



STUDY OF GEOTHERMAL POWER PLANT ELECTRICAL AND CONTROL SYSTEM WITH EMPHASIS ON RELIABILITY ASPECTS

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ABSTRACT

The main aim when constructing and installing electrical and control systems for a power plant is to have continuous and trouble free operation of the plant. Geothermal power plants are very different from hydro power plants. It is difficult to restart a geothermal power plant after shutdown and it is exposed to H₂S corrosion. This report emphasizes plants using the binary process. The electrical system of a geothermal power plant is described, including generator, power transformer, different alternatives for switchgear configuration, protective relaying, auxiliary power supply and instrumentation. The control system configuration is described along with its effect on reliability. Operation and maintenance aspects are discussed, and both the reliability and H₂S corrosion prevention aspects are discussed. Finally, the electrical and control systems in the Aluto-Langano geothermal pilot power plant are included as an example.

1. INTRODUCTION

Geothermal energy is a proven resource for direct heat and power generation. In over 30 countries geothermal resources provide directly used heat capacity of 16,000 MWt (Lund and Freeston, 2000) and electric power generation capacity of over 8,000 MWe (Huttrer, 2000). It meets a significant portion of the electrical power demand in several developing countries. The geothermal resources can be divided into low- and high-temperature systems depending on the temperature of the reservoir. The high-temperature geothermal resource can be utilized for electricity production. The utilization is mainly achieved by direct-steam or flashed steam installation. On the other hand, from low-temperature geothermal resources it is also possible to produce electricity by applying non-conventional methods of geothermal power generation, such as binary cycle generation.

In this report, the control and electrical system of a geothermal power plant is discussed, with emphasis on a binary cycle plant, like the one already in operation in Ethiopia (Bronicky, 2000). The binary cycle consists of a separate closed cycle, which uses an organic compound as a working fluid (Organic Rankine Cycle-ORC), receives the input heat from geothermal brine and releases output heat into a suitable heat sink. The geothermal brine is passed through a heat exchanger to heat up the organic compound which,

having a low-boiling point, is vaporized before entering a turbine.

Ethiopia is one of the African countries that has a large amount of waterfalls in the high mountains but has also considerable geothermal resources. The electricity supply is mostly from hydro power generation and in some parts of the country from thermal energy. The rivers are season dependent and the price of oil is rising. Thus, an alternative energy source is important to compensate for the shortage of electrical power (Aquater, 1979). Geothermal exploration in Ethiopia has been in progress since 1970 and to date. Prospects have been identified with an estimated 700 MWe potential. The three most intensely explored areas are Aluto-North, Langanjo and Corbetti in the Lake District, and Tendaho in the central Afar region. At Aluto-Langanjo, a geothermal pilot power plant was constructed by Ormat under a turnkey contract of Genz (EPC) and has been operational since 1998. It is the first geothermal power plant in Ethiopia with two units that are operating by combined steam and binary fluid.

The electrical system of a geothermal power plant needs much attention during the design process. The control system automation has a wide span of techniques and technologies. For reliable operation of the geothermal power plants, nowadays the control system is important. The vast development of PLC systems for plant control makes both local and remote mode of operation possible.

2. ELECTRICITY GENERATION FROM GEOTHERMAL ENERGY

In geothermal power plants, steam or hot water from geothermal reservoirs provides the force that drives (rotates) the turbine and generator to produce electricity. The used geothermal water is then returned down an injection well into the reservoir to be reheated, to maintain pressure, and to sustain the reservoir or can be used for district heating. There are three kinds of geothermal power plants, depending on the temperatures and pressures of the reservoir (Kestin et al., 1980).

- Dry steam reservoirs produce steam and very little water. The steam is piped directly into the power plant to provide the force to spin the turbine, which is coupled to drive the generator in order to produce electricity. The temperature and pressure of the reservoir should be high enough to boil the fluid at the wellhead. These kinds of reservoirs are not common.
- A geothermal reservoir that produces mostly hot water is called a hot water reservoir and is used for a flash power plant. Hot water is brought up to the surface through the production well where, upon being released from the pressure of the deep reservoir, some of the water flashes into steam. The steam is then separated from the water in the separator, and powers the turbines and generator for electricity production.
- A reservoir with low and medium temperatures is not hot enough to flash enough steam but can still be used to produce electricity in a binary power plant. In a binary system the geothermal water is passed through a heat exchanger, where its heat is transferred into a second (binary) working fluid, such as isopentane, that boils at a lower temperature than water. When heated, the binary liquid flashes to vapour, which, like steam, expands across and spins the turbine blades. Then, the working fluid in the vapour state is recondensed to a liquid and reused repeatedly. In this closed loop cycle, there are no emissions to the air (Ormat, 2002).

3. THE BINARY PLANT PROCESS

For moderate temperature water, binary cycle technology is generally most cost effective. In these systems, the hot geothermal fluid vaporizes a secondary or working fluid, which then drives a turbine and generator. Selection of a working fluid is an important task in designing a binary plant; usually the working fluids are isobutene or pentane. The following points are important when selecting the working fluid (Sagun, 1992):

- The thermal characteristics required for the binary system are satisfied;
- Adverse effects on environments are negligible;
- Adverse effects on human body are negligible;
- Handling is easy such as non-inflammable and non-explosive;
- Properties are stable.

A binary power plant is a cycle designed for utilizing moderate temperature geothermal resources. The binary plant is like the steam turbine, but uses a working organic fluid, which has a lower boiling point than the geothermal fluid. It is based on the Rankine power cycle (Figure 1).

The cycle starts by heating the organic fluid followed by vaporization of the fluid to steam in order to drive the turbine. The Rankine-cycle fluid, usually a hydrocarbon chosen according to

heat source, is heated and vaporized in a heat exchanger by heat transfer from the geothermal water. The pressurised vapour expands through the turbine blades from which mechanical energy is produced to rotate the generator shaft in order to produce electrical energy (Keio and Shojiro, 2000). The exhaust vapour from the turbine is passed to a condenser where it is cooled and condensed to a liquid by cold water or natural atmospheric air or by cooling fans. The organic fluid is condensed and pumped back to the vaporizer by the feed pump to recycle the working fluid. The cycle will continue as long as there is no leakage, thus leakage detectors are important in this system.

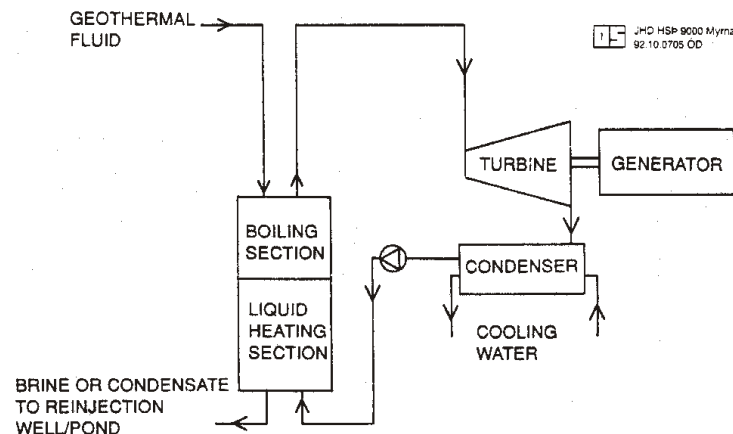


FIGURE 1: Schematic diagram of binary cycle with geothermal fluid as heat source (Sagun, 1992)

3.1 The ideal Rankine cycle

The basic Rankine cycle is presented schematically in a Ts diagram in Figure 2. The ideal simple Rankine power cycle consists of the following:

- Isentropic compression in a pump;
- Constant-pressure heat addition in a boiler;
- Isentropic expansion in a turbine;
- Constant pressure heat removal in a condenser.

The heat added in process 2-3 is from low-temperature geothermal fluid or any other low-temperature source such as fossil fuel. In the ideal case, all losses are negligible; the heat transfer to the working fluid is presented on a Ts

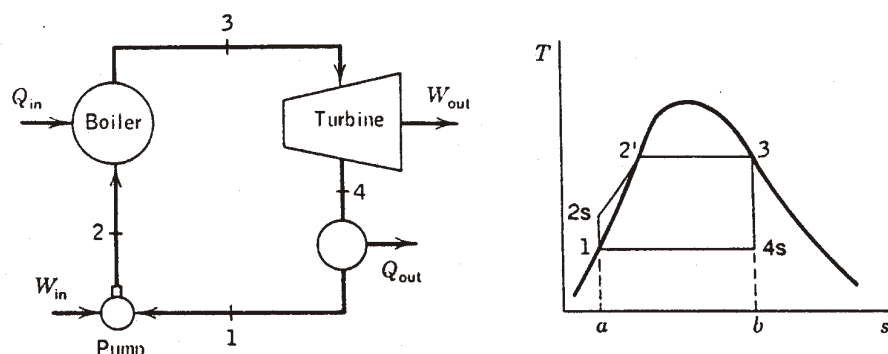


FIGURE 2: Schematic flow diagram and a Ts diagram of an ideal Rankine cycle (Wark, 1988)

diagram by the area enclosed by states 2s-2'-3-b-a-2s. The area enclosed by the states 1-4s-b-a-1 represents the heat removed from the working fluid inside the condenser. For an ideal case, the first law for an open cyclic process indicates that the heat energy lost by the working fluid inside the turbine is the work done. Thus, the net work done is represented by the difference in the areas for the net input and heat rejection, i.e., the area under 1-2s-2'-3-4s-1.

The thermal efficiency η_{th} the cycle is defined by Equation 1 (for definition of variables see Nomenclature) as

$$\eta_{th} = \frac{W_{net}}{Q_{input}} \quad (1)$$

Efficiency is a parameter used to measure the effectiveness of any cyclic heat-work converter. Expressions for the work and heat interactions in the ideal cycle are found by applying the steady flow energy equation. The basic equation for each process considering an ideal case, reduces to

$$q + w = h_{out} - h_{inlet} \quad (2)$$

The isentropic pump work is given by

$$w_{input,pump} = h_2 - h_1 \quad (3)$$

The pump work is also frequently determined within the desired accuracy from the relation

$$w_{input,pump} = v_f (P_2 - P_1); \quad s_1 = s_2 \quad (4)$$

where v_f is the saturated-liquid specific volume at state 1.

The heat input q , the isentropic work output from the turbine w , and the heat rejection in the condenser q , all on a unit-mass basis, are

$$q_{input,boil} = h_3 - h_2; \quad P_3 = P_2 \quad (5)$$

$$w_{out,turbine} = h_3 - h_4; \quad s_3 = s_4 \quad (6)$$

$$q_{out,cond.} = h_4 - h_1; \quad P_4 = P_1 \quad (7)$$

Thus the thermal efficiency of an ideal Rankine cycle may be written as:

$$\eta_{th} = \frac{w_T - w_P}{q_{input}} \quad (8)$$

3.2 The irreversible Rankine cycle

The cycle discussed above is an idealized process of the conversion of heat to an equivalent amount of network output. But the thermal efficiencies of the actual Rankine cycle are less than that assumed in the above equations. The effect of irreversibility on vapour-power-cycle performance can be seen in Figure 3. The Ts diagram in Figure 2 has been modified and represents the actual Rankine cycle. In all cases there are some losses such as frictional,

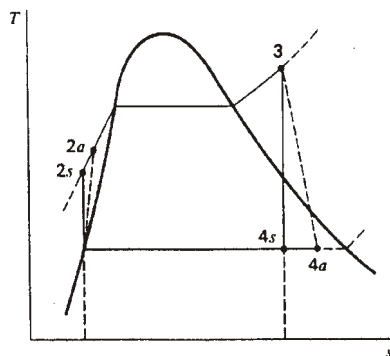


FIGURE 3: The Ts diagram of a power cycle with irreversible turbine and pump performance (Wark, 1988)

potential, kinetic, etc. throughout the equipment that make the process irreversible. Then, Equations 3, 4 and 6 in the ideal cycle must be corrected by a factor known as the isentropic or adiabatic efficiency, η .

The isentropic turbine efficiency η_T is defined as the actual work output w_a to the work w_s that could be achieved while expanding isentropically to the same final pressure. This is expressed as

$$\eta_T = \frac{w_a}{w_s} \quad (9)$$

From Figure 3, if the kinetic energy loss across the turbine is negligible, the isentropic efficiency can be approximated by

$$\eta_T = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \quad (10)$$

Similarly for the pump, or the same initial state, and the same final pressure

$$\eta_P \approx \frac{w_s}{w_a} \quad (11)$$

$$\eta_P \approx \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad (12)$$

4. ELECTRICAL SYSTEM

4.1 Introduction

The electrical system of a power plant includes generator, transformer, transmission line circuit breakers, switchgear/substation, instrumentation system, protection system and control system. The following diagram (Figure 4) illustrates the main part of a typical turbine generator. Most often geothermal power plants are sited far from consumers. Hence, on designing a geothermal power plant electrical system, great attention should be paid, especially to the transmission line system and the effect of stability on the existing network system.

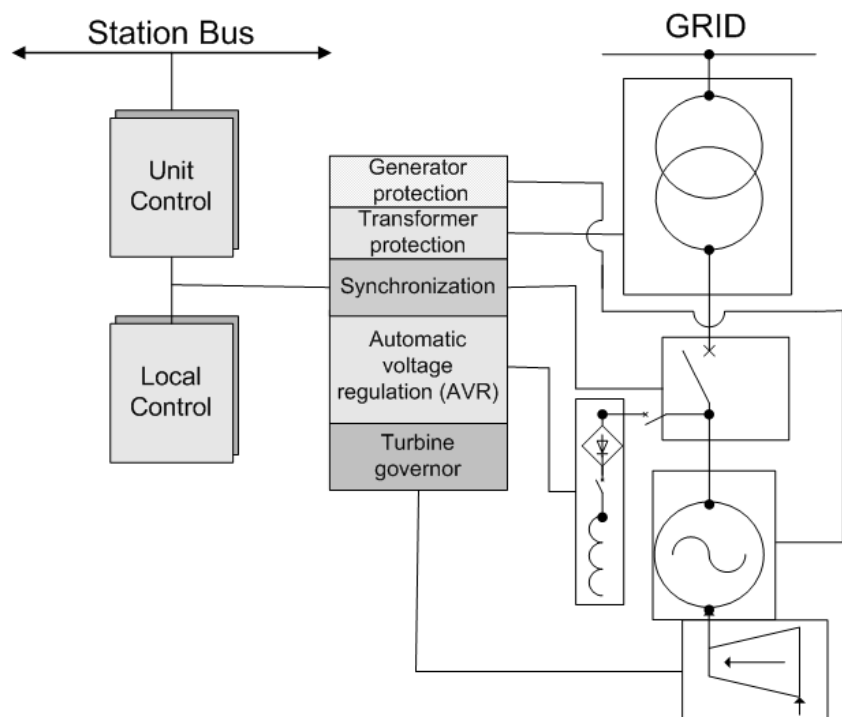


FIGURE 4: Unit control and protection of a typical turbine generator

4.2 Generator

The purpose of an electrical generator is to produce electrical energy to some load but it must do so within specified operating limits of frequency and voltage. When it operates in isolated mode it is responsible for determining these parameters but when operating in parallel mode with other generators it generally has only limited control, and the required mode of operation can be as significant as the electrical load being supplied.

The load behaviour affects the generator requirements. But the power system environment condition, the characteristics of the prime mover and the generator control systems are all relevant to the actual generator performance during steady duty or rated conditions and also during transient, sub-transient, pre-transient and all dynamic conditions encountered.

4.3 Power transformer

The terminal voltage of the generator is medium voltage and power plants are often located far from consumers. Hence, to decrease transmission line loss I^2R , the current magnitude must be reduced to a minimum value. Power transformers are equipment that convert medium voltage to high voltage with some core and winding losses. The capacity of the transformer is the same as the generator and characterised by rated MOA, voltage and current capacity.

Different types of transformers are available depending on the use and place of installation. The cooling system and type of tap changer are important for selecting a transformer type. Based on the cooling system, transformers are divided as forced air cooled, forced water-cooled or natural air-cooled. To adjust the fluctuation of voltage, power transformers often have tap positions and can be on-load or off-load tap changers. The equipment is sensitive to voltage fluctuations; therefore, transformers with on-load tap changers are common now. Figure 5 shows the use of transformers.

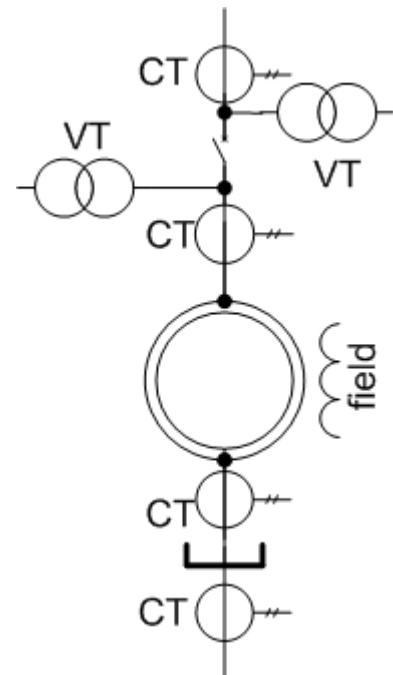


FIGURE 5: Simple generator with instrument transformers

4.4 Switchgear, substation and circuit breaker

The generator needs to connect and disconnect from the system during malfunctions and maintenance periods. This can be achieved with either *generator* switchgear or a *separate* substation, depending on the loads connected in the system at that point. Generally, there are different kinds of substations depending on the voltage, the space available, the equipment to be used, etc. Some of these are outdoor air insulated substations, outdoor gas insulated substations, and indoor gas insulated substations. Of these, the outdoor air insulated one is the cheapest, but it needs six times more space than gas insulated substations. As outdoor space is usually not a problem in geothermal plants, air insulated outdoor substations can be constructed. But attention should be paid to sulphite corrosion in copper materials used in the substation. In some places salt contamination from the sea can cause problems in outdoor, air insulated switchgear. The following items are important in designing the substation:

- Number of high-voltage transmission lines;
- Number of bus bars;
- Number of generating plants;
- Required reliability;
- Budget;
- Transmission company requirements.

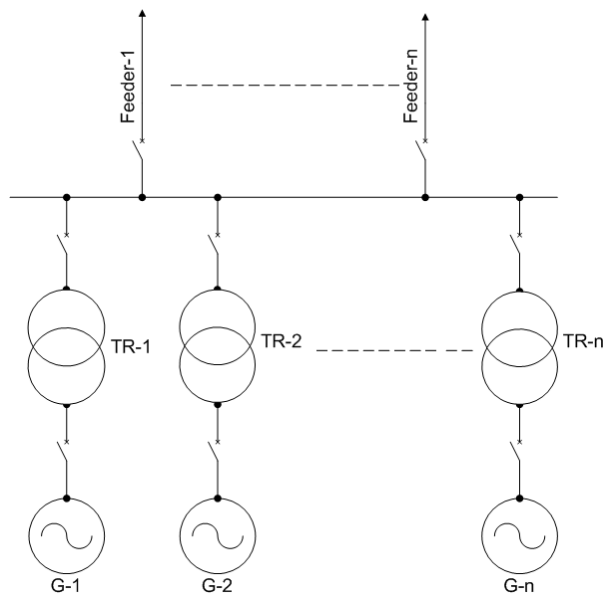


FIGURE 6: Single bus bar

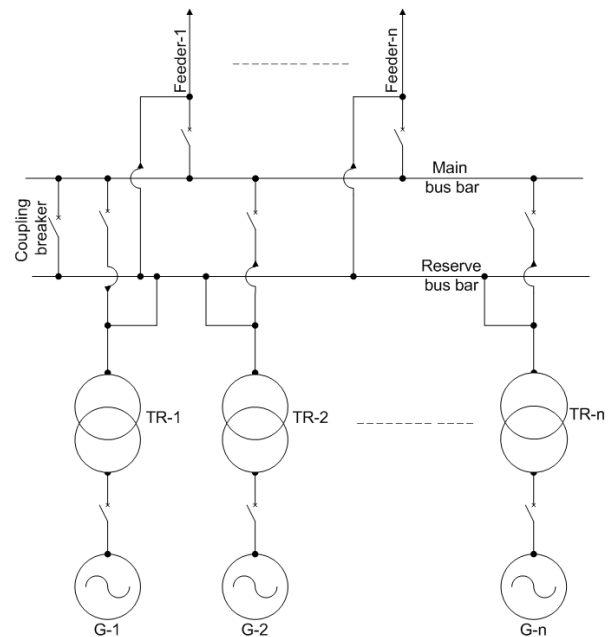


FIGURE 7: Main and reserve bus bars system

The switchgear can disconnect the generator from the grid with a full load in case of emergency shutdown. Different kinds of switching equipment are available such as metal clad, vacuum circuit breaker, minimum oil, etc. For indoor switchgear, metal clad breakers are convenient, as they take little space upon installation.

The diagram in Figure 6 illustrates a simple single bus bar substation. Compared with other types of substations, a single bus bar substation is cheapest, least reliable, and difficult to maintain.

In a two bus bars systems, the reserve bus bar is used in case of a normal breaker failure (Figure 7). It is more reliable compared to a single bus bar system, but complicated to operate and expensive compared to a single bus bar system due to the coupling breaker.

A double bus bars substation is the most reliable, and is easy to operate (Figure 8). The following are advantages and disadvantages of a double bus bars system:

- Most expensive;
- Most reliable;
- Easy to maintain breakers without interrupting production;
- Simple to operate;
- Easy to divide to limit short circuit current;
- Easy to divide the system load into two groups with separate voltage control.

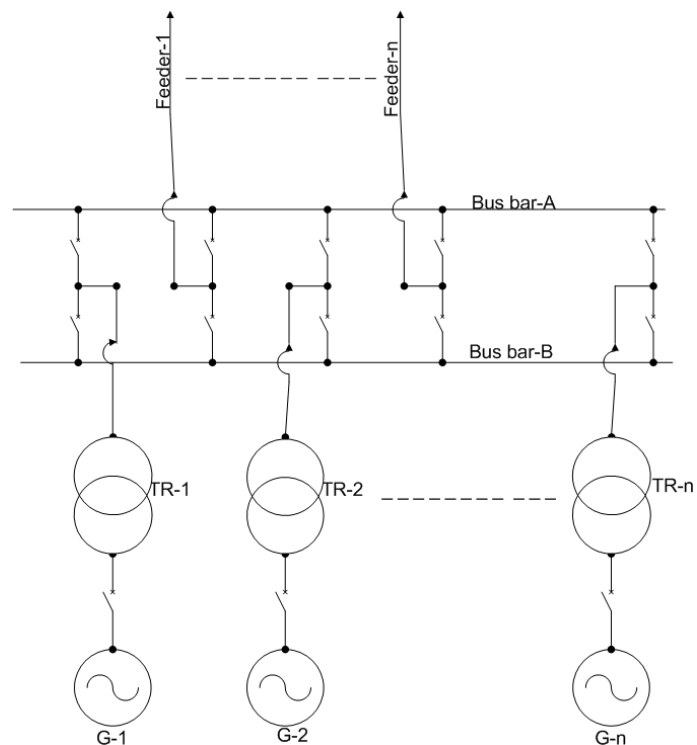


FIGURE 8: Double bus bars system substation/switchgear

4.5 Protection relays

Protection equipment is normally provided to reduce the consequences of an electrical failure or fault and plant damage. As the plant can operate in small or large systems, the protection is designed to be suitable for any system. This enables protection schemes to be developed for specific sets of standard conditions related to a fault and these are often treated as independent non-interactive systems dealing with specific electrical units such as generators, transformers, distributions, etc.

Based on the type of equipment and how important it is, different types of protection relays can be utilized. The most common relays are over current, differential, over voltage, under impedance, distance protection relay, reverse power, etc. Protection relays operate when there is fault in the system or in each piece of equipment for which the relay is selected to protect. Relays are designed so that they can carry the fault current without damage and withstand the voltage without damage to their insulation (Blackburn, 1976).

Over current relay 32 is used to protect generators, transformers, and general electrical equipment, which need careful protection from overload. It can be instantaneous, operating immediately as the fault occurs or on inverse time, depending on the magnitude of the fault current. Typical values for multirange inverse time over current relays are:

Standard inverse time: $t = 0.14 / (I^{0.02} - 1)$ sec
 Highly inverse time: $t = 13.5 / (I - 1)$ sec
 Extremely inverse time: $T = 80 / (I^2 - 1)$ sec

Differential relays 87 and 88 are mostly utilised to protect generators and transformers, as this equipment is expensive and time consuming to replace when damaged. These relays operate if there is an internal short circuit inside the equipment by comparing the incoming and outgoing current to and from the equipment. The conventional relay consists of an operating coil and restrained coil. When the differential current exceeds a set value, the operating coil energizes and gives impulse to the tripping coil of the switchgear.

Nowadays microprocessor based protection relays are becoming popular, so that it is possible to protect a generator or transformer by a single multi purpose relay. A microprocessor-based relay also provides back-up protection. Hence it is more reliable, accurate and fast responding.

Instrument transformers (CTs and VTs) in Figure 9, are used to protect personnel and equipment from high voltage and current. These transformers, namely voltage and current transformers, step down the system or generator voltage and current to reasonable values that do not damage the insulation and over heat the equipment.

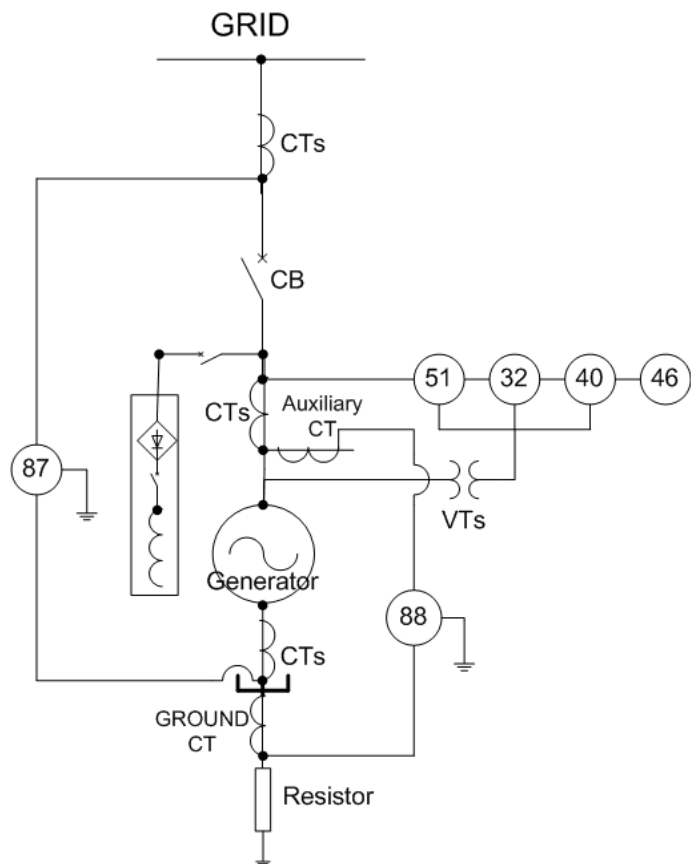


FIGURE 9: Schematic diagram of a protection and measurement system in a typical geothermal binary plant

The step down value is convenient for the protection relays and measurements. Instrument transformer performance is critical in protective relaying, since the relays are dependent on the output value of the instrument transformers. The common outputs for the secondary instrument transformers are 100 Volt and 5 or 1 Ampere. Figure 9 shows a simple generator with its circuit breaker (CB), current transformers (CTs), potential transformers (VTs), differential relays (87 and 88), field breaker, shunt exciter, over current and over voltage relays (32 and 51), and meters 40 and 46.

4.6 Auxiliary power supply

Power supply is necessary for the plant auxiliary equipment, control room and steam field equipment during generator off-line situations, generator start-up, normal generating situation or generator run down. This power is usually obtained via an auxiliary transformer supplied from the electrical system. If the power station is disconnected from the system, and there is no isolated generation occurring, there will still be a requirement for auxiliary power to operate such things as turbine/generator main lubrication oil pumps, steam field reinjection pumps and essential control room power during the turbine run down period.

There has to be an alternative source of auxiliary power, apart from the DC battery and system connection, for start-up, run-down and off-line situations. A low voltage supply from a local power utility or an emergency generator with automatic start-up and change-over to supply a dedicated LV emergency service motor control centre and the control room is the norm.

Emergency generators are not usually rated for black start situations where the auxiliary load requirements are large. For black start situations an appropriately sized standby diesel generator with automatic start-up should be included during project design. The diagram in Figure 10 shows an auxiliary power supply from two generators with a double bus bar and a standby diesel generator. The diesel generator starts automatically when both of the generator supplies are disconnected.

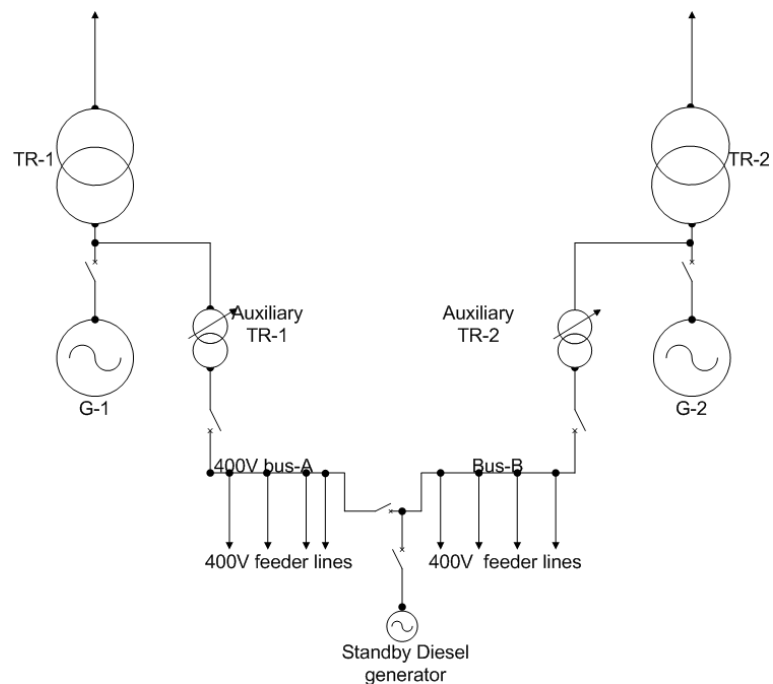


FIGURE 10: Auxiliary power supply from two generators and a standby diesel generator

4.7 Earthing

Geothermal power stations and the associated substation and steam field distribution system will always require some form of buried earthing system. The purpose of the earthing system is to

- Enable electrical equipment protective devices to operate correctly;
- Make the site safe for people under electrical fault conditions;
- Make the site safe for sensitive electronic equipment, under electrical fault condition (Parkin and Grant, 2000; Hunt, 1998).

5. INSTRUMENTATION

Instrumentation in a power plant is important and plays a major role for a safe and efficient operation. Mostly instrumentation is related to the control system of the plant. In power plants different parameters need to be measured and monitored whether they are within the limit or not. In geothermal power plants, measurements are taken for proper operation of the plant and for environmental protection (Jervis, 1993).

For environmental impact, chemicals such as hydrogen sulphide (H_2S) should be monitored. It should not be in excess, endangering personnel health and possibly causing electrical equipment damage. On the other hand, for the plant operation, pressure, temperature and flow measurement is necessary. There are limits and constraints for normal operation and for minimum impact on the environment. Turbine and generator instrumentation is also an important aspect in an electricity generating plant. The measurements in this case include, but are not limited to, the following parameters:

- Turbine – generator vibration and centring;
- Bearings oil level and temperature;
- Oil level and temperature in the gearbox;
- Temperature in the stator core and winding and rotor compartment;
- Active and reactive power of the generating unit, the reactive power is especially important so the generator will not fall out of synchronisation;
- Finally, generator voltage, current, and frequency is also important.

The control and instrumentation systems provide the following for the plant operation:

- Maintain adequate margins between operating conditions and safety and operational constraints;
- Automatically, shut down the plant if important constraints are violated;
- Monitor the margin from constraints and normal plant operation and provide immediate information and permanent records for subsequent analysis;
- Draw the attention of the operator, by effective alarm system of the monitoring system, to any unacceptable reduction in margins so that the operator can take appropriate remedial action.

Instrumentation systems can be standard, custom made, digital or computer-based depending on how old the system is and on the data to be recorded, the point where the data can be taken, and the form of the data to be processed. Normally, the measurements are either analog or digital. Digital instrumentation systems make the data easy to transmit and process and is the norm today. Figure 11 shows an example of an instrumentation system in a geothermal power plant.

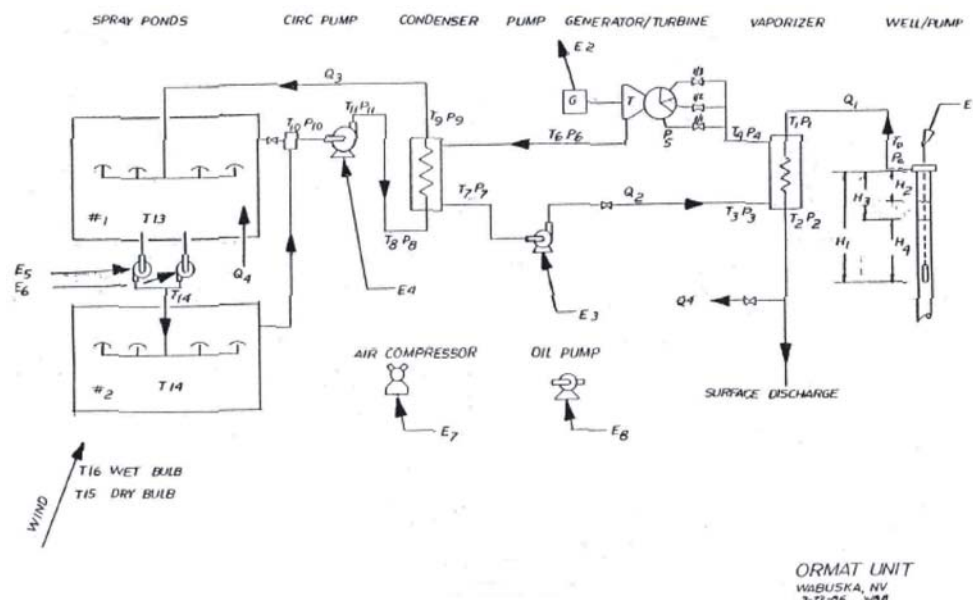


FIGURE 11: Instrumentation system of a geothermal plant (Culver, 1986)

6. CONTROL SYSTEMS

In a control system the input signal is used in some form or another to control the output variable. The control path can be either open loop or closed loop. In an open loop control system the input signal is controlled to provide an output signal of some desired value. For example, suppose the variable output of a room heater is controlled by a knob marked with the desired room temperature. Under the conditions of calibration the room temperature will be the desired temperature. If the calibration conditions are changed, such as a window is opened or the amount of heat decreased or the outside atmospheric temperature increases, then the room temperature will not be corrected. This can be corrected only by recalibrating the control system.

In the case of a closed loop control system, the output signal as feedback is added to the input signal for comparison. The comparator compares the output signal with the desired input signal and if there is a difference the control signal force the output signal to come back into line.

Generally, in an open loop control system, the input signal is independent of the output signal but is a function of calibration, whereas in a closed loop control system the input signal is influenced by the output signal as the output signal, can be varied by environment and external conditions. The schematics in Figures 12 and 13 show simple open loop and closed loop control systems.

The diagram in Figure 14 illustrates the control system of a power plant with automated control equipment, field bus, and local and remote control

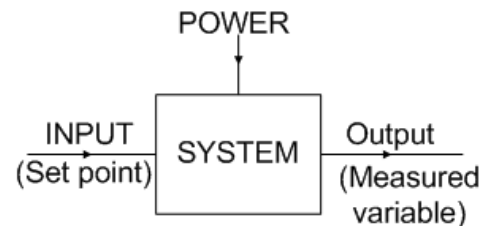


FIGURE 12: Open loop control system

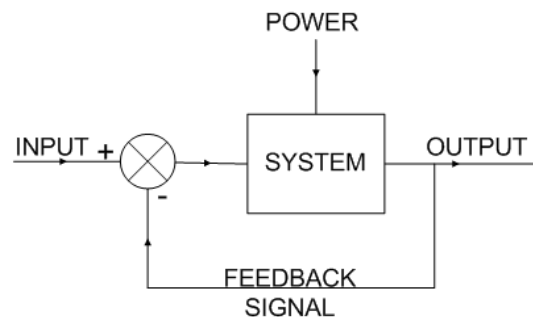


FIGURE 13: Closed loop control system

configuration. This organized control configuration enables the operation of the plant from different points of control.

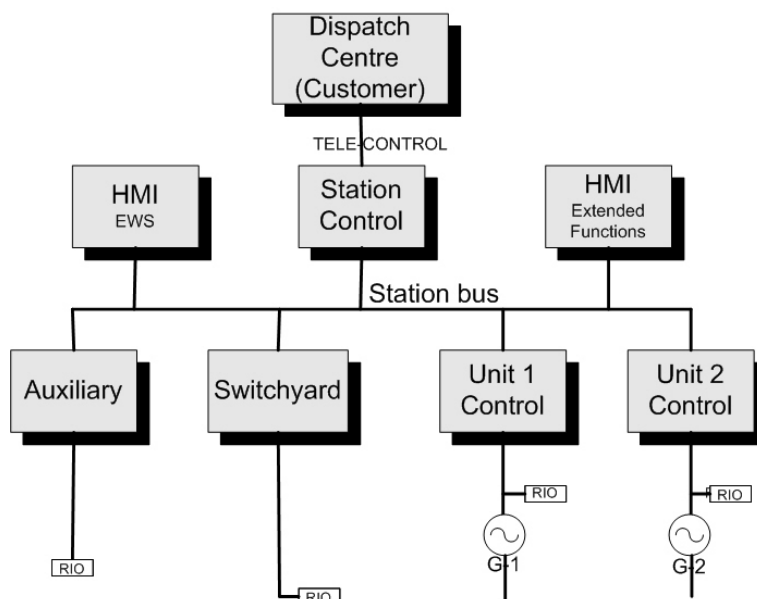


FIGURE 14: An overview of control system

6.1 Control system configuration

The control system configuration of a modern power plant is based on advanced electronics. Some key components are a SCADA system, computers, modem, transmitter, receiver, programmable controllers, etc. Recent technologies avoid usage of repeaters for transmission of data to a long distance. The configuration of the control system is designed for fast response, to a higher level of monitoring and control, proper data acquisition and

transmission. The configuration of the control system interconnected by fiber optics as in Figure 15 with different control station enables flexible operation of the plant. The SCADA package and PLC can be

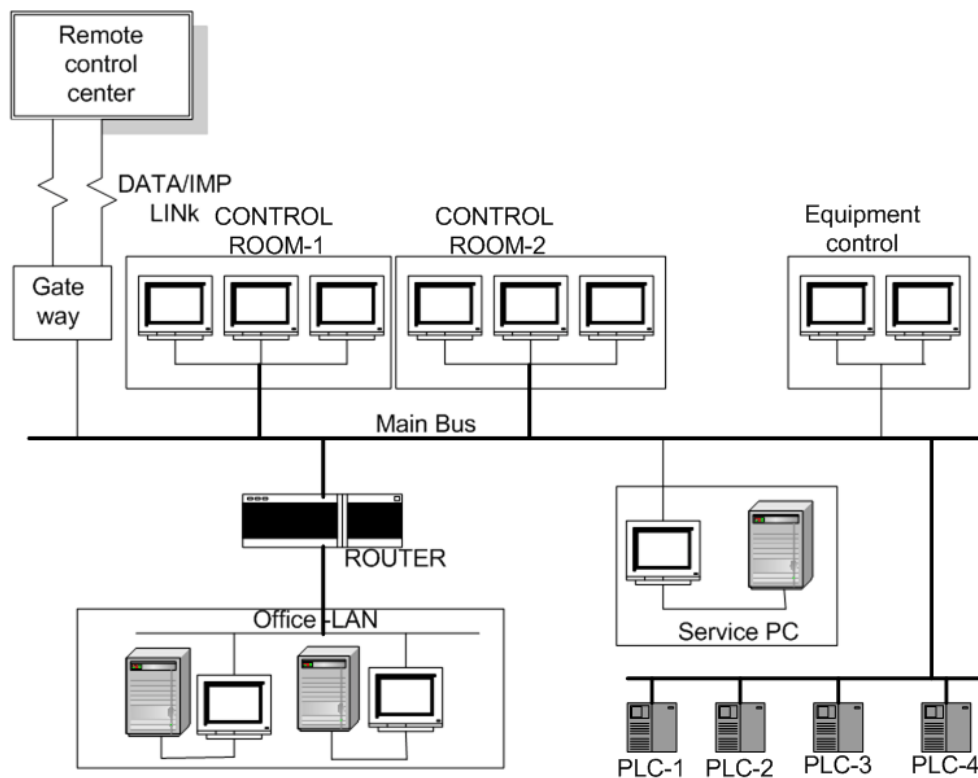


FIGURE 15: SCADA system hardware with PLC controllers

chosen and can be designed as a single control system. In addition to the plant system, other plant systems such as the exhaust fan, fire protection, compressors, etc. can be integrated into the system (Magnússon and Gunnarsson, 1989; Gunnarsson et al., 1992).

6.2 Hierarchical structuring of the control system

The control system in any power plant is one of the key parts of the plant. In geothermal power plants the control system can be split into three different levels; as remotely controlled station, local/station and backup/equipment control (see Figure 16). For reliable operation, these three control systems or levels should be in continuous operation, in case one fails. Most often the plant is controlled by a remote control

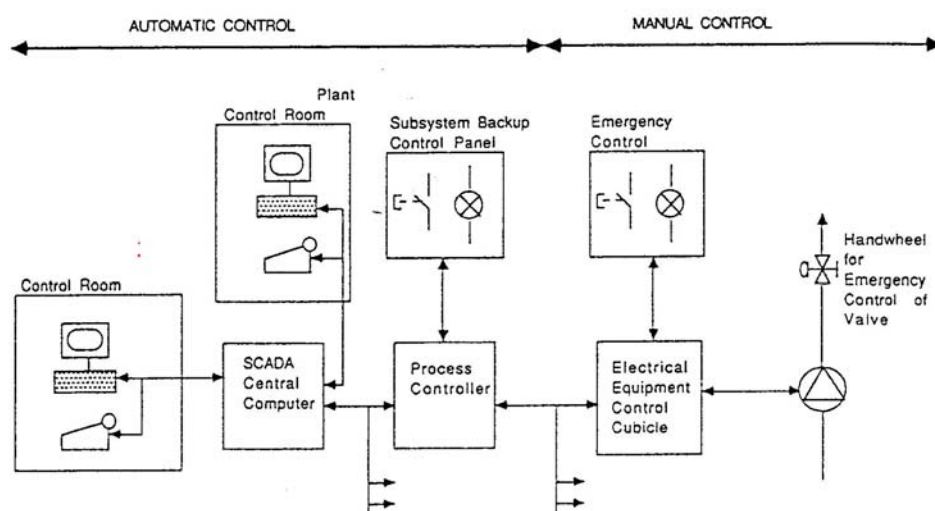


FIGURE 16: Control system hierarchy

system, as geothermal power plants are often located in inconvenient places. The local/station control system is usually a copy of the remote control system except the location. The back-up is operative in case both the remote and the station systems are not functional. Hence the back-up is used in an emergency case and is simpler.

6.3 Control system redundancy

Sometimes manual control is difficult or cannot be applied to an operation when the main control system fails. A standby or redundancy control system is, therefore, important for reliable and uninterrupted operation of the plant. In geothermal power plants, control equipment for the steam and heat exchanger subsystem cannot be controlled manually, as they are too fast to control manually. Automatic control system is therefore necessary (Emanuel, 1965).

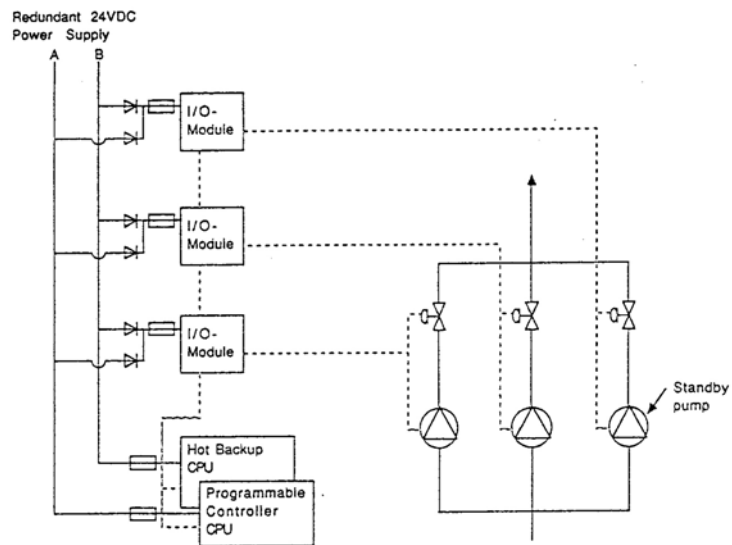


FIGURE 17: Control system redundancy

The diagram in Figure 17 shows typical control redundancy for pumps. The standby pump starts automatically when one of the main pumps fails. The configuration of the I/O modules takes into account redundancies. If one I/O module fails, only one pump will be unoperational. Common control system components, such as a power supply and even PLC CPUs can also be made redundant for critical plant systems.

7. OPERATION AND MAINTENANCE

7.1 Hydrogen sulphide corrosion

Corrosion in a geothermal environment from hydrogen sulphide is a continuous problem. Large heavy copper current carrying items like bus bars, clamps and conductors are exposed outdoor and particularly vulnerable. Other items exposed to this type of problem are multi layered flexible copper straps used for connections in outdoor HV disconnecter switches and for flexible connections of bus bar. Corrosion of cadmium plated mild steel items, like nuts, bolts and washers will produce highly toxic residue. Indoor electrical equipment, particularly electronic printed circuit boards with plug-in copper connections associated with control, instrumentation and protection equipment are also particularly vulnerable to corrosion and failure. The following methods help to overcome outdoor electrical equipment problems:

- Use of tinned and epoxy painted bulk copper;
- Use of corrosion resistant materials such as aluminium and stainless steel;
- Use of heat shrink material on exposed copper;
- Use of tinned copper wires;
- Varnishing and painting indoor items;
- Epoxy encapsulation of small components;

- Careful selection of paint systems and sealing gaskets;
- Mild steel galvanising and epoxy painting.

For indoor electrical equipment the following applies:

- Specification of H₂S rated instruments and connections;
- Specification of gold plating on printed circuit board connections;
- Placing all sensitive equipment in a positive pressurised and H₂S filtered room and controlling the temperature and humidity;
- Provision of control cubicles with anti-condensation heaters.

7.2 Daily operation, maintenance and monitoring

The primary concern with a geothermal power plant is to produce electricity without interruption and failures. To have a good and long life for the equipment and materials in the plant, there should be scheduled procedures for daily operation, maintenance and monitoring. These include data recording, unit start up and stop, checking oil levels in the gearbox, bearings, condition of pump temperatures, etc.

The power plant can be operated manned or unmanned depending on the control system configuration. Remote operated power plants are unmanned during the night but there should be daytime staff for monitoring and maintenance in the plant. For continuous operation and maximum availability of the plant, planning of monitoring and maintenance tasks is important and is necessary to follow strictly. The staff will operate equipment, oversee production and respond to emergencies, and monitor regularly and maintain both the power plant and the well field. It is important if possible, for the plant staff to participate in the design process, installation, commissioning and, in general, plant construction. Involvement of the operational and maintenance staff provides practical feedback to ensure the plant design configuration and control system is acceptable. This participation is the best training opportunity the staff will get. And it helps them in troubleshooting in case of equipment failure during operation and maintenance (Bell, 1988).

7.3 Remote control and monitoring

Geothermal power plants are mostly located in remote and inconvenient areas so that it is often difficult for operators to be there the whole operating time. This problem can be overcome by remote control and monitoring from a remote monitoring station, which is conveniently located for personnel assignment. In recent years, remote monitoring and control are being used worldwide and solve the difficulty in assigning personnel in geothermal sites.

Remote control and monitoring of geothermal plants are easy and safe compared to other power plants such as fossil fuel because of the following:

- Steam pressures and temperatures are relatively low and there is no threat of fire hazard caused by the steam;
- Adopting an air-cooled generator, instead of hydrogen cooling, eliminates the possibility of hydrogen explosion;
- Operation and maintenance of a geothermal power plant is easier than in a fossil fuel thermal power plant, because it has no boiler, and plant systems are much simpler;
- A geothermal power plant is usually operated at full load and, thus, its operation and monitoring is simpler than for a fossil fuel plant.

The following functions are common in remote control and monitoring:

1. Unit start up and stop through the remote control communication system;
2. Alarm acknowledgement transmitted from the local control equipment and alarm reset;
3. Manipulating load and reactive power control during normal load operations and emergency shut down;
4. Viewing the status of pumps, circuit breakers, etc.

Moreover it is possible to use television cameras to monitor the surrounding of the geothermal field. This enables a general outlook of the geothermal field and the inside of the power plant such as the turbine-generator and the central control room at the remote control station.

7.4 Spare parts

As power plants are often very far from equipment suppliers, failure or damage of components may cause plants to be out of service. During constructing and installing the power plant, sufficient supplies of important spare parts should be ordered. In most cases one of each kind or ten percent of the most important or those that are suspected to be easily damaged will be ordered with the main equipment. This avoids interruption during commissioning and plant operation and facilitates continuous service of the plant.

7.5 Reliability aspects

The main aim of the power plant after construction, installation and commissioning is to have a continuous and uninterruptible operation. Nowadays, electrical power is one of the basic needs for the daily activity of human beings. Hence, power interruption should be minimized as much as possible. For continuous operation of the plant the reliability aspect is important. The availability of redundancy in control, protection and measuring equipment, two or double bus bar switchgear, standby power supply, etc. increase power plant reliability (Gonsalves and Knox, 1988; Frederiksens et al., 2000).

8. THE ALUTO-LANGANO GEOTHERMAL POWER PLANT

8.1 Power plant description

The Aluto-Langano geothermal power plant is a pilot power plant in Ethiopia constructed by Ormat and started operation in 1998. It consists of a combined cycle steam turbine and binary turbine and is the first of its kind in Africa. The power plant is designed for a capacity of net output 7.28 MWe (8.52 MWe gross) with two units. These are: (i) A geothermal combined cycle unit (GCCU), which comprises a steam turbine integrated with a binary turbine that generates 3.9 MWe; and (ii) an Ormat Energy Converter (OEC) binary turbine with an output of 4.6 MWe (Tassew, 2001; Ormat, 2001). Currently, the pilot power production has declined to 4 MWe and is still declining (EEPCo, 2002).

8.2 Production wells

In Aluto-Langano there are four production wells that produce both steam and brine (LA-3, LA-4, LA-6 and LA-8) and one re-injection well (LA-7). Wells LA-3 and LA-6 are high-enthalpy wells and supply steam to the GCCU and brine from a flash tank to heat the binary fluid in a pre-heater. Wells LA-4 and LA-8 are medium-pressure wells and supply hot geothermal water for the Ormat Energy Converter unit to the evaporator for vaporizing the binary fluid (Isopentane).

8.3 Electrical system

8.3.1 Generator circuit breaker

The generator circuit breaker connects and disconnects the generator with the grid in normal operation and can disconnect the generator with a full load in case of a fault. The vacuum circuit breaker is enclosed inside the generator breaker board. It is spring operated and the spring is motor charged with a 110 V electrical motor. The breaker open/close operation is electrical and it also has a mechanical tripping device in case the power supply fails.

8.3.2 Protection system of the power plant

The electrical protection system consists of time over current relay, ground fault over-voltage relay, differential relay, generator over voltage and under voltage and generator phase balance relay. The time over-current relay protects the generator from overload and faults. The ground over voltage relay provides protection against a high resistance grounded system. This relay senses the voltage across a resistor connected to the neutral point of the generator. The differential relay is the highest level of fault protection for both a generator and the power transformer. During fault conditions such as a short circuit in the winding, the current into the protected zone is not equal to the current out of the protected zone. The relay will sense the fault current and activate to trip the circuit breaker. The over/under voltage relay insures that the generator does not operate beyond the preset voltage limit. The phase balance relay protects the generator from mis-operation or false tripping when there is a sudden loss of sensing voltage due to a fuse blowout.

In addition to these protection relays, monitoring of generator winding temperature is important. The thermistor relay, connected with a thermistor that is inserted in the generator winding, senses the temperature of the winding and protects the generator from over-heating.

8.3.3 Transducers and measuring devices of the power plant

The output of transducers for measuring generator current, voltage, active and reactive power and generator speed are 4-20 mA. The inputs for the current transducers are 0-5 A and for the voltage transducers, 0-150 V. For active and reactive power measurement, Watt and Var transducers are used, respectively, with inputs from current and voltage transformers.

8.4 Control system of the power plant

The control system is designed to control and monitor the following:

- Start-up procedure;
- Normal operation;
- Shutdown procedure (both emergency and normal);
- Warning and failure conditions.

The control system of both the GCCU and the OEC are based on a programmable logic control (PLC). The inputs for the PLC are both digital (logic) and analog signals from the input devices such as position of motor operated drives, measuring sensors, etc. The PLC processes the input signals based on the software and outputs both logical and analog commands to each controlling centre. The central processing unit (CPU) is the main processor of the control system and processes the input signals received through the input modules, that converts the electrical signals to logic levels, from input devices. On the other

hand, the output modules convert processed signals from the CPU for driving the controlling components. The input and output modules provide electrical isolation for the CPU from electrical noises.

8.4.1 Feedback control system

The feedback control system of the GCCU unit comprises the following closed-loop control circuit:

- Steam turbine speed governor control valve;
- Vaporizer fluid level and temperature control circuit system;
- Organic turbine speed governor control valve;
- Organic turbine bypass control valve;
- Vaporizer non-condensable gas control circuit.

Both the steam and organic turbine speed governor control valves control the flow of steam to the turbine. When the turbine is not connected to the grid the governors regulate the turbine speed and after synchronization they regulate the power with the speed droop function. The vaporizer level and temperature control circuit control the level of the organic fluid level and temperature in the vaporizer to a preset value. The vaporizer non-condensable gas (NCG) control circuit controls emission of steam through the preheater by measuring the temperature of the NCG and regulating the flow.

The feedback control system of the OEC unit comprises three closed-loop circuits:

- Heat source control;
- Vaporizer fluid level and temperature control circuit;
- Turbine speed governor control valve.

The heat source control circuit controls the geothermal waterflow through the heat exchanger (vaporizer) in order to control the pressure of the organic fluid to regulate the pressure to a preset value. The other two control circuits have similar functions as in the GCCU unit.

8.4.2 Turbine control backup unit (TCU)

The turbine control backup unit is an electro-mechanical printed circuit, which acts if the PLC fails to shutdown the turbine. It is independent of the PLC system and controls the valves in case of emergency. The TCU acts when one or more of the following failures occurs:

- The pressure in the vaporizer is high;
- The pressure in the condenser is high;
- Main phase imbalance;
- Generator winding overheat;
- Emergency stop.

This system helps only in shutting down the turbine when one of the above failures occurs by initiating the hydraulic valves to act in order to close the pipelines. When it acts, turbine injection valves close, turbine main seal oil valves shut off the heat source, the turbine bypass valve opens and the heat source bypass valve opens.

9. CONCLUSIONS

Geothermal power plants are most often located in remote areas and it is, therefore, difficult to assign people to 24-hour shifts. The remote control systems enable people to solve this problem, making it possible to control from a remote site. Nowadays the automation of control equipment increases the flexibility of operation. The automation technology also provides more than one independent control system level in single or multi unit power plants.

To summarize, for a geothermal power plant operation without failure and interruption, the following are important:

- Availability of spare parts, if possible, at least one of each kind;
- Standby power supply for restart after shutdown or failure;
- Redundant control equipment for those plant subsystems that are difficult to operate manually or are critical during emergency shutdown;
- H_2S is a common and primary problem in geothermal power plant equipment corrosion. This is important to consider during design and to monitor during operation. H_2S corrosion can be prevented by using special filters in the air conditioning system and good sealing of the control rooms and control cubicles;
- The staff responsible for operation and maintenance should be thoroughly trained and, if possible participate from the design stage on until final plant testing and commissioning (Hunt, 2000);
- Proper maintenance of equipment according to manufacturer manuals.

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NOMENCLATURE

h	= Specific enthalpy	kJ/kg;
I	= Current	A;
P	= Absolute pressure	bar;
Q_{input}	= Total heat duty in the evaporator	kJ/s;
q	= Specific heat flow	kJ/s-kg;
s	= Entropy	kJ/kg-K;
t	= Time	s;
v_f	= Specific volume at liquid state	m ³ /kg;
W	= Total work	kW;
w_a	= Specific actual work	kW/kg;
w_s	= Specific isentropic work	kW/kg;
η	= Efficiency.	

Subscripts

1	= Pump suction;
2a	= Actual pump discharge condition;
2s	= Isentropic pump discharge condition;
3	= Turbine inlet;
4a	= Actual turbine outlet condition;
4s	= Isentropic turbine outlet condition;
T	= Turbine;
P	= Pump.

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