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COMPLETION OF KRAFLA GEOTHERMAL POWER PLANT

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ABSTRACT

The preparation for the construction of the 60 MW Krafla Geothermal Power Plant started in 1974. Almost simultaneously volcanic activity started in the region and affected the chemistry of the geothermal fluid. This gave serious problems in the harnessing of the steam and the treatment of the geothermal fluid. Originally two 30 MW units were purchased but the installation of the second unit was postponed until further notice as a result of steam shortage. The volcanic activity ended in 1984 and since then the chemistry of the fluid has improved considerably. In 1996 Landsvirkjun (the National Power Company) decided to complete the installation of unit 2 and to drill for additional steam to reach fully rated power on the plant. The project has been successfully completed and the plant has been running on full load since 1998. The battle of completing the power plant and furnish it with the latest and most modern technology has lasted over a period of 25 years. Although Mother Nature resisted human intervention the battle has been won by Icelandic know-how. The future of the plant is promising and there are good prospects for further extension of the plant.

1. HISTORICAL BACKGROUND

High temperature geothermal areas may be considered as a byproduct of volcanism. Heat generation has been constantly in process over some 100 thousand years and is functionally the general heat source for the geothermal reservoir (Stefánsson 1981). In other words a sustainable energy resource. The importance of knowing the behavior of the particular volcano is therefore obvious. In this case the Krafla Central Volcano in North-East Iceland, (Fig. 1), is part of an active volcanic system extending from the north coast to SSV at the length of 100 km. This active volcanic fissure zone reveals the boundary between the American and Eurasian continental plates where they drift apart and new land is in process of formation. The Krafla volcano has been activated every 250-1000 years and each episode has lasted 10-20 years. Hyaloclastite ridges extending NNE-SSW, parallel to the main fractures systems characterize the landscape around Mt. Krafla. Between them are valleys and at higher elevation platforms covered mostly by lava and partly by soil and mud. The geothermal manifestations are predominantly fumaroles and mud pots at the main upflow zones on the southern and western slopes of Mt. Krafla.

Protests against an enlargement of a hydropower plant in northeast Iceland demanded some other alternatives in electricity production. For this reason the Icelandic Parliament, Althingi, in 1974 passed a legislation permitting the building of a geothermal power plant of up to 55 MW. The preparation started immediately by drilling two exploratory wells and purchasing two equally sized turbine generator sets for the plant (Stefánsson 1981).

In 1975 as the construction of the power plant began a volcanic eruption period started and lasted until 1984. A magma chamber was located down below and as consequences of the magma movements into and out of the magma chamber the ground inflated and deflated 21 times. In 9 of the events a volcanic eruption burst out. In the other 12 events magma filled up fractures making intrusions without reaching the surface. Volcanic gasses severely affected the geothermal reservoir seriously reducing the quality of the geothermal fluid. Soon it also became evident that there would only be steam available for partial output from one of the turbine generator units. Therefore it was decided to cease any further construction work related to unit 2 and the installation of the unit was postponed until further notice.

The construction work and installation of unit 1 continued, however, and was completed with the commissioning of the unit in 1978. After completing the drilling of 11 wells the max. power output was only 7 MW, and the operation of the plant intermittent due to steam shortage. In the following years additional drilling took place and the output gradually increased to full power in 1984. The unit has since then been operating constantly on full power, except for scheduled maintenance during the summer time.

During this time the geothermal area was monitored. The chemistry of the well fluid, fluid pressure and temperature as well as the composition and concentration of gases in accessible fumaroles were systematically observed. Monitoring observations at the end of the last two decades indicated a decline in volcanic gas content in the geothermal reservoir and decreasing influence on the fluid chemistry.

Early in 1996 Landsvirkjun considered installing unit 2 to increase electrical power production in phase with increased market demand. Two consulting engineering companies, VGK hf. and Rafteikning hf. were contracted to carry out a feasibility study and to recommend future developments. Soon after receiving their report Landsvirkjun decided to go ahead with the completion of the plant. Orkustofnun was subsequently contracted to the group of consultants as specialists in geothermal field development.

2. GEOTHERMAL FIELD

Comprehensive investigations on the extensive high temperature areas in the Mývatn region have been carried out in the last decades. At a late stage in these studies the Krafla geothermal field was investigated in more detail. Geology and surface geothermal activity were mapped. Geophysical methods available at that time were used to look deeper into the system before exploration drilling started. Resistivity measurements were used to map the extent of the area and the geochemistry of fumarole fluid (gas) used to map the temperature distribution in the reservoir. After drilling of the first 11 wells in the Leirbotnar field it was realized that the geothermal system was more complex than anticipated and different from the known high temperature areas elsewhere in Iceland (Stefánsson 1981). In addition the invasion of volcanic gases contaminated the geothermal system resulting in higher gas concentration and lowered pH values in the deeper aquifers. The consequences were increased corrosion and scaling in the production wells.

It was moreover observed that the geothermal reservoir consists of two separate geothermal zones. The shallower one is water dominated, extending to 1000-1200 m depth with temperature of 190-210°C. The extent of the deeper zone is at least down to 2200 m depth and it is vapor dominated with temperature over 300°C, close to the boiling curve. The subsurface geology is characterized by two thick hyaloclastite formations down to 800-1000 m depth separated by 100-200 m thick basaltic lava. Below that depth the intensity of the intrusions are up to 80-100% of the formation. In the deepest part intrusions of granophyric composition are common and frequently strongly connected to aquifers. The pH value is, however, too low (2-4) for the fluid to be harnessed. The alteration mineral pattern reflects the temperature distribution. In the upper part cooling is obvious where chlorite-epidote alteration is overprinted by calcite, but in the deeper part there is good correlation of existing minerals to measured temperature.

In the years 1977-78 an extensive gas sampling program was initiated to map the area affected by the volcanism. Samples were collected from all known geothermal outflows. The gas components in the steam and their concentrations were measured. Based on the ratio of CO_2/H_2S (< 30-50) two fields were pointed out, Sudurhlídar and Hvíthólar at the caldera rim about 2 km south of the steam separation station. To emphasize the complexity of the area, both these fields revealed a different character from that already known for the Leirbotnar drilling field. Sudurhlídar appeared to be a vapor dominated system more or less from the bottom up to 200-400 m depth. The main aquifer zones are connected to a thick acidic rock complex at 800-1200 m depth and again below 1900-2000 m depth. In the Hvíthólar field a reverse character appears. The uppermost 800 m are vapor dominated and water dominated below that depth. Sufficient steam was obtained by drilling in these three areas to generate 30 MW_e (Ármannsson, H. et al. 1987).

The decline of the gas concentration in the steam in well 15, (Fig. 2), was a good indicator of the improved conditions and that the influences from the volcanic activity were on the vain. From previous drilling it was known that the permeability was mainly connected to fractures zones. Therefore all effort was concentrated on locating the fracture zones deep in the reservoir before the drilling started.

3. OVERVIEW AND OPERATING DATA

Figure 3 shows a plan layout of Krafla geothermal power plant and the surrounding area. The power plant is located centrally at the edge of the well zone Leirbotnar. The separator station is located approximately 500 m away from the powerhouse in the middle of the zone. Over the years a total of 34 wells have been drilled in different zones. There are three main zones, Leirbotnar, Sudurhlídar and Hvíthólar. The most recent drilling has been directed to extend the drilling zones towards northeast. Using the latest technique of directional drilling the expansion on the surface has been much less than down below in the reservoir. The latest well, well no 34, was drilled in a new area with promising results.

The 34 wells can be grouped as follows:

- 16 wells producing HP steam
- 5 wells producing LP steam only
- 7 wells not in use
- 5 wells no longer existing
- 1 injection well

Figure 4 illustrates the principles of the process for the present 60 MW power plant. Originally the process design was based on the fundamental criteria that the reservoir would be water-dominated and have an average enthalpy of 1200 kJ/kg corresponding to a temperature of 273°C. This led to the adoption of a double flash system and dual pressure system for the turbine generator. Once the turbine generator units were firmly decided and designed, other parameters had to be adjusted accordingly. However, the enthalpy of the geothermal fluid turned out to be a good deal higher than originally assumed. Whether it was due to the influence of the volcanic activity will never be known for certain. This has nevertheless resulted in having to drill specially for low-pressure steam and a little more complicated operation of the steam supply system.

The turbines are Mitsubishi turbines, dual pressure, double axial flow, five stages with 30 MW rated output each. The inlet design pressure is 6,7 ata for the high-pressure steam and 1,9 ata for the low-pressure steam. At 30 MW rated output the steam consumption is 52,5 and 17,8 kg/s of high- and low-pressure steam respectively. By raising the inlet pressure and increasing the mass flow the rated output of each present turbine generator could be raised to 35 MW.

The plan for the completion project was originally to drill for sufficient low- and high-pressure steam and to install unit 2 according to the original design. However, during the construction it became evident that equipment had deteriorated to such an extent that a comprehensive renewal had to be performed. This applied particularly to the electrical equipment, which had been badly influenced by the concentration of H_2S in the atmosphere. Subsequently it was decided to modify and modernize the plant and bring it up to the general standards mandatory for power plants owned by Landsvirkjun.

4. DRILLING 1996-1999

The drilling policy adopted encompassed obtaining both high- and low- pressure steam. Initially it was planned to increase the steam production from existing drilling fields. The results proved insufficient, however, so the drilling area in the vicinity of well 15 was expanded to the north and the east where observations indicated a more open system of reservoir fractures and acceptable fluid quality. For environmental reasons the locations and design of steam production drilling sites and pipelines were carefully planned to minimize surface disturbances. As a part of that program directional drilling was adopted.

The drilling included the wells shown in Table 1. The total output is calculated as average net output. The yield of these 8 wells is 7,5 MW_e on average. This is a tremendous improvement compared to pervious results of drilling in the Krafla area. This data plus that of all other wells gives the total available steam as 183,3 kg/sec of HP steam and 29,2 kg/s of LP steam. This equals approximately 90 MW_e of electrical power generation.

The output of well no. 34 is quite exceptionally high not only as regards the Krafla geothermal area but also in relation to other geothermal fields in the world. A total of 20 MW for electrical generation from one well is quite outstanding.

5. REFURBISHMENT OF THE POWER PLANT

In the beginning of the completion project the overall design of the plant was systematically reviewed. Modifications and improvements to the plant auxiliaries were proposed to improve efficiency, increase output, improve reliability, and reduce operating costs.

5.1 Steam supply system

Modifications such as moving the steam control valves to the separator station have over the years been carried out on the steam supply system. The system has been extended as additional wells have been drilled and connected. The piping design and equipment design has on the other hand proved reliable. Neither corrosion nor erosion problems have been encountered and the quality of the steam has been good.

A reconstruction of the high-pressure part of the separator station was carried out based on the operating experience in Krafla and other geothermal fields in Iceland. Two horizontal separators of double capacity sufficient for both units replaced the six old spiral intake cyclones. The new separators could be placed within the same building that previously only housed the separators for the first unit.

The exhaust of geothermal effluent from the separator station was modified as well by constructing two steam stacks , one for the excess steam from both high and low pressure control valves and the other for geothermal fluid flashed from the low-pressure separators. The geothermal effluent from the separator station is disposed of on the surface. The control strategy of maintaining constant steam pressure was reviewed to minimize the exhaust of steam. The pressure is set at a fixed value and the control valves of the turbines keep the pressure at the set point. Only in the case of sudden surplus of steam will the pressure increase and the control valves relieve the pressure.

A separate feasibility study dealing with utilization of the geothermal effluent from the low-pressure separators to generate electricity and so cooling the 120°C hot fluid was made. It depends on the technology used how much energy it is feasible to generate. The maximum peak power is expected to be 4,2 MW or 2,9 MW as annual average, corresponding to cooling the effluent down to 55°C. This of course implies higher production costs than in bigger plants but may be acceptable considering the increased use of the energy resources and the environmental improvement achieved in decreasing the geothermal effluent temperature.

5.2 Turbines

After 20 years of operation of unit 1 the turbine generator was in an acceptable condition. In 1979 there was an isolated incident where one of the wells started to give off highly corrosive superheated steam containing Cl gas. Both rotor and diaphragms were severely damaged. The rotor and the diaphragms were subsequently replaced and actions taken to prevent any further corrosion from the steam. Apart from this incident plant operation and maintenance has been normal.

All rotors and diaphragms were carefully analyzed as part of the completion program. Apart from the damages in 1979 wear on the equipment was found to be normal and minor cracks (stress corrosion cracking) in the blades of the last stages detected. All three rotors originally purchased have been used in unit 1. It was decided to repair the old diaphragms and rotors from unit 1, and the spare rotor, which in 1979 was installed in unit 1, was given an overhaul. All these repairs were successfully completed in time and unit 2 was commissioned in 1997.

The present condition of both units is considered fairly good, the units are running on full load, and even on slight overload. Further refurbishment of the units are being considered such as new rotors and diaphragms with higher efficiency to increase the power output and energy production.

5.3 Vacuum pumps

The original system employed steam driven gas ejectors. The ejectors have proved very reliable. Their steam consumption is, however, high. For both units approximately 10 kg/sec of HP steam were required, which corresponds to an average output of 4,5 MW electric. As an alternative to the steam ejectors, electrically driven vacuum pumps (water ring) were considered. The corresponding electricity consumption is 2,4 MW. The improved efficiency proved to pay back the investment in relatively short time.

The design load of the vacuum pumps is 1% pr weight of noncondensable gases in the steam. During the operating time of unit 1 the gas content has been reducing gradually. At the start of the completion project in 1996 the gas content was well below 1%. However the most recent and powerful wells in the area contain more gas than the older ones. The average has thus increased considerably and is at present approximately 1,4%. This is too high a load for the vacuum pumps and both systems are therefore operated at present to maintain the condenser pressure commensurate with maximum output of both units.

5.4 Electrical power and control system

Originally the basic design criteria for the plant were a fail save operation, have redundant facilities and be suitable for a black start operation. The station was further designed to be fully manned at all times. A new single line diagram, (Fig. 5), based on original design concept, shows the main electrical power system after the erection of unit 2.

The precondition for the installation of unit 2 was to ensure that all installed equipment be designed to be technically up to date and durable for operation for the next 20-30 years. Also referring to the H_2S corrosion a comprehensive renewal of all electrical components, except the generator excitation and step-up transformer was decided. The generator and the brushless exciter were kept in good condition in wooden boxes and the step-up transformer had been in operation for several years, serving as a back up for the station auxiliary power. Most of the other electrical power components were renewed, including 11 kV switch gear, the distribution transformers, the main distribution board, and the MCCs (motor control center).

While the new design of the power system was in most respects according to the original design, this was not the case regarding the control and protection systems. The original design was based on a fully manned station with no automatic start-up or shut down sequences. In the new design it was decided to take advantage of all the latest technology and make the unit fully automatic and remotely operated. In other words, it is possible to operate the steam turbine from warm up through running up to speed remotely, synchronizing and fully loading, provided that steam is available at the isolating valves. In the same manner, the turbine can be unloaded and shut down. A safe shut down in the event of turbine trip is also provided during unmanned hours.

The control system configuration is based on one PLC (programmable logical controller) for each unit, one for the steam supply system and one for station auxiliaries and high voltage system. In addition to this comes a redundant SCADA system, which again is connected to Landsvirkjun's dispatch center. All on-line process regulators in the PLC are backed-up by stand alone electronic regulators that in normal operation follow the PLC control signal and are automatically switched on-line in the event of PLC failure. Therefore PLC failure does not trip the units and they can be safely operated further.

The originally delivered protective relays were of the electro-mechanical type. They were all replaced with new digital relays. All the new relays are connected to the control system via data communication links and time synchronized from a GPS system through the control system. The protective relays are provided with time tagging of events with less than 2 ms resolution and are sending time tagged event records to the control system. The PLC system is provided with time tagging of events with a resolution of less than 10 ms. All sensors, transmitters, controllers and other field equipment were renewed. Screened cables and special connection clamps used for screen grounding to prevent EMC (electromagnetic compatibility) disturbances replaced also all control cables.

The AVR (automatic voltage regulator) for the generator excitation system was also renewed and a new vibration and temperature supervision system for both turbine generator units installed. New electronically based governors with an electro/hydro converter and a pilot valve were installed instead of the original mechanical governor. All control and protection equipment essential for operation of the station is now provided with redundant 110 V d.c. power supply and is connected to two independent battery sets.

5.5 Ventilating systems

The original ventilating system did not cope with the H_2S content in the atmosphere. A new system had to be designed where all precautions were taken to limit the H_2S concentration in the electrical and control rooms to 3 ppb.

The ventilation comprises three systems. There is one large system for the main machine hall where the air intake was carefully moved to a location with less concentration of H_2S than in the original system. Originally the noncondensable gases were led out on top of the powerhouse. This gave some operating difficulties as a result of steam moisture as well as high concentration of gas that could under special weather conditions gain direct access to the ventilating inlet. As a result the gas outlet was led into the cooling tower for more even distribution of the gas into the atmosphere.

Secondly there are two smaller systems with active coal filters and with the air intake in the machine hall. Not only is the filtering important but equally so is the air tightness of the enclosures. The pressure is thus higher in the rooms where the cleanest atmosphere is required. Not all electrical installations or cabinets can be located in separate special enclosures. In such instances clean air is fed into the corresponding cabinets to maintain a slight over-pressure and ensure protection from H_2S corrosion.

All electrical equipment is now protected and all measurements indicate that the 3 ppb maximum allowable H_2S limit in the atmosphere has been met.

6. PROJECT COST

The total costs in million US dollars for the completion of the Krafla geothermal power plant are as follows:

Installation of unit 2, incl. auxiliary equipment	6.4
Electromechanical modifications	12.3
Production well drilling for unit 2	17.9
Production well drilling for future expansion	6.2
Total project cost	*42.8*

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Table 1. The total steam of wells 27-34.

Well no.	*HP steam kg/s*	*LP steam kg/s*	*Total output MW_e*
27	6.5	1.5	3.2
28	0.0	9.0	2.7
29	4.8	0.4	2.3
30	30.3	0.2	13.7
31	4.9	0.0	2.2
32	14.0	0.3	6.4
33	19.9	0.9	9.3
34	43.6	0.2	19.7
Total:	124.0	12.5	59.5

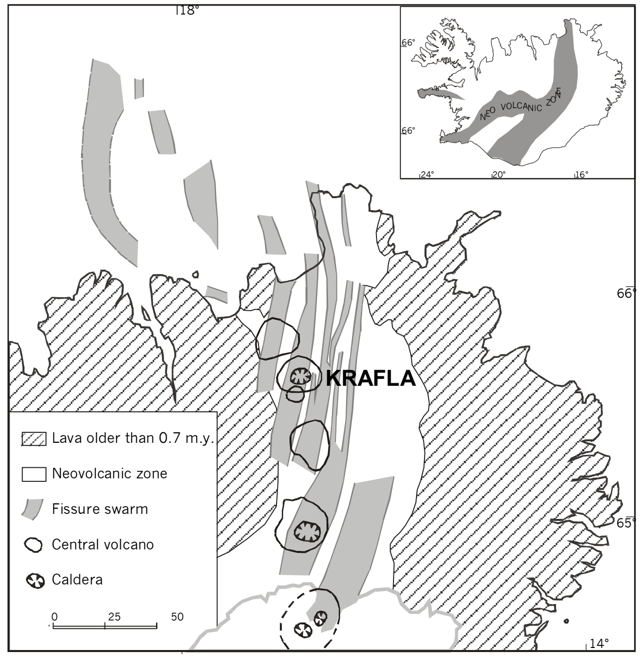

Figure 1. Location of the geothermal high temperature area in Krafla

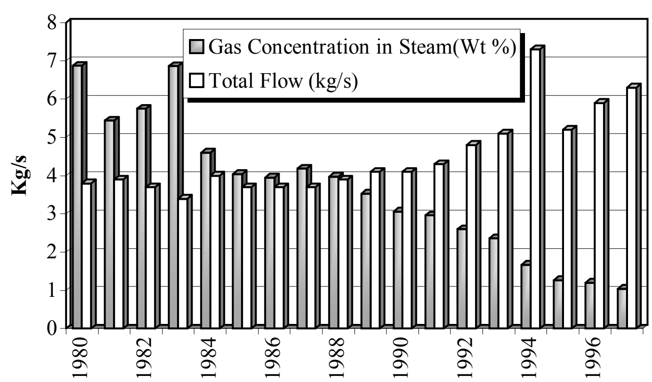

Figure 2. Flow from well KJ-15 1980-1997

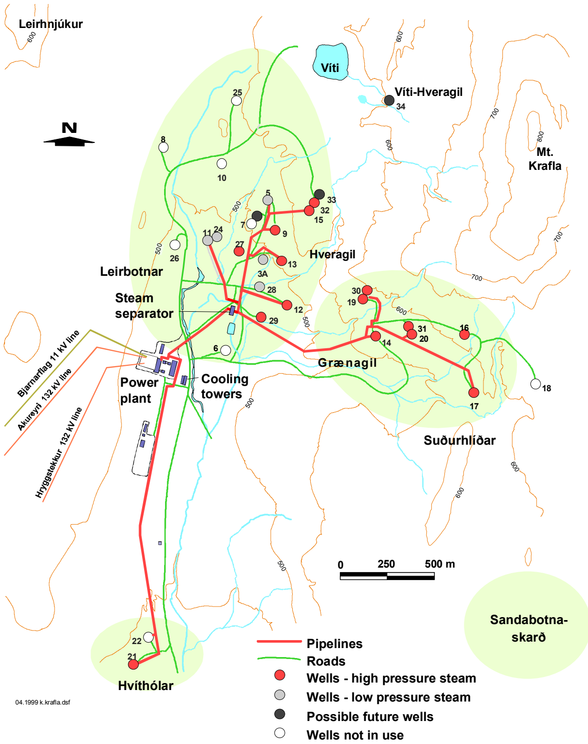

Figure 3. Schematic map of the Krafla geothermal power plant and the surrounding area.

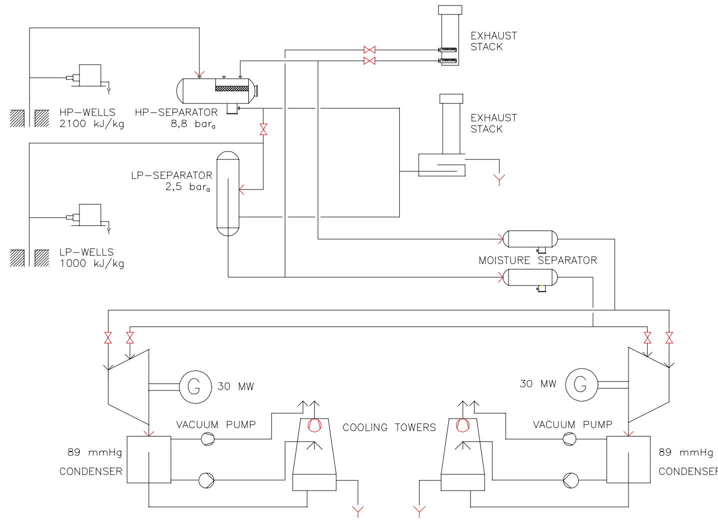

Figure 4. The principles of the process for the present 60 MW power plant

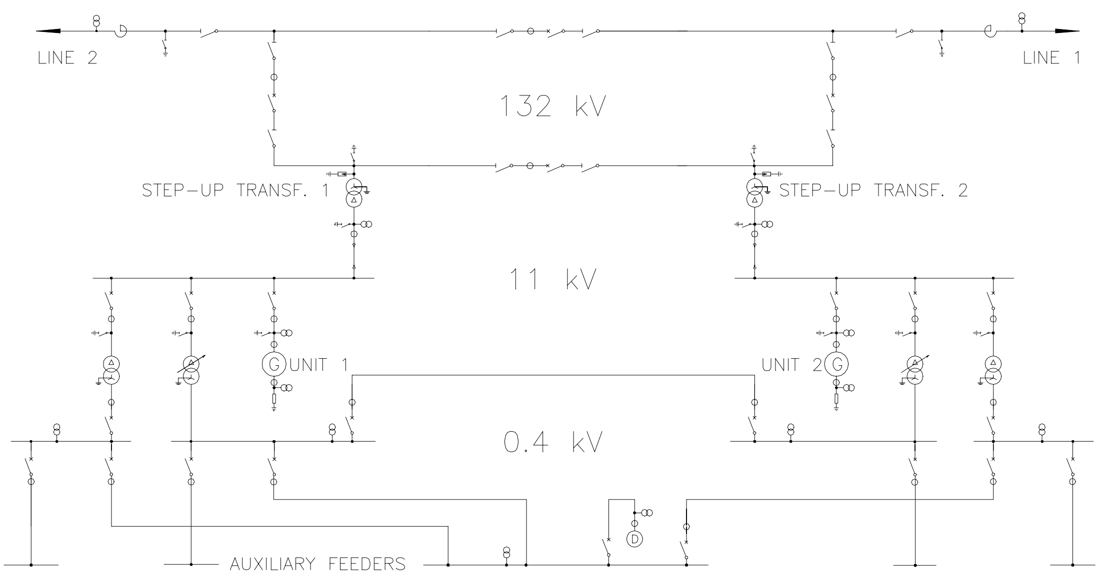

Figure 5. Design concept of the main electrical power system after the erection of unit 2.