Proceedings, 7th African Rift Geothermal Conference
Kigali, Rwanda 31st October – 2nd November 2018

Successful Commissioning of Geothermal Power Plants

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Keywords:

Geothermal power plants, Testing, Commissioning, Organization, Scheduling

ABSTRACT:

The subject of testing and commissioning in this paper is related to power plants with respect to surface equipment, in the sense of engineering aspects. As an example, testing of geothermal wells is an immensely important subject but is not addressed in this paper.

Testing and commissioning is a crucial element in the development of all powerplants and is the last step before commercial operation. The significance is profound for Geothermal Power Plants, as the power source is not a fully controlled steam boiler but steam from a natural underground source of thermal energy and fluids, that will most likely include complications regarding the chemistry and physics of the extracted substances. All equipment and systems need to be properly checked and tested to assure that the plant is ready to function in both normal and emergency conditions, in a safe, efficient and controlled manner. Efficient and systematic planning of these activities is the key to successful finalization of projects together with extensive involvement of the teams in place as well as internal and external stakeholders.

The main purpose of planning and execution of commissioning-, testing- and start-up activities is to make sure that the power plant is delivered timely and cost-effectively by the contractor(s) and as specified in the tender documents. Another important aspect is the operation of the power plant in a safe, efficient and controlled manner, avoiding incidents having negative impact on the environment, geothermal reservoir, steam gathering system, plant equipment and customers. Last but not least, it is of utmost importance to protect the image of the Plant and its Owner to e.g. its neighbors, authorities and general public during the difficult phase of starting-up a new plant. Specific emphasis is usually on planning and coordination of the testing and commissioning activities, requiring experience, anticipation of potential issues and coordination of the different parties.

This paper will present various aspects of planning and implementation of successful commissioning of geothermal power plants through recent examples mostly in Iceland, but also in Turkey and Hungary.

1. Introduction

The authors of this paper and their colleagues at Mannvit and Verkís Consulting Engineers have been involved and playing key roles in the testing and commissioning of many geothermal plants. This is true for example the Nesjavellir Power Plant Iceland, commissioned in the years 1990-2005 (120 MW_e in 4 units and 300 MW_{th}), the completion of Krafla Power Plant in Iceland in the years 1997 to 2002 (60 MW_e in 2 units), Hellisheidi Power Plant in the years 2006 to 2011 (303 MW_e in 7 units and 133 MW_{th}) and Theistareykir Power Plant in the years 2017 to 2018 (90 MW_e in 2 units). All these plants are furnished with extensive steam gathering systems, one of them with two separate systems with different steam pressure. All the plants are flash type with condenser turbines and considered to be large scale geothermal plants. Further, the team has conducted testing and commissioning of a few smaller plants of different types, e.g. a 3 MW back pressure unit in Iceland, two 25 MW binary plants in Turkey and 3 MW binary plant in Hungary. Work on a 5 MW back pressure unit in Iceland is ongoing.

What is important in this aspect is, that even though the oldest project mentioned above started in 1990, most of the engineers involved are still working at Mannvit and Verkís and ready for new demanding assignments. Work in this category demands not only engineers with appropriate skills, training and experience, but also specialized tools, measuring and testing equipment that can be provided along with the commissioning engineers. A methodology for work has been developed. Another important aspect is that the testing team was for most of the plants mentioned above also involved in the design phase, and as a result are well familiar with the design merits of the plant subject to testing and commissioning.

In this paper, the aspects of successful testing and commissioning of a geothermal power plant will be stipulated. Inevitably, some aspects of the subject will be valid for all thermal power plants. However, emphasis will be laid on the particularities valid for geothermal power plants.

2. Particularities of geothermal power plants

In many aspects, geothermal power plants are quite similar to conventional coal fired thermal power plants that are provided with steam boilers for conversion of the energy stored in fossil fuels to thermal energy by means of steam production. In these plants, the steam temperature and -pressure can be regulated and the quality of the steam with respect to e.g. solids and non-condensable gas [NGC] is very high. In geothermal plants, the steam temperature and -pressure values are mostly variable between production wells, as well as the chemical composition. In a common steam gathering system, the pressure must be selected with the goal to maximize the power output / efficiency of the reservoir, while the chemical composition of the fluid can act as a constraint on the selection. Thus, the desired steam system pressure is controlled by pressure regulating control valves to ensure correct inlet pressure at the steam turbine. In most cases, the drilling well output is a function of the wellhead pressure and thus the regulating valves cannot be located directly at the wellhead. The output of each drilling well will then be close to constant and the regulating function will have to take place at the steam gathering system, downstream of the steam separators and upstream of the mist eliminators. Further, the steam will typically contain certain amounts of solid particles and NGC. Whereas the solid particles can be almost eliminated prior to entering the turbine by e.g. long steam gathering pipes and steam strainers, the NGCs cannot be eliminated and constitute a significant proportion of the equipment- and operation effort as well as environmental impact of geothermal plants.

Another issue which applies for many geothermal plants is that their location, obviously close to the geothermal power source, will be in relatively remote areas compared to the location of conventional thermal power plants. This means that it may be more difficult to access possibilities of extensive operation- and maintenance work. For this reason, it is advantageous that systems are assembled and tested at the manufactures workshop prior to installation on site. Control and distribution panels can be assembled, wired and tested in the workshop of the manufacturer and once installed, only external wiring and cabling needs to be tested. Mechanical systems such as oil systems and gas extraction system, can be assembled on a skid and function tested in the workshop. By assembling and testing systems prior to installation on site, the commissioning phase on site can be shortened and the overall cost lowered.

Both aspects imply the profound importance of reliable operation, based among other factors on thorough testing and commissioning of equipment, systems and overall performance.

3. Purpose, definitions and organization of testing

Obviously, the purpose of testing is generally to ensure that the function of equipment and systems is in reality in accordance with the intended / designed properties. For mechanical and electrical equipment used in power plants, this is mostly highly standardized at the manufacturing stage (Factory testing). This is mostly conducted prior to shipping to site and is not discussed further in this paper. As stated earlier, the subject of this paper is to describe testing and commissioning of power plants and related surface equipment and -systems, applicable after installation and connection.

3.1 Testing stages

For testing and commissioning in general, the authors of this paper have defined the following groups:

A. **Acceptance tests**, applicable for all equipment, cabling, piping etc. These tests are to ensure that individual equipment or assemblies is manufactured, installed and connected (piping and wiring) as required.
B. **Control system test**. These tests are managed thoroughly and continuously by the testing team, based on an extended control system signal list.
C. **Cold commissioning** of individual systems.
D. **Hot commissioning** of systems and total plant.

Each of the four groups is divided into subgroups as follows:

A1: Factory Acceptance Tests, FAT. Conducted according to contractual stipulations by vendors at the vendor’s workshop. In some cases witnessed by the Owner and Consultant. Test program supplied by vendor in advance.

A2: Site Acceptance Tests, SAT. Conducted according to contractual stipulations by vendors after installation at Site. In all cases witnessed by the Owner and Consultant, as well as testing team.

A3: Loop testing of cables and hard wired connections for control- and protection circuits. Conducted by Contractors for cabling and connections and witnessed and managed by the testing team.

A4: Loop- and function testing of communication buses (Modbus, Profibus, IEC61850 etc.). Conducted by Contractors for cabling and connections and witnessed and managed by the testing team.

B1: Pre-testing of SCADA system visualization displays, i.e. the HMI displays. Checking of readability, animation, signal codes, written descriptions and instructions etc. Predecessor of actual functionality tests.

B2: Pre-testing of hard wired signals at the control system terminals. Inputs simulated and checked within the control system. Outputs generated within the control system and checked at the terminals. For some projects, this stage not applied for all signals, but used as sample tests for equipment groups and/or HMI display samples.

B3: Pre-testing of hard wired signals all the way between the control system and equipment in the field. Inputs generated at the field side and checked within the control system. Outputs generated within the control system and checked at the field side.

C1: Functional testing of individual equipment in the field and the interaction with the control system. Sensors, control valves, motors etc.

C2: Functional testing of systems and the interaction with the control system. This stage includes the “interlock test”, where all protection- and safety circuits are checked and confirmed to allow safe start-up of the plant.

D1: Start-up of individual equipment, systems and plant by the control system. Tuning of threshold values, regulators and other parameters within control system and individual equipment to ensure correct functionality. A substantial task at this stage is review of alarms, to check that alarms are issued and displayed as required (nothing missing, nothing excessive).

D2: Testing of plant performance under various operation conditions, including the most important “unusual” conditions and emergency conditions. This stage is concluded with the “performance test”, where the output and efficiency of the plant is checked with precision instruments to confirm contractual obligations.

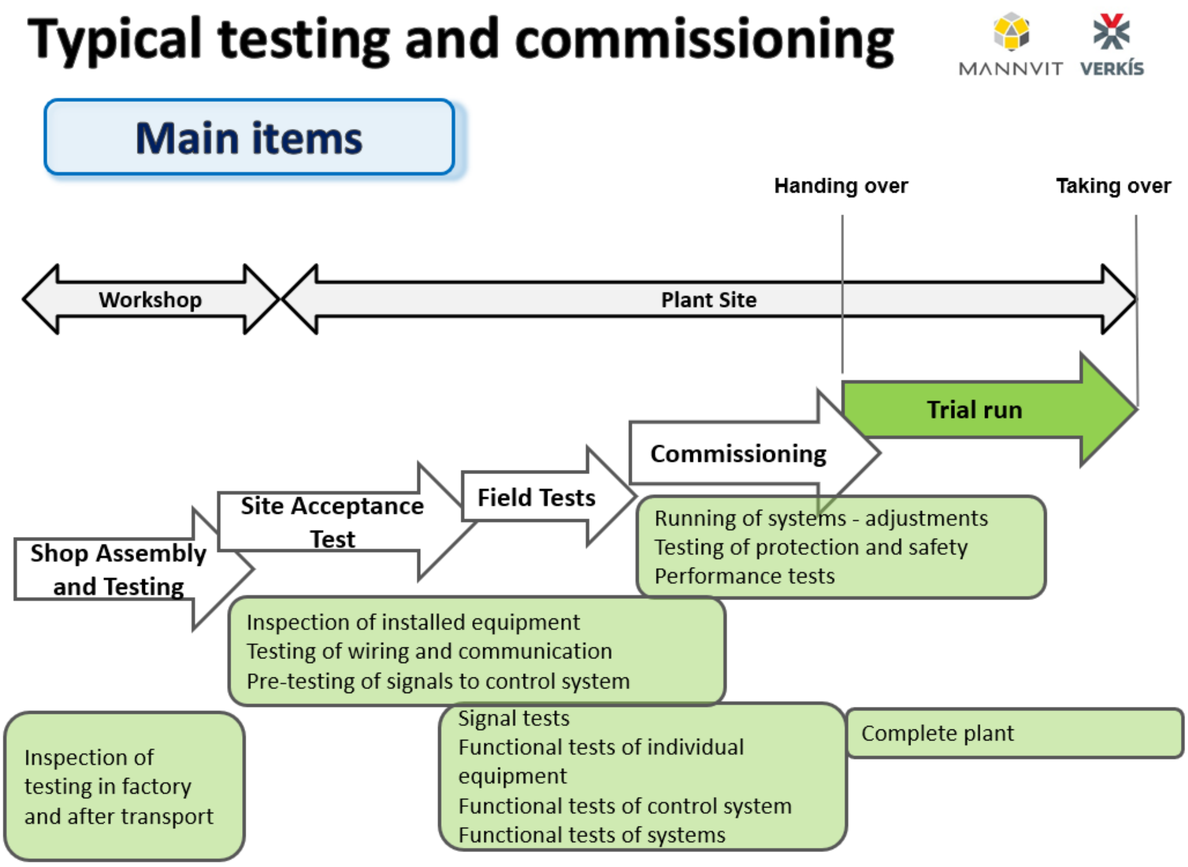

Figure 1: Flow and organization of test process.

Figure 2: Equipment setup for performance testing.

3.2 Test organization

The testing process is managed by the testing team, which is headed by one engineer who is assigned "test manager". This engineer is tasked with the organization and planning of the testing process, manning of all positions and co-ordination of all parties. The testing team consists of a few test teams for larger projects, but for smaller projects more tasks are covered by a single test engineer along with assistants as required for each task. For a fairly large project, the organization chart may be as shown on the following sketch:

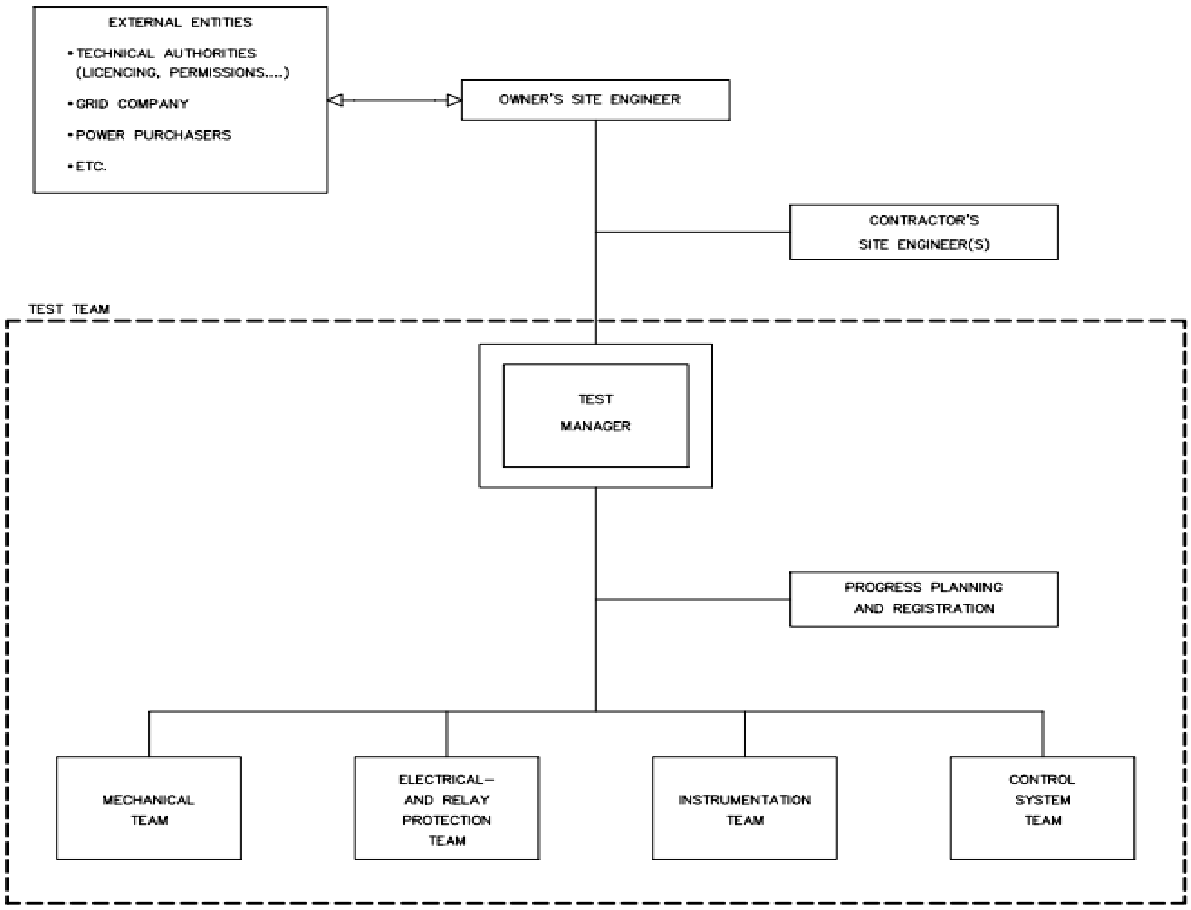

Figure 3: Organization chart for testing and commissioning.

As shown on the organization chart, it is important to note that the test manager is operating under the authority of the Owner's site Engineer. The same applies for all relevant contractor's site engineers as applies for each project. It will be the task of the test engineer to gather information from the contractor's site teams regarding their test requirements, availability of specialists etc. He will also communicate with all relevant authorities (permissions, licensing, grid company and customers). This will result in an overall schedule for testing and commissioning.

3.3 Test progress management

The test schedule described above must be thoroughly maintained, with respect to its progress. For this purpose, it is valuable to organize short meetings on a regular basis. For fairly large projects, a morning briefing at the start of each working day will be appropriate. Here, all relevant parties attend and state briefly the status of their work, requirements for co-operation of others, readiness to co-operate with others etc. Also, HSE matters will be discussed, i.e. what potential personal hazards, environmental matters etc. might be imminent. After these meetings, all parties should be well informed about all requirements, activities of others etc.

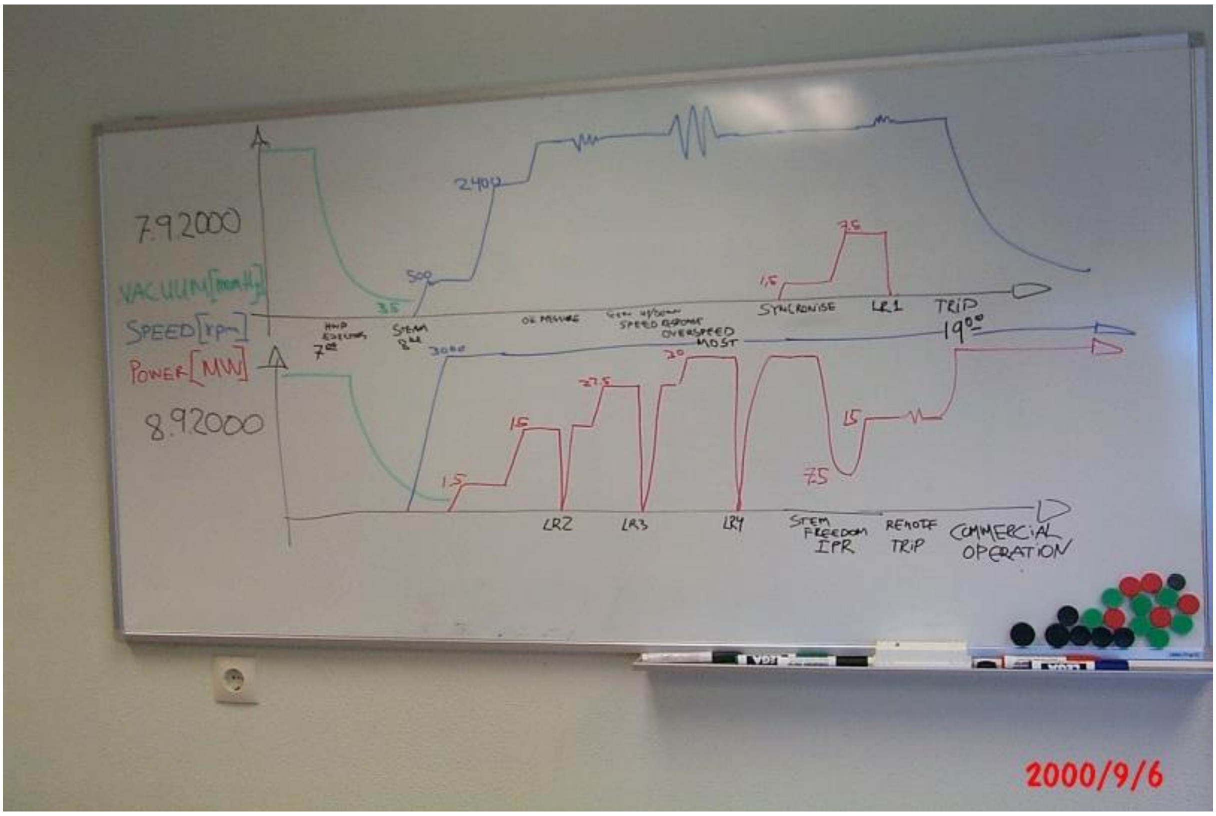

Figure 4: A typical sketch drawn up on a morning briefing (Krafla in 2000).

To monitor the progress, it is essential to maintain an electronic test database where all equipment and instruments are included. The database enables the team to mark which tests have performed and in case the test fails the team can put a remark on the cause and assign responsibility for fixing the problem. The database also facilitates reports on the status which show the progress and allows for groupings, such as equipment or signal types, locations etc., that enables the test team to monitor the progress and identify potential bottlenecks in commissioning.

For some tasks, an update of progress schedules will apply on the briefings. This might be true e.g. for the progress of tests in group B3 [Pre-testing of hard wired signals], with a database which is based on the plant's control system signal list.

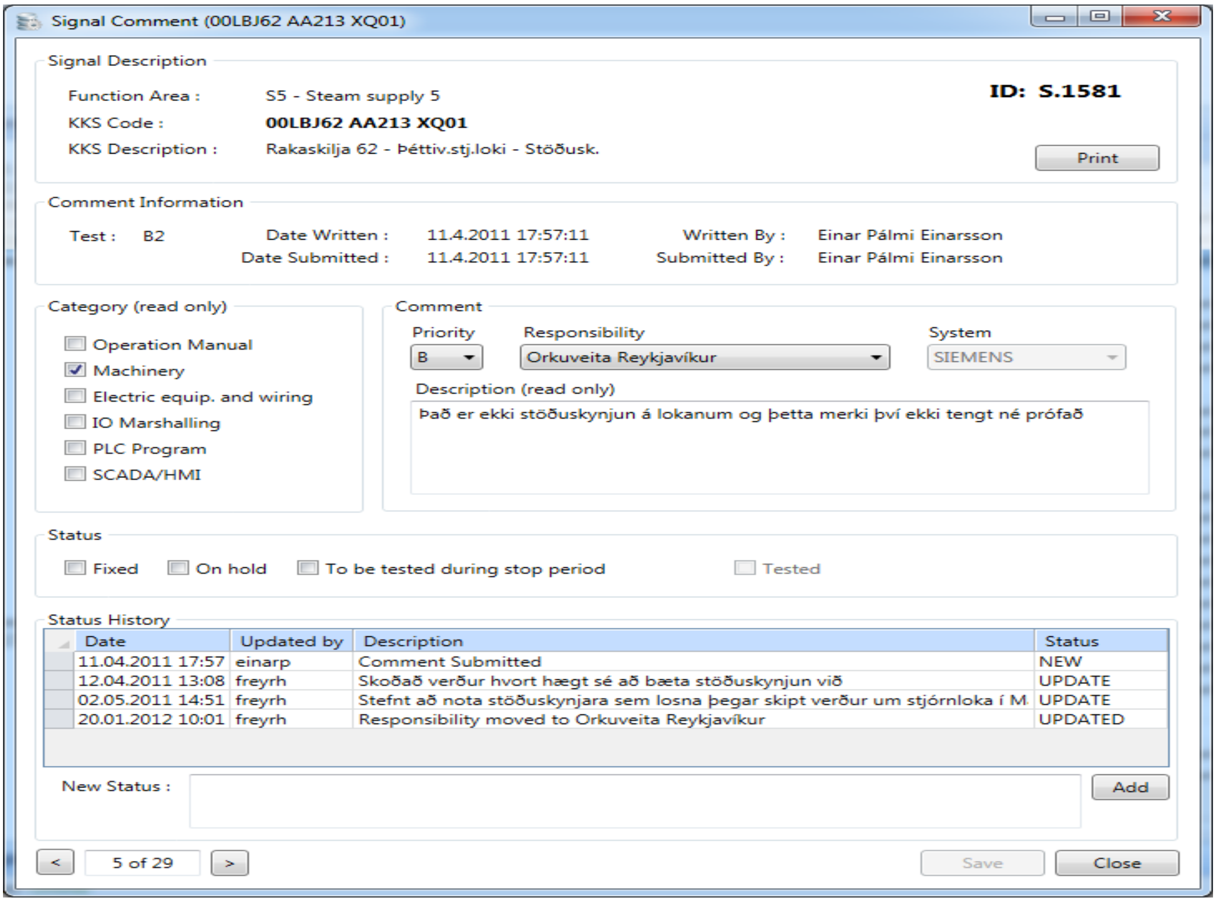

Figure 5: Database for tracking of test progress.

4. Commissioning test program

As stated above, geothermal power plants are in many aspects quite similar to conventional fossil fuel fired thermal power plants. However, they do differ in a few important points. For this article, the “conventional” test program will not be discussed in any detail. Instead, some items relevant specially for geothermal plants will be discussed. These do mainly apply for the actual commissioning part, i.e. tests in groups D1 and D2.

4.1 Steam supply

Prior to start of commissioning of the steam supply, all connected geothermal wells have been tested and measured to verify that they are able to provide the necessary pressure and flow needed for the plant. Furthermore, chemical analysis is necessary to determine the characteristics of the well, if there are risks involved with deposits, gases or corrosive content. Finally, before commissioning the wells should be exhausted to silencers for some time to minimize the amount of solid particles to the steam supply.

In power plants that utilize steam from flashed geothermal fluid, the steam supply is typically comprised of the steam wells, steam gathering pipelines, steam separators, steam pipelines, steam control valves, mist eliminators, reinjection pipeline and reinjection wells. The two-phase fluid from the wells is piped from the wells to one or more steam separators where the steam is separated from the water. The steam is then piped through mist eliminators to the turbine. Steam control valves are connected to the steam pipelines and vent the steam to steam silencers. The water from the steam separators is disposed of, either into reinjection wells or open pounds. The two main control functions, thereby the main potential sources of instability, are the control of the steam pressure and the control of the liquid level in the steam separators. The systems are coupled in such a way that changes in steam pressure will affect the liquid level in the separators.

The operation of the steam supply must facilitate the operation of the turbines at variable load and handle abrupt changes in the power output of the turbine/generator units without any delay in the operation of the units due to instability or transient behavior of the steam supply system. Thorough testing of the steam supply for all foreseeable events that can happen and tuning of the control functions to handle these events is important to prevent future failure of the steam supply.

4.3 Cooling water emergency supply test

Cooling water is essential for the operation of thermal power plants in general and even more so for geothermal power plants. This applies not only for the cooling of exhaust steam in condensers, but also for equipment cooling (e.g. generators, oil units etc.). Thus, it is of utmost importance to conduct thorough testing of these systems under various conditions, e.g. max. and min cooling water demand, redundancy testing to verify the system's functionality in the event of a power failure, equipment failure etc.

4.4 Dynamic testing of governor and Automatic Voltage Regulator (AVR)

In this chapter, the term "governor" is used for the regulating system for the rotational speed of the turbine units, measured in revolutions per minute [rpm] and active power output of the plant, designated with the letter P and measured in megawatts [MW]. Respectively, the abbreviation term "AVR" (Automatic Voltage Regulator) is used for the regulating system for the output voltage of the generator units, measured in kilovolts [kV] and reactive power output of the plant, designated with the letter Q and measured in Megavoltamperes-reactive [MVAr]. The power system stabilizer ("PSS") is an added feature to the AVR, intended to help maintain transmission system stability during- and following transient events.

As stated above, geothermal power plants are typically located in close vicinity of geothermally active areas and may thus be quite remote from the main load centers. This means that they may well be located in remote areas, where the high voltage transmission system is relatively weak and connections to the main grid may be vulnerable. This is e.g. true for most geothermal power plants in Iceland and many geothermal power plants in Africa, but less true for more densely populated and highly industrialized locations. Connecting a geothermal power plant to a weak high voltage transmission system will place a higher demand on the dynamic performance of governors and AVR systems.

Weak high voltage transmission systems ("HV-grids") will typically require the connected units to be increasingly flexible in the event of e.g. sudden changes of power demand, both increased (in the event of loss of generation and/or transmission lines) and decreased (loss of load and/or transmission lines). The physics of interconnected power networks are such that at any given moment, the generation must be equal to the sum of loads and losses. This is a constantly ongoing regulation process, mainly conducted by the governors of the connected power plants and keeping the system frequency at the nominal value (50 or 60 Hz). The governors will constantly measure the system frequency and react to changes, i.e. increase power output in the event of frequency drop and decrease power output in the event of frequency rise. The rate of this response will be different between units, i.e. large for peak load units and small for base load units.

The desired “normal” operation mode of geothermal power plants will typically be base load, with close to constant power output and thus constant steam consumption. This allows the power output setpoint to be slowly adapted to the steam conditions, so that the steam supply pressure regulating valves can be kept at an equilibrium with a very low opening position. This will maximize the utilization of the available geothermal steam and minimize the exhaust of geothermal gases into the atmosphere. However, the disadvantage is that under these operating conditions the plant is unable to deliver a sudden load increase in the event of frequency drop. Therefore, a compromise between these aspects must be worked out. If the geothermal units are connected to a relatively strong grid with many participating units, it may be allowed to operate as a base load. But if it is connected to a relatively weak grid with few participating units, it may be required to switch to a condition closer to peak load service and thus participating more actively in maintaining the system frequency. As described above, this feature will require some compromises in the utilization of the available geothermal steam and exhaust of geothermal gases into the atmosphere.

The response to frequency deviations on the grid must be tested thoroughly for geothermal plants, as these will affect i.e. the dynamic response of the steam supply system and eventually other systems (reinjection system, cooling water system etc.). This must be thoroughly co-ordinated with the grid company operating the high voltage transmission system. For full scale testing, frequency steps on the grid side must be generated by tripping other generators and loads. These tests will also involve the AVR system responses to system voltage deviations, including PSS for transmission system stability.

4.5 Black starting of plant and HV transmission system

Again, here it is important to remember that geothermal power plants will in many cases be located remotely from densely populated areas and connected to relatively weak HV transmission grids. For these reasons, the possibility of black starting of these plants is often required – allowing the plants to be started in the absence of power from the adjacent transmission grid. This may be required to maintain power supply to isolated loads, in the event of emergency due to time consuming failures in power plants or the transmission system. This is e.g. true for most geothermal power plants in Iceland, a country with very low population density, long transmission lines and long traveling distances, e.g. for repair work, supply of spare parts etc.

For the newest geothermal power plant in Iceland, extensive black start features were implemented on the design stage and even extended during the construction stage. At the center of all black start features is normally a diesel powered emergency generator, that is able to start automatically within seconds ($\leq$ 15 s) after a power outage and resume power supply to all auxiliary systems (DC supply for control and protection, lights, HVAC, cooling water supply, pressurized air supply etc.). The most important auxiliary systems must also be provided with sufficient storage capacity to be able to sustain supply until the diesel generator is started (e.g. batteries for DC supply and emergency lights, tank storage for cooling water and pressurized air).

With all essential auxiliary systems running but main turbine/generator sets still out of operation, the diesel generator must have sufficient capacity to start the most important generation support systems at lowest possible output. These will typically include the cooling water system (cooling tower circulation pumps, gas extraction system, oil system and a few other users). Normally, no cooling tower fans are required for starting of the turbine and operating at low (≤5%) power output.

Further, it must be possible to energize unit step-up transformers “from below” to allow energizing of the HV grid system. Normally this cannot be achieved by means of normal switching on from the generator side, as this would mean a too high stress of the generator due to inrush currents. Thus, the AVR system must be provided with a “soft start” feature for use only during such emergency situations and of course only with close co-operation with the HV-grid operator. For this function, the HV side circuit breaker must be opened and the generator circuit breaker closed, after the turbine has reached nominal speed but prior to energizing of the generator (voltage build-up). With these conditions in place, the AVR is switched on and the generator voltage is gradually built up to nominal voltage. In this way, the HV side of the step-up transformer will also gradually reach nominal value and allow energizing of the HV side grid system. Now, other parts of the HV grid can be connected, other generators can be started normally with power from the grid side and eventually the loads can be reconnected.

One complication is that the “black start unit”, i.e. the unit that was initially used for black starting, must now be “re-synchronised” with the rest of the system or alternatively shut down for reconnection after black start. This is due to the reason that the generation support systems of this unit will still be running on power from the diesel generator, which is running as an “electrical island” and thus not in synchronization with the rest of the grid.

All the features described above were tested extensively during the commissioning stage of Theistareykir power plant in Iceland, in good co-operation by the plant owner and -operators, the HV grid owner and -operators, specialists from various manufacturers and last but not least by the testing team provided by Mannvit-Verkis. All the testing involved extensive planning and co-ordination, preparations of all sides and proper manning of all positions by skilled engineers. The result was that it was confirmed by real life testing that starting of the plant without power from the HV-grid can be achieved. Thorough check-lists were prepared and reviewed and modified as a result of the tests. One important issue is that the plant operators were involved in the testing process from the beginning to the end and should be well prepared if/when the respective emergency conditions will occur, e.g. during difficult operating conditions (severe weather, heavy failures etc.).

4.6 Other tests

Other tests were also conducted by the testing team for Theistareykir power plant, including testing of safety interlocks, testing of system redundancy in the control system, testing of relay protection for generators and transformers, testing of redundancy of mechanical systems etc. These tests are not different from tests in other types of power plants, but are mentioned here to stress that the testing team of Mannvit-Verkis is trained and equipped for extensive testing of all power plant components and systems. For some specialized equipment, the participation of specialists from manufacturers is required. This applies e.g. for governors, AVRs and diesel generators, whereas these specialists work under the governance of the testing team and are required to provide thorough site training for operators and provide all related operation- and maintenance documentation.

5. Conclusions

In the previous chapters, it has been discussed how important it is to conduct thorough testing of geothermal plants, through all phases but specially during the final commissioning. An important aspect in this respect is the availability of skilled engineers to conduct the planning, preparations and finally the execution and documentation of these tests. Experience, along with proper training, appropriate test equipment and other means for the testing team is essential for successful results. Skills in organization, planning and co-ordination between stakeholders is also an important aspect. Finally, it is of vital importance to have the willingness, support and participation from the plant owner and plant operators for conducting a thorough test program during the commissioning stage, instead of pushing for commercial operation too early. The time, effort and cost involved in thorough testing should be viewed as an investment in a far more stable future operation of the plant.

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