UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
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Reports 2010
Number 7

MAIN CONSIDERATIONS IN THE PROTECTION SYSTEM DESIGN FOR A GEOTHERMAL POWER PLANT

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ABSTRACT

A proper protection system guarantees reliable and safe operation for a geothermal power plant. It is one of the most important factors during system engineering design and must be carefully selected to avoid equipment damage due to failures. The process design should include the selection of a protection scheme as well as adequate main and auxiliary equipment and installation considerations. An adequate process design guarantees the reliable operation of protection systems and prevents damage to main equipment if an electrical or mechanical fault occurs in a geothermal power plant. The information and data obtained are based on documents from Berlin power plant in El Salvador and Hellisheidi power plant in Iceland.

1. INTRODUCTION

Geothermal energy is one of the most important forms of renewable energy in the world and has several uses. In El Salvador, the main use for geothermal energy is power generation. There are two geothermal fields in El Salvador that have operating power plants: Ahuachapán and Berlin. Their combined installed capacity is 204.4 MW.

Protection systems are one of the most important factors in geothermal power plants and ensure safe and reliable operation of the plant. Protection systems can be divided into two groups, electrical protection and mechanical protection. Electrical protection functions are identified by device function numbers found on each device installed in electrical equipment (IEEE, 1996).

In geothermal power plants, the electrical protection systems are almost the same as in other generation plants, such as hydroelectric or thermal generation plants, as the electrical components of the system are almost the same, with only minor differences or sizes.

The main difference between geothermal power plants and other kinds of generation plants is the generation process. Therefore, mechanical protection is the main speciality for geothermal power plants. Mechanical protection includes process protection, like pressure or temperature measurements, and turbine-generator protection, like vibration or eccentricity.

The most important equipment taken into account in protection systems for a geothermal power plant in the present report are: turbine, generator, unit transformer and main motors, such as circulation pump motors and cooling tower fan motors. However, the protection considerations described in this report can be applied to other equipment such as auxiliary transformers or pump motors.

The protection system design considerations involve the electrical and mechanical protection functions for the most important equipment as well as other important factors which, although they may seem small, are equally important. These considerations include technical characteristics for main and auxiliary equipment selection, as well as installation considerations for reliable operation.

2. MAIN EQUIPMENT PROTECTION

2.1 Generator protection description

In the power plant, the generator is one of the most expensive pieces of equipment; therefore, electrical faults must be identified and cleared in due time (Estevez, 2009). Synchronous generator protection requires consideration of harmful abnormal operating conditions more than that of any other power system element.

A simplified functionality of a synchronous generator can be described as follows: An electromagnetic field is developed by circulating direct current through loops of wire wound around stacks of magnetic steel laminations. These are called field poles, and they are mounted on the perimeter of the rotor. The rotor is attached to the turbine shaft, and rotates at a fixed speed. When the rotor turns, it causes the field poles (the electromagnets) to rotate and move past the conductors mounted in the stator. This, in turn, causes a voltage to be induced in the generator stator windings that are connected to the output terminals (Faraday's law of induction).

2.1.1 Generator grounding

It is common practice to ground all types of generators through some form of external impedance. The purpose of this grounding is to limit the thermal and mechanical stresses and fault damage in the machine, to limit transient overvoltages during faults and to provide a means for detecting ground faults within the machine (IEEE, 1995).

The most common grounding method for large generators is high resistance grounding. In this method, a distribution transformer is connected between the generator neutral and ground and a resistor is connected across the secondary. For a single phase to ground fault at the machine terminals, the primary fault current will be limited to a value in the range of about 3-25 A. In some cases, the distribution transformer is omitted and a resistance of high value is connected directly between the generator neutral and ground. The resistor size is selected to limit ground-fault current to the range of 3-25 A. While this method of grounding is commonly used in Europe, the physical size of the resistors, the required resistor insulation level and the cost may preclude its use.

2.1.2 Excitation system

The most common excitation system used in geothermal power plants is the alternator rectifier exciter and rotating rectifiers (brushless exciter). Figure 1 shows an excitation system that uses an alternator, but by mounting the DC field winding on the stator of the exciter and the AC armature winding on the rotor, all brushes and commutators have been eliminated. In this system, the AC armature of the exciter, the rotating three-phase diode bridge rectifier, and the main field of the AC generator are all mounted on the same rotating shaft system. All electrical connections are made along or through the centre of this shaft (IEEE, 1995).

2.1.3 Generator stator thermal protection

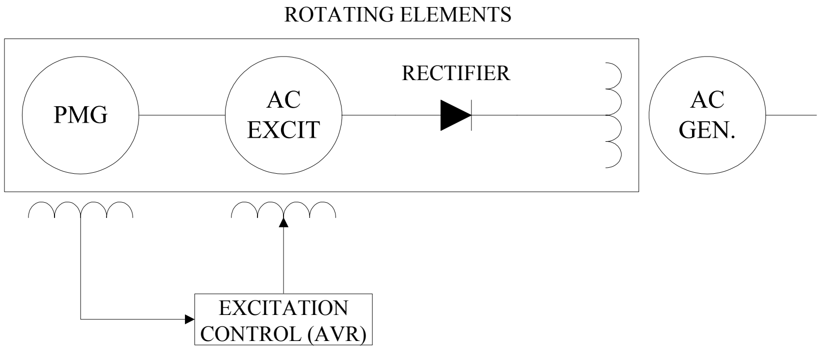

FIGURE 1: Brushless excitation system

Thermal protection for the generator stator winding (49) may be provided for generator overload. Most generators are supplied with a number of temperature sensors to monitor the stator winding temperature. These sensors are usually resistance temperature detectors (RTD) or thermocouples (TC). These sensors are used to continuously monitor the stator winding. The sensors may be connected for alarm purposes. In some applications, a current measurement is combined with a timing function to establish a thermal image of the stator winding temperature.

2.1.4 Generator stator fault protection

Generator faults can cause severe and costly damage to insulation, windings and the core; they can also produce severe mechanical torsional shock to shaft and couplings. Fault current can continue to flow for many seconds after the generator is tripped from the system and the field disconnected because of trapped flux within the machine, thereby increasing the amount of fault damage (IEEE, 1995).

The differential relay (87G) is commonly used as primary protection for phase fault of generator stator windings. This function is mostly completely selective and can be used with very short tripping times. Differential relays will detect three phase fault, phase to phase fault and double phase to ground faults. Differential relays will not detect turn to turn faults in the same phase since there is no difference in the current entering and leaving the phase winding.

2.1.5 Ground fault protection

Differential relays will not provide ground fault protection on high impedance grounded machines where primary fault current levels are limited to 3-25 A. For high impedance grounding generators the most widely used protective scheme is a time delay overvoltage relay (59GN) connected across the grounding impedance to sense zero sequence voltage; a time overcurrent relay with instantaneous element (50/51GN) or an overvoltage relay across open delta connected VTs (see Section 4.2) on the line end terminals, may be used as backup protection.

The conventional protection to detect stator ground fault in high impedance grounding systems only provides sensible protection to about 95% of the stator. This is because the failure in the remaining 5% of the winding near the neutral will not cause enough residual voltage and current of 60 Hz to operate these relays.

For larger and more important machines, it is considered important to protect the entire generator stator winding with an additional ground fault protection system so as to cover 100% of the winding. There are several methods used as a means of detecting faults near the stator neutral:

a) Third harmonic voltage at the neutral (27);
b) Third harmonic voltage at the terminals (59T);
c) Third harmonic differential between neutral and terminals (59D);
d) Sub-harmonic voltage signal injection and the neutral (59I).

2.1.6 Generator rotor field protection

The field circuit of a generator is an ungrounded system. A single ground fault will not generally affect the operation of a generator, however, if a second ground fault occurs, a portion of the field winding will be short-circuited, thereby producing unbalanced air gap fluxes in the machine. These unbalanced fluxes may cause rotor vibration that can quickly damage the machine; also, unbalanced rotor winding and rotor body temperatures caused by uneven rotor winding currents can cause similar damaging vibrations (IEEE, 1995).

The probability of the second ground occurring is greater than the first, since the first ground establishes a ground reference for voltages induced in the field by stator transients, thereby increasing the stress to ground at other points on the field winding. A voltage relay (64F) is used to detect overvoltage in the field winding produced by a ground fault.

On a brushless excitation system, continuous monitoring for field ground is not possible with conventional field ground relays since the generator field connections are contained in the rotating element. One method used is the addition of a pilot brush or brushes to gain access to the rotating field parts. The pilot brush can be periodically dropped to monitor the system. The ground check can be done automatically by a sequencing timer and control, or manually by the operator.

2.1.7 Generator loss of field

When a synchronous generator loses excitation it will over speed and operate as an induction generator. It will continue to supply some power to the system and will receive its excitation from the system in the form of VAR. During this condition, the stator currents will be increased and, since the generator has lost synchronism, there can be high levels of current induced in the rotor that can cause dangerous overheating of the stator windings and the rotor within a very short time.

The most widely applied method for loss of field protection (40) is the use of distance relays to sense the variation of impedance as viewed from the generator terminals. Both the active and reactive part of the impedance must be evaluated. Figure 2 shows a 50 MVA generator capability curve with excitation capability at 0.8 lagging or 0.9 leading.

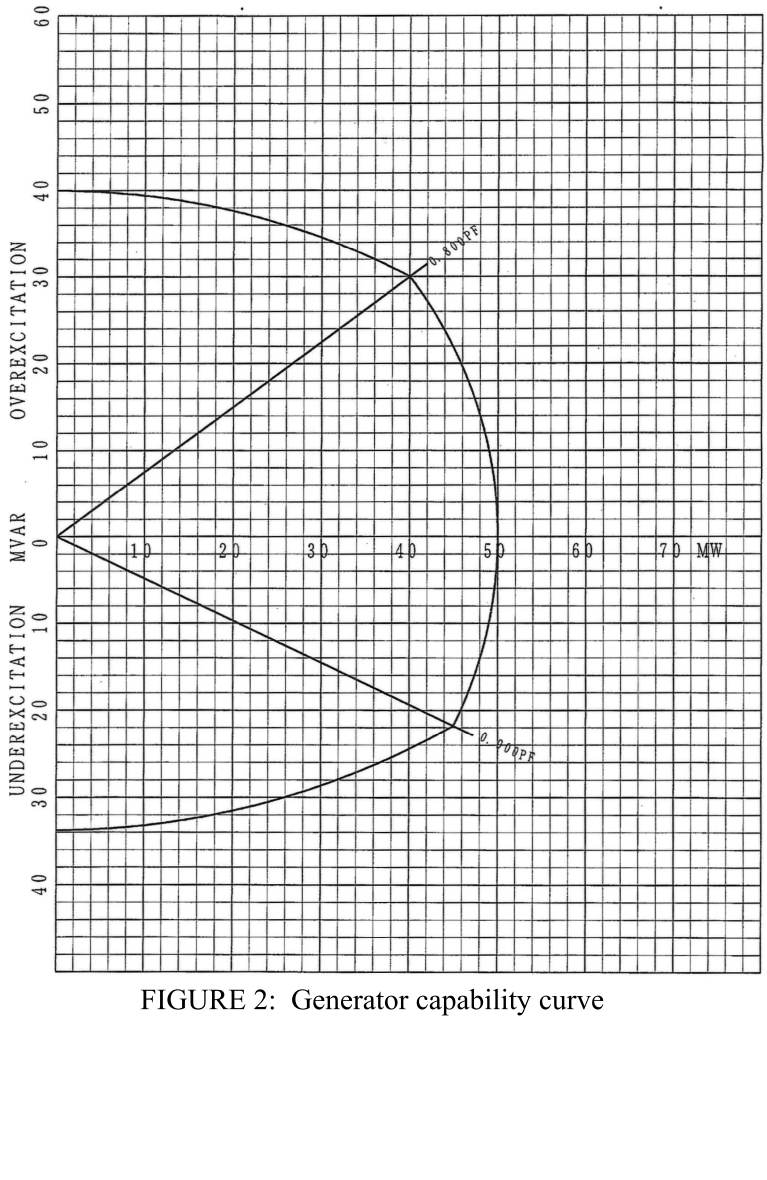

FIGURE 2: Generator capability curve

2.1.8 Unbalanced currents

Generator unbalanced currents produce negative phase sequence components of current which induce a double frequency current in the surface of the rotor, the retaining rings, the slot wedges and in the field winding. These rotor currents can cause high and dangerous temperatures in a very short time. Negative sequence protection (46) consists of a time overcurrent relay which is responsive to negative sequence currents, protecting the machines before their specific limits are reached.

2.1.9 Loss of synchronism

When a generator loses synchronism, the resulting high peak currents and off-frequency operation cause winding stresses, pulsating torques, and mechanical resonances that are potentially damaging to the generator and turbine generator shaft (IEEE, 1995).

The conventional method for loss of synchronism protection (78) is an impedance relay that analyzes the variation in apparent impedance as viewed at the terminals of the system element.

2.1.10 Overexcitation

Overexcitation of a generator will occur whenever the ratio of the voltage to frequency (volts/hertz) applied to the terminals of the equipment exceeds 1.05 per unit (pu) on the generator base. When these volts/hertz (V/Hz) ratios are exceeded, saturation of the magnetic core of the generator can occur and stray flux can be induced in nonlaminated components which are not designed to carry flux and can also cause excessive interlaminar voltages between laminations at the ends of the core. The field current in the generator can also be excessive. This can cause severe overheating in the generator and eventual breakdown in the insulation.

Volts/Hz (overexcitation) protection (24) is a function that measures both voltage magnitude and frequency over a broad range of frequency and determines the Volts/Hz relationship in the generator.

2.1.11 Motoring

Motoring of a generator (reverse power) occurs when the energy supply to the prime mover is cut off while the generator is still online. When this occurs, the generator will act as a synchronous motor and drive the prime mover. Motoring causes many undesirable conditions. For example, in a steam turbine, the rotation of the turbine rotor and blades in a steam environment causes idling or windage losses. Windage loss energy is dissipated as heat. This can cause severe thermal stresses in the turbine parts (IEEE, 1995).

Reverse power protection (32) is a power relay set to look into the machine and is, therefore, used on most units. Although listed along with generator protection functions, reverse power protection is actually designed for the protection of the steam turbine.

2.1.12 Overvoltage

Generator overvoltage may occur without necessarily exceeding the V/Hz limits of the machine. Upon load rejection, the speed may increase and cause a proportional rise in voltage. Under this condition on a V/Hz basis, the overexcitation may not be excessive but the sustained voltage magnitude may be above permissible limits. Overvoltage conditions can also occur due to voltage regulator failure. Protection for generator overvoltage is provided with an overvoltage relay (59).

2.1.13 Abnormal frequencies

Both the generator and the turbine are limited in the degree of abnormal frequency operation that can be tolerated. The turbine is usually considered to be more restrictive than the generator at reduced frequencies because of possible mechanical resonances in the many stages of the turbine blades. Departure from rated speeds will bring stimulus frequencies closer to one or more of the natural frequencies of the various blades resulting in an increase in vibratory stresses. As vibratory stresses increase, damage is accumulated that may lead to cracking of some parts of the blade structure.

Primary under-frequency protection for steam turbine generators is provided by the implementation of automatic load shedding programs on the power system. These load shedding programs should be designed so that for the maximum possible overload condition, sufficient load is shed to quickly restore system frequency to near normal. Backup protection for under-frequency conditions should be provided by the use of one under-frequency relay (81) on each generator.

2.1.14 System backup protection

It is common practice to provide protective relaying that will detect and operate for system faults external to the generator zone that are not cleared due to some failure of system protective equipment. This protection, generally referred to as system backup, is designed to detect uncleared phase and ground faults on the system.

Two types of relays are commonly used for system phase fault backup, a distance type of relay (21) or a voltage-controlled time overcurrent relay (51 V). The choice of relay in any application is usually a function of the type of relaying used on the transmission system. In order to simplify coordination, the distance backup relay is used where distance relaying is used for transmission line protection, while the overcurrent type of backup relay is used where overcurrent relaying is used for line protection.

2.1.15 Generator breaker failure protection

When the protective relays detect an internal fault or an abnormal operating condition, they will attempt to trip the generator and at the same time initiate the breaker-failure timer. If a breaker does not clear the fault or abnormal condition in a specified time, the timer will trip the necessary breakers to remove the generator from the system.

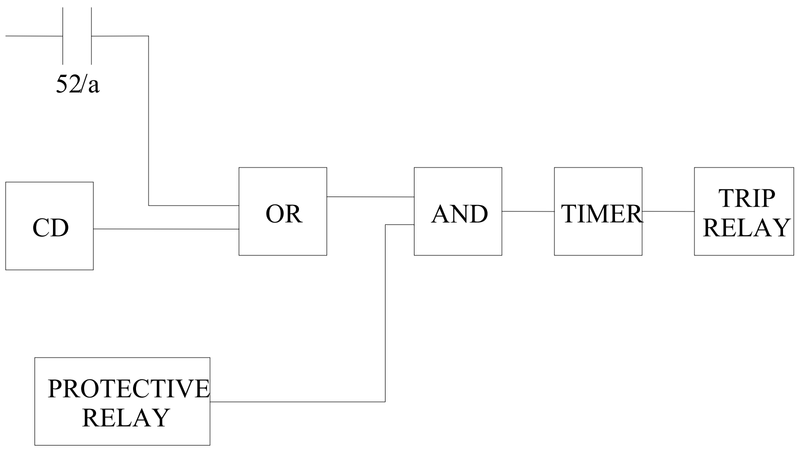

FIGURE 3: Breaker failure scheme

Figure 3 shows that to initiate the breaker-failure timer, a protective relay must operate and a current detector or a breaker "a" switch must indicate that the breaker has failed to open. Breaker-failure schemes (50BF) are connected to energize a hand-reset lockout relay (86BF) which will trip the necessary backup breakers.

2.1.16 Voltage transformers

Loss of the voltage transformer (VT) signal can occur due to a number of causes. The most common reason is fuse failure. Loss of VT signal can cause protective relay misoperation/failure to operate or generator voltage regulators to run away, leading to an overexcitation condition.

To eliminate the possibility of misoperations, it is common practice to apply a voltage balance relay (60) which compares the three-phase secondary voltages of two sets of VTs. If the fuses blow in one set of VTs, the resulting imbalance will cause the relay to operate. If a fuse blows, the relay will alarm and block possible incorrect tripping by protective relays whose performance may be affected by the change in potential.

2.1.17 Inadvertent energizing

Operating errors, breaker head flashovers, control circuit malfunctions or a combination of these causes have resulted in generators being accidently energized while off-line. When a generator is energized from the power system (three-phase source) it will accelerate like an induction motor. While the machine is accelerating, high currents induced into the rotor can cause significant damage in only a matter of seconds.

Dedicated protection schemes are necessary to protect the generator when it is off-line. Consideration should be given to locating this protection in the switchyard where it is less likely to be disabled during generator maintenance. Common schemes used to detect inadvertent energizing are:

a) Directional overcurrent relays (67);
b) Frequency supervised overcurrent (50/81);
c) Distance relay scheme (21);
d) Voltage supervised overcurrent (50/27);
e) Auxiliary contact scheme with overcurrent relays (50/41).

2.1.18 Protective arrangements and tripping modes

Table 1 gives an example of trip logic for protective devices on a geothermal power plant generator. The typical protective arrangement for a geothermal power plant generator is shown in Figure 4.

TABLE 1: Geothermal power plant generator trip scheme

Device	Generator Breaker trip	Field breaker trip	Transfer Auxiliaries	Turbine Trip	Alarm only
21 or 51V	×				
24	×	×	×		
27	×	×	×	×	
32	×	×	×	×	
40	×	×	×		
46	×				
49					×
50BF	×				
50/51 GN	×	×	×	×	
59GN	×	×	×	×	
60					×
64F	×	×			
67	×				
78	×				
81	×				
87G	×	×	×	×	

2.2 Transformer protection description

The power transformer is a major and important piece of equipment in geothermal power plants. There is no one standard way to protect all transformers, or even identical transformers that are

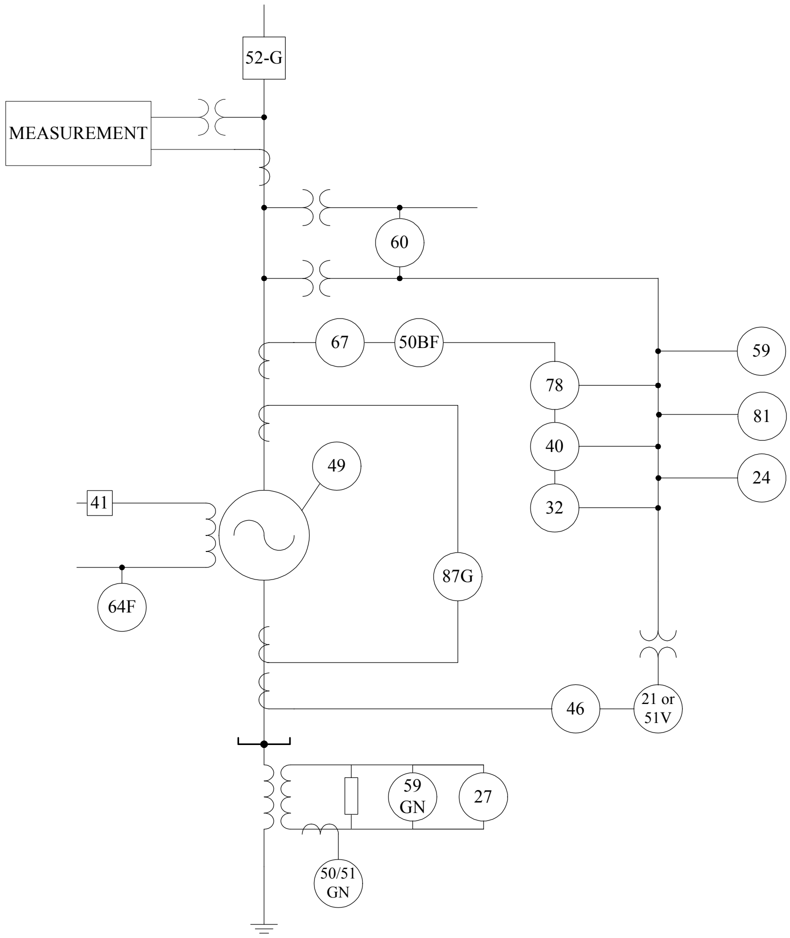

FIGURE 4: Typical generator protection scheme

applied differently. It will vary with the application, size and importance of the transformer. Most installations require individual engineering analysis to determine the best and most cost-effective scheme.

This section will consider a unit generator-transformer configuration, where a generator and its transformer (unit transformer) are connected as a unit to the system. The generator is usually wye-connected and high-resistance grounded through a distribution transformer. The unit transformer is most commonly a grounded wye-delta connection.

Unit transformers using grounded wye-delta connections create a 30° phase shift between the respective terminals of the transformers. This phase shift has to be considered for the protection configuration. Some differential relays can internally accommodate the phase shift of the transformer, allowing for choosing current transformator (CT) connections at the transformer that suit other schemes connected to the same CTs. Many relays do not have this versatility and, therefore, the CTs must be connected to create the same phase shift as the primary transformer windings.

2.2.1 Differential protection

The electrical windings and the magnetic core in a transformer are subject to a number of different forces during operation, for example, expansion and contraction due to thermal cycling, vibration, local heating due to magnetic flux, impact forces due to through-fault current and excessive heating due to overloading or inadequate cooling. These forces can cause deterioration and failure of the winding electrical insulation.

Current differential relaying (87T) is the most commonly used type of protection for transformers. The term refers to the connection of CTs such that the net operating current to the relay is the difference between input and output currents to the zone of protection. In big and important power plants, block differential (87U) is used, covering both the transformer and the generator as backup protection.

2.2.2 Overcurrent protection

A fault external to a transformer can result in damage to the transformer. If the fault is not cleared promptly, the resulting overload on the transformer can cause severe overheating and failure.

Overcurrent relays may be used to clear the transformer from the faulted bus or line before the transformer is damaged. Overcurrent relays may be used to provide relay backup for differential or pressure relays (IEEE, 2000a).

There are two types of overcurrent relays used for transformer protection, phase instantaneous overcurrent (50) which provides fast clearing of internal faults of the transformer and phase time overcurrent (51) which provides protection for external faults.

2.2.3 Ground fault protection

Sensitive detection of ground faults can be obtained by differential relays or by overcurrent relays specifically applied for that purpose. Several schemes are practical, depending on transformer connections, availability of CTs, zero sequence current source, and system design and operating practices (IEEE, 2000a).

For an impedance-grounded system, it may be necessary to apply a sensitive time overcurrent relay (51G) in the transformer impedance-grounded neutral or a time overvoltage relay connected across the neutral.

2.2.4 Overexcitation protection

Overexcitation of a transformer can occur whenever the ratio of pu voltage to pu frequency (V/Hz) at the secondary terminals of a transformer exceeds its rating of 1.05 pu on the transformer base at full load. When an overexcitation condition occurs, saturation of the laminated steel cores of the transformer can occur. This can cause severe localized overheating in the transformer and eventual breakdown in the core assembly or winding insulation.

In some cases, overexcitation protection for the transformer (24T) is provided by the generator overexcitation protection which uses the VTs connected to the generator terminals. In other cases, however, the rated transformer voltage is different than the rated generator voltage and protection may not be provided. It may, therefore, be desirable to provide supplementary protection for the transformer.

2.2.5 Transformer breaker failure

The breaker failure scheme for transformer protection (50BF) uses the same scheme as generator breaker failure protection. When the protective relays detect any fault, they will attempt to trip the transformer breakers and at the same time initiate the breaker-failure timer. If the breaker trip does not clear the fault in a specified time, the timer will trip all the necessary breakers to remove the transformer fault.

2.2.6 Gas accumulator relay

This type of relay, commonly known as the Buchholz relay, is applicable only to transformers equipped with conservator tanks and with no gas space inside the transformer tank. The relay is placed in the pipe from the main tank to the conservator tank and is designed to trap any gas that may rise through the oil. It will operate for small faults by accumulating the gas over a period of time or for large faults that force the oil through the relay at a high velocity (IEEE, 2000a).

2.2.7 Pressure relay

When high current passes through a shorted turn, a great deal of heat is generated. This heat, along with the accompanying arcing, breaks down the oil into combustible gases. Gas generation increases pressure within the tank. A sudden increase in gas pressure can be detected by a sudden-pressure relay

(63) mounted on the transformer tank below oil level. The sudden-pressure relay usually operates before relays sensing electrical quantities, thus limiting damage to the transformer. This function is also known as a pressure relief valve.

2.2.8 Winding temperature

Transformer windings may overheat because of high ambient temperature, failure of the cooling system, external faults not cleared promptly, overload or abnormal system conditions. Overheating shortens the life of the transformer insulation in proportion to the duration and magnitude of the high temperature. Thermal relays (49) in the high and low voltage windings are normally provided for transformer protection.

2.2.9 Top oil temperature

A liquid temperature sensor (26) measures the temperature of the insulating liquid at the top of the transformer. Because the hottest liquid is less dense and rises to the top of the tank, the temperature of the liquid at the top partially reflects the temperature of the transformer windings and is related to the loading of the transformer.

Because the top-oil temperature may be considerably lower than the hot-spot temperature of the winding, especially shortly after a sudden load increase, the top-oil thermometer is not suitable for effective protection of the winding against overloads. The liquid temperature sensor can be equipped with one to three adjustable contacts that operate at preset temperatures. The contacts are normally used for alarms or to initiate different stages of fans, when forced air cooling is employed (IEEE, 2001).

2.2.10 Oil level protection

An oil level sensor (71) is used to measure the level of insulating liquid within the tank or conservator with respect to a predetermined level, usually indicated at 25 °C. An excessively low level could indicate the loss of insulating liquid (IEEE, 2001). Alarm contacts for low liquid level are normally used. The alarm contact is set to close before an unsafe condition actually occurs.

2.2.11 Protective arrangements and tripping modes

The typical protective arrangement for a unit transformer is shown in Figure 5. Internal transformer faults trip the high voltage and low voltage circuit breaker for complete isolation of the fault. Internal faults also trip the generator circuit breaker, field circuit breaker and turbine.

2.3 Motor protection description

Circulations pumps, cooling tower fans and gas extraction pumps (in case these are used instead of steam-jet ejectors) are essential in geothermal power plants. The protection system for these applications is very similar because conventional AC motor protection can be applied in all cases. There are a few differences related to mechanical protection that will be discussed in this document. Motors commonly used for these functions are large, however, the same basic principles apply as when small motors are used.

2.3.1 Phase overcurrent protection

The current flowing to a fault within a motor can vary greatly in magnitude. The main factors that affect the magnitude of fault currents are the source, motor feeder, and grounding impedance; the type of fault (phase or ground); and the location of the fault in the motor winding (IEEE, 2000b).

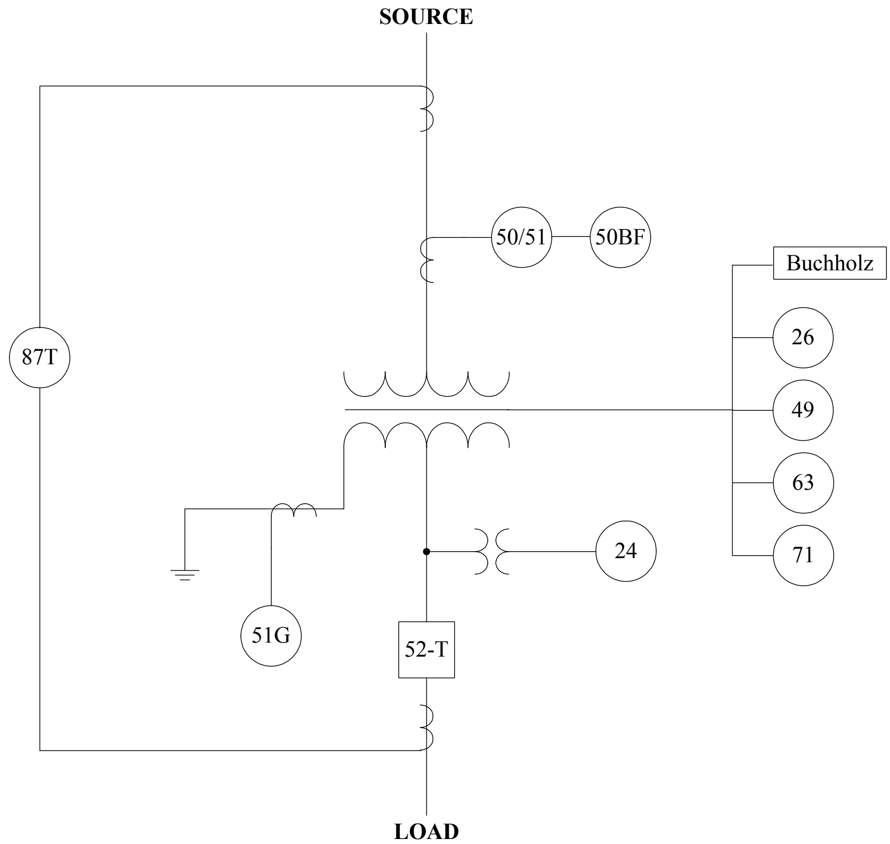

FIGURE 5: Typical transformer protection scheme

In the case of high-magnitude, short-circuit currents, immediate isolation of the faulted motor is always necessary. However, when the fault current is only a few amperes and the motor is a critical one, an alarm without immediate tripping is sometimes justified.

Instantaneous overcurrent relays (50) are used to detect motor supply cable faults as well as severe stator faults. In cases of essential service motors, a time overcurrrent relay with an instantaneous overcurrent relay (51/50) can be used. Alarms are sufficient for moderate overloads below the instantaneous overcurrent setting and trips for more severe overloads or faults.

2.3.2 Negative sequence protection

Negative-sequence current is contributed by the motor or system when an unbalanced voltage condition exists (e.g., open-phase faults, single-phase faults, or unbalanced load), a stator coil cutout occurs during a repair or there are shorted turns in the stator winding. These negative sequence currents induce double line-frequency currents that flow in the damper or rotor parts.

The magnitude of the double line-frequency current depends on the location of the fault, number of turns shorted, mutual induction, and system and motor impedance. The danger to the rotor parts is a function of the imbalance in the stator current. Phase-balance relays (46) compare the relative magnitudes of the phase currents. When the magnitudes differ by a given amount, the relay operates.

2.3.3 Ground fault protection

On solidly grounded systems, phase overcurrent relays, direct-acting trip devices and fuses afford a certain measure of ground-fault protection. For motors where greater sensitivity to ground faults is required, ground relays shall be used. Residually connected ground relays (51N) use a toroidal CT that encircles all three-phase conductors (IEEE, 2000b).

2.3.4 Stall or locked rotor protection

Failure of a motor to accelerate when its stator is energized can be caused by several types of abnormal conditions, including mechanical failure of the motor or load bearings, low supply voltage, or an open circuit in one phase of a three-phase voltage supply. Stall detection for an induction motor is usually provided by an overcurrent relay (51R), with an inverse characteristic set to detect current above the breakdown torque level.

2.3.5 Stator winding overtemperature

The purpose of stator winding overtemperature protection (49) is to detect excessive stator winding temperature prior to the occurrence of motor damage. This protection is often arranged to just sound an alarm on motors operated with competent supervision. Sometimes two temperature settings are used, the lower setting for the alarm, the higher setting to trip. Stator winding temperature protection is commonly specified on all motors rated 190 kW and above. RTDs are commonly specified in all motors rated 370 kW and above (IEEE, 2001).

2.3.6 Vibration monitors and sensors

Vibration monitoring has advanced from an important start-up function to an effective tool during operation of the process. It increases safety and reliability and may reduce costs over the life of the plant. The three components of a vibration monitoring system are transducers, monitors, and machine diagnostic equipment (IEEE, 2001).

There are two types of sensors normally used in motor protection, proximity transducers and accelerometers. Non-contacting proximity transducers accurately indicate displacement of the rotor relative to the housing and accelerometers indicate motor vibration acceleration.

Circulation pumps are vertical pumps, a type that requires proximity transducers in the motor-pump coupling and accelerometers in the motor bearings and pump case. Cooling tower fan motors require an accelerometer at the gearbox.

2.4 Turbine-generator mechanical protections

In geothermal power plants, the turbine has to be protected in all events that could damage it. Part of the generator protection system described before provides protection to the turbine but there are other faults that need to be covered by an additional protection system.

Geothermal turbines require protections against mechanical faults that can be produced in the turbine components, in the geothermal generation process or in auxiliary equipment. Figure 6 shows a typical geothermal power plant P&ID with the most important components in the generation process.

2.4.1 Steam turbine inlet

The steam turbine inlet consists of the following three main components:

a) *Steam collector.* Collects the steam from all the geothermal platforms in the field. This system has an overpressure protection that bypasses the steam line to a silencer in a case where the pressure increases. When the high pressure cannot be relieved by the silencer bypass, it sends a trip signal to the turbine.
b) *Demister.* Eliminates all the water that is contained in the steam. The most important protection is the water level in the demister, monitored to prevent water from entering the turbine and damaging the blades. The high level protection sends a trip signal to the turbine.

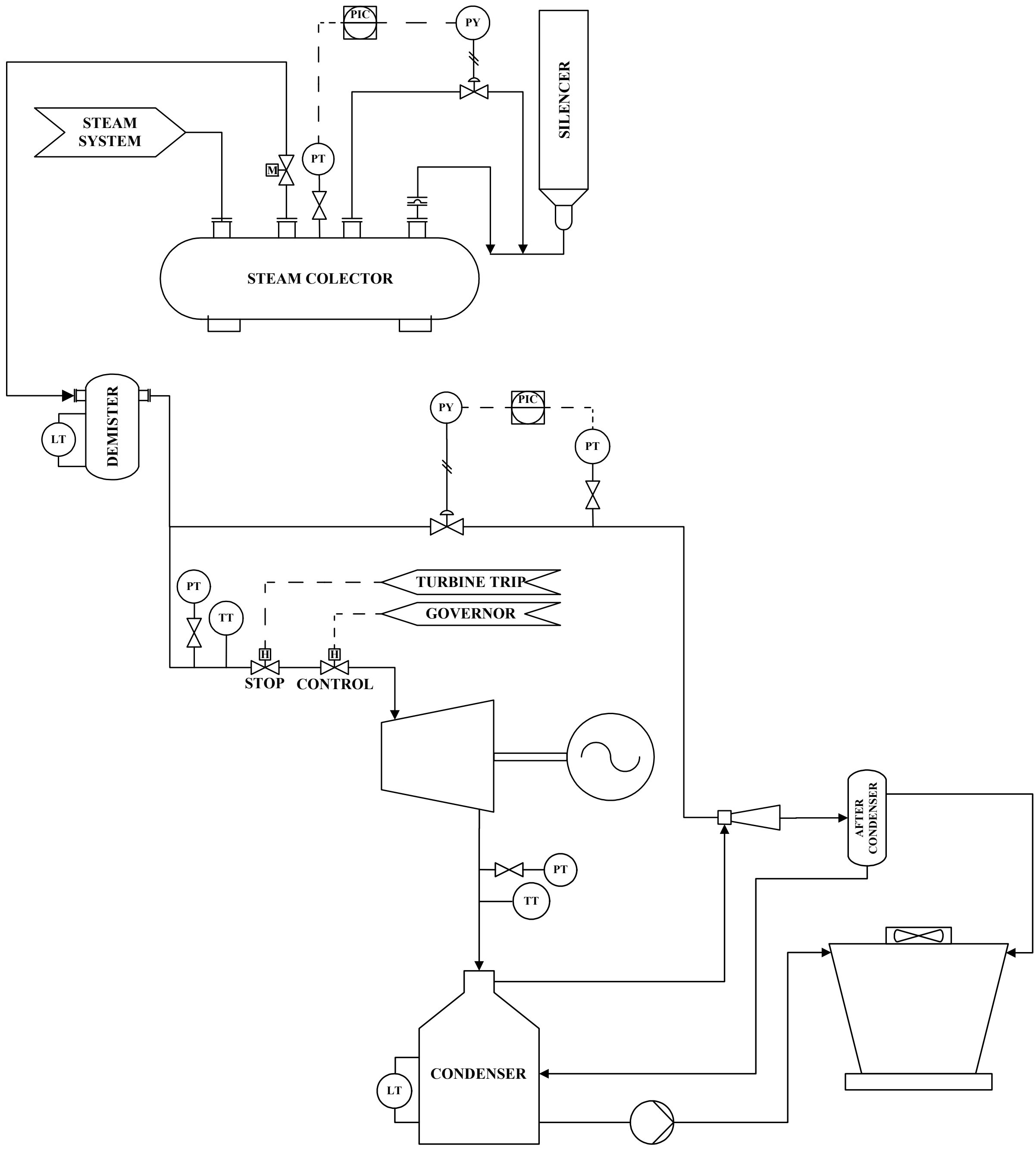

FIGURE 6: Geothermal power plant P&ID

c) *Turbine control valves.* There are two control valves in series in the turbine inlet, one is for turbine stop that closes in case of turbine trip signals and the other is for the steam control inlet and is controlled by the governor system.

The turbine inlet has steam pressure and temperature measurements to ensure safe operating conditions for the turbine.

2.4.2 Turbine

The turbine requires special protection equipment against mechanical faults. Turbine mechanical protection measurements include vibration, oil temperature, bearing metal temperature, steam seal pressure, overspeed, axial movement, eccentricity and differential expansion. Turbine mechanical variables are normally monitored and processed in a dedicated turbine supervisory system.

There are two auxiliary systems that are very important in turbine operation, the steam seal system and the oil system for control and lubrication. Pressure measurements guarantee normal operating conditions for both systems. For the oil system an oil level measurement in the oil tank is also necessary.

2.4.3 Condenser

The condenser system includes three main components that can affect turbine operation:

a) *Turbine exhaust.* Is the turbine outlet; the most important variables are the steam pressure and temperature. High steam pressure will increase turbine exhaust temperature and can cause serious damage in the last stage of blades.
b) *Condenser.* Makes the turbine more efficient; the most important variables are the water level measurement and the condenser pressure (vacuum).
c) *Gas extraction system.* Is in charge of the non-condensable gas extraction from the condenser. Non-condensable gas extraction can cause turbine exhaust pressure increase. The most common gas extraction system for geothermal power plants uses steam-jet ejectors but vacuum pumps with electrical motors can also be used for this purpose.

Table 2 show the most important mechanical protection for a geothermal turbine-generator group and Figure 7 shows a schematic diagram with all the mechanical protections.

TABLE 2: Geothermal power plant turbine trip scheme

Description	Location of measurement	Trip 1	Trip 2	Trip 3
Demister high level	Demister	×	×	×
Turb. exhaust high press.	Turb. exhaust	×	×	×
Turb. exhaust high temp.	Turb. exhaust	×	×	×
Cond. high level	Condenser	×	×	×
Turb. bearings high temp.	All journal bearings	×	×	×
Gen. bearings high temp.	All journal bearings	×	×	×
Oil bearing temp.	All bearings	×	×	×
Thrust bearing temp.	Thrust bearing on both sides	×	×	×
Turb. high eccentricity	Turbine Rotor	×	×	×
Turb. differential exp.	Turbine casing	×	×	×
Turb. rotor position	Turbine rotor	×	×	×
Turb. overspeed	Turbine rotor	×	×	×
Lube oil low pressure	Lube oil system	×	×	×
Control oil low press.	Control oil system	×	×	×
Turb.-gen. shaft vibrat.	All bearings in X and Y dir.	×	×	×

Trip 1: Turbine trip; Trip 2: Field circuit breaker trip; Trip 3: Generator circuit breaker trip

3. PROTECTION RELAY SELECTION

3.1 General description

A relay is an electric device designed to respond to input conditions in a prescribed manner and, after specified conditions are met, to cause contact operation or similar abrupt change in associated electric control circuits (IEEE, 1989). Digital numeric relay is the new generation of protective relays, where

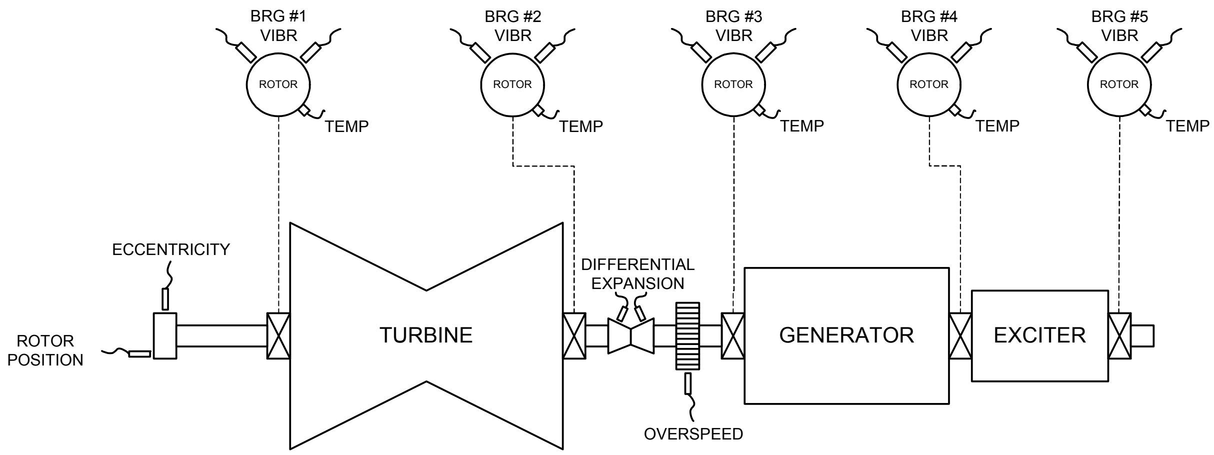

FIGURE 7: Turbine-generator mechanical protections

many functions can be implemented by the microprocessor programming. That means that in one digital relay device, the implementation of one or all of these device functions can be performed.

The protecting functions are generally divided into two groups for redundancy purposes. Each group function is executed by a number of relay protections and is associated with different digital outputs. Relay redundancy is used for geothermal power plant protection, where two identical protection relays are employed and are connected to the same instrument transformer or two independent instrument transformers, if applicable. Two different power supply sources are used for the protection relay supply and for trip circuits. Circuit breakers often have two independent trip coils.

3.2 Protections relay specifications

Digital relay technology provides an economically viable alternative for electrical equipment protection. In addition, digital technology provides several other advantages, like improved performance, greater flexibility, reduced panel space and wiring, metering of various parameters, event reporting, fault data recording, remote communication, continuous self-checking and easy configuration (Estevez, 2009).

3.2.1 Function selection

Protection relays for geothermal power plants should be of a multifunction type and include the minimum functions required for the equipment to be protected according to the description provided in this report and by international standards.

Protection relays should include current inputs, voltage inputs, digital inputs, contact outputs and optionally RTD inputs for thermal protection. The relays should have programming capacity to perform control and protection logistics, define the function of digital inputs, configure the contact output operations and timer functions (SEL, 2010).

The relays should include metering and monitoring functions to indicate different electrical variables and non-volatile memory for events records that could help for faults analysis. The relays should be capable of being serviced by Microsoft Windows based software with a friendly graphic interface.

For data access the relays should provide a front panel LCD display and different kinds of communication ports for data download, relay configuration and main SCADA communication.

3.2.2 Auxiliary inputs and outputs

Protection relays should include at least 6 digital inputs and 8 contact outputs. They should be configured and defined by programming software for different functions and could be used as part of any control and protection logic program. Digital inputs should be opto-isolated contact inputs and contact outputs should be configurable as either normally open (a contact) or normally closed (b contact). The trip contacts should be configurable to be either latched (relay reset required) or non-latched (no resetting of the relay required).

The relays may optionally include RTD inputs, too, for thermal protection monitoring (49). The RTD types and locations should be individually configurable by programming software.

3.2.3 Communication features

The communication port type and communication protocols available in the protection relays should correspond to the most common applications used in industry. The particular ports and communication protocols selected for a determined application should be compatible to the SCADA system ports and communication protocols where the relays will be connected.

In case the protection relays and the SCADA system communication protocols are not compatible, a communication protocol converter should be considered. In this case the relay communication protocol should be selected according to the most common communication protocol converters used in the industry. The most primitive means of communication is using relay outputs that are wired to PLC inputs for signalling relay operations.

4. INSTRUMENT TRANSFORMER SELECTION

4.1 Current transformers (CT)

A CT transforms line current into values suitable for standard protective relays and isolates the relays from line voltages. A CT has two windings, designated as primary and secondary, which are insulated from each other. The secondary is wound on an iron core. The primary winding is connected in series with the circuit carrying the line current to be measured; the secondary winding is connected to protective devices. The secondary winding supplies a current in direct proportion and at a fixed ratio to the primary current.

4.1.1 Rating of current transformers

The ratings of a current transformer should include:

a) Basic impulse insulation level in terms of full-wave test voltage;
b) Nominal system voltage or maximum system voltage;
c) Frequency (in Hertz);
d) Rated primary and secondary currents;
e) Accuracy classes at standard burdens;
f) Continuous thermal current rating factor based on 30°C average ambient air temperature;
g) Short-time mechanical current rating and short-time thermal current rating.

4.1.2 Standard burdens

Burden is the load connected to the secondary terminals and is expressed as volt-amperes and power factor at a specified value of current, total ohms impedance and power factor, or Ohms of the resistance and reactive components. Table 3 shows standard burdens for relaying CTs according to IEEE (1993). Burden selection for CTs should consider cable and relay input impedance.

TABLE 3: Relaying current transformers burdens

Burden designation	Resistance (Ω)	Inductance (mH)	Impedance (Ω)	Volt-amperes (at 5 A)	Power factor	Secondary terminal voltage
B-1	0.50	2.30	1.00	25.0	0.5	100
B-2	1.00	4.60	2.00	50.0	0.5	200
B-4	2.00	9.20	4.00	100.0	0.5	400
B-8	4.00	18.40	8.00	200.0	0.5	800

4.1.3 Accuracy

Protective-relay performance depends on the accuracy of the CTs, not only at load currents but also at all fault current levels. The CT accuracy at high overcurrent depends on the cross section of the iron core and the number of turns in the secondary winding. The greater the cross section of the iron core, the more flux can be developed before saturation. Saturation results in a rapid decrease in transformation accuracy. The greater the number of secondary turns, the less flux required to force the secondary current through the relay. This factor influences the burden the CT can carry without loss of accuracy.

According to IEEE (1993), the relaying accuracy class is designated by use of one letter (C or T) and the classification number. C means that the leakage flux in the core of the transformer does not have an appreciable effect on the ratio, and T means that the leakage flux in the core of the transformer has an appreciable effect on the ratio. The classification number indicates the secondary terminal voltage that the transformer delivers to a standard burden at 20 times the nominal secondary current without exceeding a 10% ratio correction. The ratio correction should not exceed 10% at any current from 1 to 20 times the rated current at standard burden.

4.1.4 Nameplates

Nameplates should include, as a minimum, the following:

a) Manufacturer's name or trademark;
b) Manufacturer's type;
c) Manufacturer's serial number (SER);
d) Rated primary and secondary current;
e) Nominal system voltage (NSV) or maximum system voltage (MSV) (None for bushing CTs);
f) Basic impulse insulation level (BIL kV) (None for bushing CTs);
g) Rated frequency (Hz);
h) Continuous thermal current rating factor (RF);
i) Accuracy rating.

4.2 Voltage transformers (VT)

A VT is basically a conventional transformer with primary and secondary windings on a common core. Standard VTs are single-phase units designed and constructed so that the secondary voltage maintains a fixed ratio with primary voltage. The required rated primary voltage of a VT is determined by the voltage of the system to which it is to be connected and by the way in which it is to be connected (e.g., line to line, line to neutral). Most VTs are designed to provide 120 V at the secondary terminals when nameplate-rated voltage is applied to the primary. In Europe, 110 V and 100 V are common values for VT secondary voltages.

4.2.1 Rating of voltage transformers

The ratings of a voltage transformer should include:

a) Basic impulse insulation level in terms of full-wave test voltage;
b) Rated primary voltage and ratio;
c) Frequency (in Hertz);
d) Accuracy ratings;
e) Thermal burden rating.

4.2.2 Standard burdens

Standard burdens for VTs with a secondary voltage of 120 V according to IEEE (1993) are shown in Table 4.

TABLE 4: Relaying voltage transformer burdens

Characteristics on standard burdens			**Characteristics on 120 V basis**			**Characteristics on 69.3 V basis**		
Designation	**VA**	**Power factor**	**R (Ω)**	**I (mH)**	**Z (Ω)**	**R (Ω)**	**I (mH)**	**Z (Ω)**
W	12.5	0.1	115.2	3.0400	1152	38.4	1.0100	384
X	25.0	0.7	403.2	1.0900	576	134.4	0.3649	192
M	35.0	0.2	82.3	1.0700	411	27.4	0.3560	137
Y	75.0	0.85	163.2	0.2680	192	54.4	0.0894	64
Z	200.0	0.85	61.2	0.1010	72	20.4	0.0335	24
ZZ	400.0	0.85	30.6	0.0503	36	10.2	0.0168	12

4.2.3 Accuracy

Standard accuracy classifications of VTs range from 0.3 to 1.2, representing percent ratio corrections with which to obtain a true ratio. These accuracies are high enough so that any standard transformer is adequate for most industrial protective relaying purposes as long as it is applied within its open-air thermal and voltage limits.

4.2.4 Nameplates

Voltage transformer nameplates should include, at minimum, the following:

a) Manufacturer's name or trademark;
b) Manufacturer's type;
c) Manufacturer's serial number (SER), numerals only;
d) Rated voltage (PRI);
e) Ratio or ratios;
f) Basic impulse insulation level (BIL kV);
g) Rated frequency (in Hertz);
h) Thermal burden rating or ratings at ambient temperature or temperatures, in voltamperes or degrees centigrade;
i) Accuracy rating: maximum standard burden at which the accuracy rating is 0.3 class, as a minimum.

4.3 Safety considerations

Instrument transformers, like other transformers, transform the secondary impedance to the primary side. Therefore, it is important for CTs that the secondary circuit is never opened, as this will be transformed to the primary side as very high impedance that the primary current is forced through. This will result in a dangerously high voltage across the CT secondary. Equally, the short circuiting of a VT secondary must be prevented with a proper fusing or fast mini circuit breaker (MCB). Otherwise, the primary side will be short circuited to ground through the VT primary, which may result in an explosion of the VT.

5. AUXILIARY EQUIPMENT SELECTION

5.1 Auxiliary relays

During a fault in any of the equipment of a geothermal power plant, the protection relay described above will detect the fault and send a trip signal via a contact output. In most cases, it is necessary to multiply this trip signal for different applications such as circuit breaker trip coil, SCADA system fault register, mimic panel alarm and the trip and interlock circuit for other main equipment. Auxiliary relays are used for this application. Figure 8 shows a typical high speed auxiliary relay.

FIGURE 8: High-speed auxiliary relay

The most important characteristic for auxiliary relays is high-speed operation in order to avoid delays in trips due to fault conditions. Current carrying capacity for auxiliary relay contacts should be 30 A for 200 ms and 20 A for 1 s. The number of contacts for the auxiliary relays should be selected according to the number of applications required for circuit breaker trips, process trips, alarms or other auxiliary relay operations. One of the contacts of the auxiliary relay is used directly for trips to avoid delays in fault protections. The typical number of contacts available for this relay ranges from 2 to 15, and could be combined between normally open and normally closed types.

5.2 Lockout relay

Lockout relays are utilized for locking out the main circuit breakers or process in a geothermal power plant. These relays are hand reset types avoiding an instantaneous restart of the operated circuit breakers or process and forcing the power plant technical personnel to check the system conditions before a system restart. These relays are used also as multiplying contact relays. Figure 9 shows a typical lockout relay.

FIGURE 9: Typical lockout relay

A lockout relay is normally operated by main protection relay contact output or by an auxiliary relay. In both cases it is necessary to take into account the fact that the current carrying capacity to the operating contact must be equal or higher than the coil current required to trip the relay. The number of contacts for a lockout relay should correspond to the number of trips, lockouts and alarm signals required for each particular application and should also depend on whether it is utilized in combination with other auxiliary relays. The typical number of contacts available for these relays normally ranges from 2 to 40 and could be combined between normally open and normally closed types.

5.3 Control and measurement cable

Cables are utilized for two applications, instrument transformer signals (CTs and VTs) and control signals for trip, contacts, circuit breakers or other equipment status. These are located along the power plant and at the high voltage substation and are necessary to bring signals to connection boxes, control rooms, power rooms and protection relays.

Because H_2S is present in the atmosphere, the cable conductors should be tin-coated copper conductors to protect against corrosion. The cable should be approved for installation indoors or outdoors, in conduits, ducts or cable trays. Cable insulation and jacket should be flame-retardant and with low-halogen emission. The cable jacket should be sunlight resistant.

Cable size selection has to consider secondary fault currents for CT circuits, voltage drop for VT and control circuits and distances between equipment and panel rooms. Typical cable sizes for CT circuits are 10-12 AWG (4-6 mm^2) and typical cables sizes for VT and control circuits are 14-16 AWG (1.5-2.5 mm^2). The number of conductors per cable depends on the particular application.

5.4 Marshalling box

Marshalling boxes are normally used for signal concentration and as connection boxes between field equipment and the panel room. Marshalling boxes should include all the accessories required for connections: terminal blocks, circuit breakers for control feeders and secondary VT circuits, short circuit terminal blocks for secondary CT circuits, plastic cable channels, grounding bar, internal light, and heaters.

Because of the H_2S presence, the marshalling box material should be corrosion resistant, such as stainless steel or polyester. The protection degree for indoor and outdoor installation should be NEMA 4X (IP 66). All metallic parts of marshalling boxes should be grounded, including mobile parts like doors. The boxes should include a removable rear wall for component installation. Marshalling box installation should be designed for wall mounting or floor mounting, depending on particular applications.

5.4.1 CT and VT circuits considerations

CT and VT terminal blocks should be of a heavy duty type with a screw connector for the use of ring terminals in cable termination. CT terminal blocks should include a short circuit bar. Terminal block continuous current capacity should be enough to support the maximum fault current for the CT secondary. Figure 10 shows a typical terminal block for CT and VT circuit and ring terminals. VT secondary circuits should include circuit breaker protection. All the cables and terminals blocks should have identification labels for easy revision and fault corrections.

FIGURE 10: CT and VT terminal block and ring terminals

5.4.2 Control circuit considerations

Control circuit terminal blocks should be of the DIN rail mounting type with a screw clamp cable connection. Terminal blocks should accept at least cable sizes from 10 AWG to 18 AWG (1-6 mm^2). Cable terminations should include pin terminals. Control voltage feeders should include circuit breaker protection. Figure 11 shows a typical DIN rail mounting terminal block and pin terminals. All the cables and terminals blocks should have identification labels for easy revision and fault corrections.

FIGURE 11: DIN rail mounting terminal block and pin terminals

5.5 Installation considerations

There are some installation considerations that must be taken into account for the correct operation of protection systems. These considerations apply for all the measurement and control circuits.

Superficial cable installation should be made in rigid metal conduits or cable trays. For final connections between rigid metal conduits or cable trays and field equipment, it is necessary to use liquid-tight flexible metal conduits or cable glands. According to the National Electric Code (2008), there should not be more than the equivalent of four quarter bends (360° total) between pull points, such as conduit bodies and boxes.

In superficial installations, distances between supports for these rigid metal conduits or cable trays should not exceed 900 mm. The space utilization in any type of conduit for superficial or underground installation should not exceed 40% of the whole cross section area and all conduit edges should be eliminated to avoid cable damage during installation.

For underground cable installation, rigid PVC non-metallic conduits should be used to avoid corrosion. It is necessary to use concrete pull boxes in conduit derivations or direction changes. Outdoor pull boxes should be of water-tight construction and be provided with drains at the bottom.

6. ELECTRICAL CONTROL SCHEMES

6.1 Substation control

An electrical substation is an important part of an electricity generation system where voltage is transformed from medium to high, using transformers. Electric power may flow through several substations between a generating plant and the consumer, and may change voltage levels in several steps. Figure 12 shows a typical substation single-line diagram.

The most important elements of an electrical substation are the disconnecting switches and circuit breakers. The disconnecting switches are used for no-load operations, like isolating a circuit breaker for maintenance or as bypass equipment, and cannot be operated with load. The circuit breakers are load operation equipment used to isolate part of the electrical system in normal operations such as in fault cases. Substation control refers to all the conditions that permit the operation of a determinate element to the substation. These controls make sure that the different elements are not operated under inappropriate conditions that could produce damage in any part of the generating plant. Each particular case requires a different control scheme, but according to the single line diagram shown in Figure 12, the control scheme must take into account the following conditions:

a) *Disconnecting switches* (89TA1 & 89TA2). This equipment normally has an opening circuit and a closing circuit operated by an electrical motor. The most important condition for the opening or closing of this equipment is that the circuit breaker 52-T must be open.
b) *Earthing switch.* The earthing switch is part of one of the disconnecting switches and is used for grounding the bus for security during maintenance work. It can be operated manually or by electrical motor. The most important condition for the closing of this equipment is that the circuit breakers and disconnectors in both sides must be open.
c) *Circuit breakers.* This equipment has one closing circuit and two independent trip circuits. The most important conditions for the closing circuits are: disconnecting switches must be closed, the earthing switch has to be open and no trip conditions can be active. The trip conditions block the closing circuits by using lockout relays. The trip circuits should not have any conditions except the trip signals from the protection relays. The protection schemes divide the trips into two groups and each group is associated with one trip circuit.

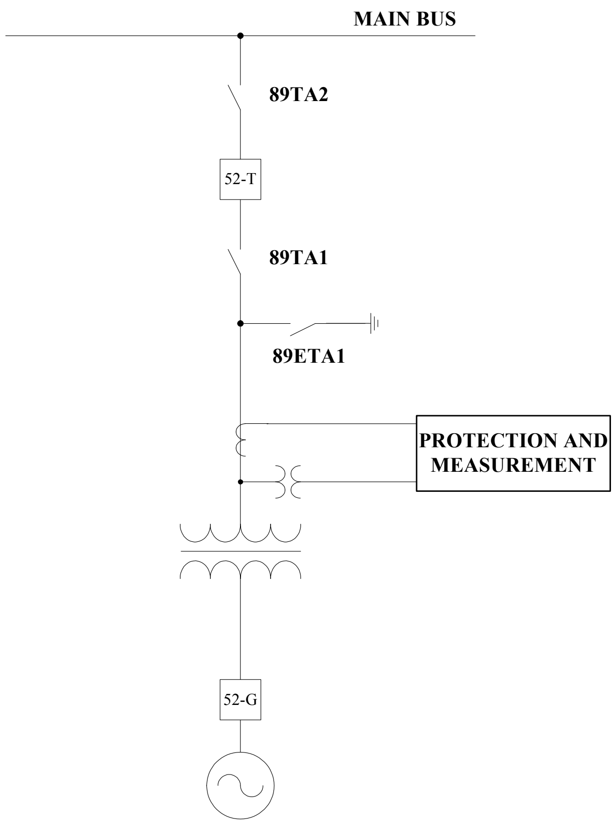

FIGURE 12: Typical substation single-line diagram

6.2 Mimic panel

A mimic panel simulates the generation process and electrical system in a geothermal power plant, showing the most important measurements, conditions and alarms. Figure 13 shows a typical mimic panel for the electrical system in a geothermal power plant. The mimic panel normally works as a manual control system, too, permitting the manual operation of parts of the process or equipment. The mimic panel for the electrical system displays the single line diagram and includes the following:

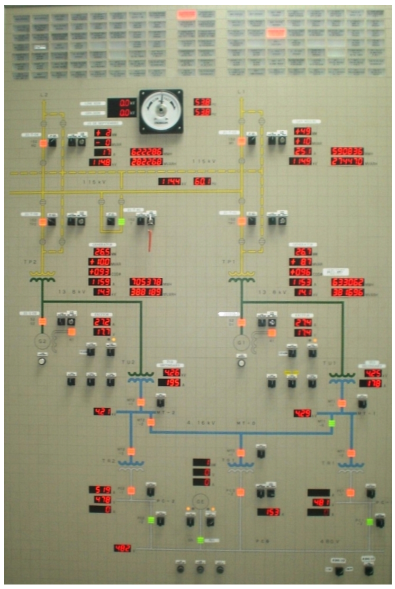
FIGURE 13: Electrical system mimic panel

a) *Electrical variables and states.* The most important electrical variables are displayed in the mimic panel. They come from the measurement instrument transformers and are converted by transducer to 4-20 mA or 0-10 V signals. The mimic panel also displays the state of equipment, like circuit breakers or disconnecting switches.
b) *Manual control.* The mimic panel permits manual control and operation for some parts of the electrical system like substation equipment operation, circuit breaker remote operation, automatic and manual synchronism.
c) *Alarms.* The mimic panel shows the most important electrical alarms like relay trips, transformer mechanical protection alarms, generator mechanical protection alarms, and turbine mechanical protection alarms. The visual alarm is normally accompanied by an audible alarm.

6.3 Hardwire interlock

The safest protection schemes in geothermal power plants are hardwired interlocks that consist of electrical connections between the different equipment to a protection system through hardwiring, avoiding the use of communication protocols or extra electronic equipment that could add an external fault to the system. In this way, the protection schemes do not depend on external factors or equipment like PLCs or communication protocols. This is an important consideration for the safe and reliable operation of protection systems. Hardwired interlock can be divided into two applications, trip applications hardwire interlock and control applications hardwire interlock.

6.3.1 Trip applications hardwire interlock

In protection systems, the only electronic equipment that should be present in a trip circuit is the protection relay. Protection relays receive the measurement signals from the instrument transformers and other mechanical protection measurement equipment, such as RTD for winding temperature measurement, then process the information and send the trip signal directly to the circuit breaker or through high speed auxiliary relays.

The electrical connections between the protection relay, instrument transformers, mechanical protections and circuit breaker trip circuits should be made through hardwire to avoid external fault conditions that could be caused by electronic devices or protocol communication faults. A marshalling box is normally used as an interface between the field equipment and the protection panels inside the power plant.

6.3.2 Control applications hardwire interlock

Electrical connections for control applications should be hardwired between the field equipment, like circuit breakers or disconnecting switches, and the auxiliary relays contacts used with protections relays. These hardwire connections should be made in the marshalling boxes and should avoid the use of PLCs for control or interlock functions.

For substation control in the particular case described above, a marshalling box is normally located in the substation and all the auxiliary contacts and control circuits to the substation elements are connected in it. This marshalling box works as an interface between the field equipment and the control panels inside the power plant. All the interlocks for the substation element operation should be made in the marshalling box through hardwire to avoid external fault conditions that can be caused by electronic devices or protocol communication faults.

7. CONCLUSIONS

The protection system is one of the most important components of a geothermal power plant for reliable and secure operation of all plant equipment. The correct design and selection of protection systems ensure that the power plant will be protected and any electrical or mechanical fault will not cause serious damage to the main equipment.

The protection scheme selection for the main equipment requires special attention to obtain high levels of availability in the operation of a geothermal power plant. An adequate scheme selection avoids unnecessary trips and minimizes loss conditions of the process, thus allowing the rapid return of the unit to normal operating conditions.

During the start up of the protection systems design, it is necessary to consider all the components for a complete protection system operation. These components should include main equipment such as protection relays or instrument transformers, and auxiliary equipment such as cable terminals or auxiliary relays to avoid delays in the construction and installation process.

Adequate protection system equipment selection avoids unnecessary trips or unsafe conditions during a fault and permits quick trips to eliminate the fault and minimize the damage in the protected equipment. Insufficient protection equipment selection or configuration can cause protection system failures in detecting a fault or cause excessive delay in the detection. A delayed trip of the equipment or a no trip condition could damage the equipment.

Correct tripping action for a turbine generator set requires an understanding of the technical characteristics of the turbine, the capacity of the system generator/ turbine, the operation of the unit, and the process of geothermal energy conversion. An adequate trip selection avoids a complete power plant trip and permits rapid recovery of normal operating conditions.

ACKNOWLEDGEMENTS

I would like to give my sincere gratitude to all the staff of United Nations University Geothermal Training Programme in Iceland, for giving me the opportunity to participate in this programme. Special thanks to Dr. Ingvar Birgir Fridleifsson, Director, and Mr. Lúdvík S. Georgsson, Deputy Director, for their patience, dedication and support throughout this training, and for the enthusiastic work of all the staff. I want to give special thanks to my supervisor Mr. Snaebjörn Jónsson for invaluable guidance which made this project possible.

I would like to extend my gratitude to my employer, LaGeo S.A. de C.V., especially to Mr. Jorge Burgos, Mr. Ricardo Escobar and Mr. José Luis Henríquez for their support during this 6 month training. My gratitude to the people who generously shared their data and time for this report: Mr. Jorge Castillo, Mr. Carlos Melgar and Mr. Mario Avila.

I am deeply grateful to my wife, Maricela, for her patient support and unconditional love. Also, I warmly thank my parents, Luis and Kenny, for their guidance and support throughout my life. Finally, I give thanks to the unconditional lord and friend God, who makes all things possible.

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