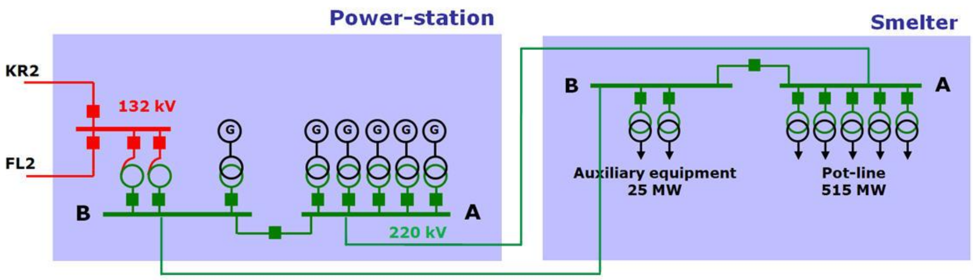

Figure 8. 220 kV system configuration in normal operation.

4 Startup and operation.

On October 1, 2003, a technical committee with members from Alcoa and Landsvirkjun was established. The mission was to achieve optimized best overall performance of the electrical equipment of the smelter and the power network. The work of the committee resulted in a number of technical solutions and operational rules and guidelines to secure the operation of the aluminium plant and the power network. Amongst other things this included sophisticated area-wide protection schemes for the power network.

The Hydro Project commissioning was delayed several months due to very difficult conditions in a part of the headrace tunnel. Due to this delay the aluminium plant was started up (on April 1st 2007) using alternate power imported from the 132 kV network. This was made possible by utilising one of the generators in the powerstation as a synchronous condenser (decoupling the waterwheel and starting the generator using a static speed converter). The headrace tunnel was filled with water in October 2007 and the first unit started production on November 1st 2007.

In the elapsed operation period since startup the behaviour of the divided structure of the transmission system has proven to be successful. The separation of the pot-line with five generating units from the grid in case of load rejection of the pot-line, highly limits the influence on the grid.

5 Conclusions.

During the preparation and design of Kárahnjúkar powerstation and the pertinent transmission systems high importance was on the reliability of the power delivery to the aluminium smelter. The overall station was designed according to the N-1 principle and the same criterion was applied on the individual structures and systems. High emphasis was placed on the separation of the individual generating units to avoid total shutdown of the station and a special setup is used in the transmission system. Safety of personnel and equipment due to fire and flooding were also important design criteria.

The Aluminium Plant and the Hydro Station have now been operated for more than two years. No serious problems have occurred, and the project in whole is a success.

The Authors

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