UNITED NATIONS
UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2009
Number 19

DESIGN OF MONITORING AND CONTROL SYSTEMS FOR GEOTHERMAL STEAM GATHERINGS SYSTEMS – COMPARISON WITH THE EXISTING SYSTEM FOR THE MIRAVALLES GEOTHERMAL FIELD

Rodrigo Mora Salas
Instituto Costarricense de Electricidad – ICE
Suministro de Vapor – Mantenimiento Instrumentación de Campo
Guayabo de Bagaces, Guanacaste
COSTA RICA
romoras@ice.go.cr

ABSTRACT

Geothermal energy is an important source of electricity production in Costa Rica. Development and management of Miravalles geothermal field has been done by the Costa Rican Institute of Electricity, ICE, for many years. Miravalles activities have spread through a 21 km^2 area where five geothermal plants, seven separation stations and 54 geothermal wells have been developed. Therefore, it is necessary to have a good monitoring and control system that acquires, stores and controls the different variables which are involved in the exploitation of the geothermal resource. SCADA (Supervisory Control And Data Acquisition), a monitoring and control system, is currently utilized for the gathering system in Miravalles geothermal field. This system includes all of the operation and production information from separation stations and geothermal wells. However, this is an 11 year old system which has become obsolete and will be upgraded soon.

This report first describes how the monitoring and control system is currently utilized for the gathering system in Miravalles geothermal field, its function and identified problems. Then, some design aspects of modern monitoring and control systems in geothermal plants are described, including recent examples from Iceland. The life-time of SCADA systems, their network characteristics and the redundancy of the systems are some of the most important aspects analyzed, as well as a description of general and specific characteristics related to instrumentation and control equipment as a part of the SCADA system. Analysis, comparing this modern design and the current monitoring and control system used by Miravalles has revealed the need for some improvements in Miravalles.

1. INTRODUCTION

Costa Rica is located in Central America between Nicaragua and Panamá; it is also bordered by the Caribbean Sea to the east and by the Pacific Ocean to the west. Costa Rica has a high potential in renewable energies, such us hydroelectric, geothermal and wind power. In 2008, the total installed electrical capacity was 2.027 MWe, 67% of which comes from renewable energies.

The geothermal potential in Costa Rica is about 900 MWe (Moya, 2008). Geothermal energy has been exploited successfully in the country at the Miravalles geothermal field. The first unit began production in 1994 and since then the Miravalles installed capacity has been increased to 163 MWe or 8% of the total installed electrical capacity and the production is approximately 13% of the electrical energy produced in Costa Rica.

The Costa Rican Institute of Electricity (Instituto Costarricense de Electricidad or ICE) is the governmental company responsible for electrical development in the country. Currently, ICE is developing a new geothermal field called Las Pailas where a 35 MWe unit will begin production in the year 2011, according to the national plan of Costa Rica.

1.1 The Miravalles geothermal field

Miravalles geothermal field is the only field under commercial exploitation in Costa Rica. Its operation began in 1994 with the first unit, which is 55 MWe. Installed capacity increased to 163 MWe over a 10 year period with the development of 5 units, as shown in Table 1. To reach this production, it was necessary to drill 54 wells: 27 production wells, 15 injection wells, 3 monitoring wells, 6 failed wells, and 3 wells that are not production wells. The production wells are divided into neutral and acid wells depending on the composition of the water. Currently, there are 4 acid wells that were neutralized before they were incorporated into the production line.

TABLE 1: Actual installed capacity in Miravalles geothermal field

Unit	Name	Power (MWe)	Type	Start-up date	Owner
Unit 1	Miravalles 1	55	Single flash	March, 1994	ICE
WHU* 1	Boca de Pozo 29	5	Back-pressure	January, 1995	ICE
Unit 2	Miravalles 2	55	Single flash	August, 1998	ICE
Unit 3	Miravalles 3	29	Single flash	February, 2000	GG
Unit 5	Miravalles 5	19	ORC Binary	November, 2003	ICE

WHU*: Wellhead unit; GG: Geoenergía de Guanacaste Ltd., on a BOT contract with ICE

During the production time of the Miravalles plants, monitoring and automatic control systems in separation stations and production wells have played an important role for the operation and maintenance staff as well as the reservoir engineering side in order to manage, assess and provide enough steam for each generating unit.

1.2 Gathering system in Miravalles geothermal field

Currently, the gathering system in Miravalles includes seven separation stations (see Figure 1) and twenty-seven production wells. Each separation station is provided with a control room where the control equipment and complementary systems are located. In each separation station, an automatic process of steam-water separation is carried out without human intervention. Additionally, each separation station is provided with several measuring devices concerned with the main variables involved in the

FIGURE 1: Separation station in Miravalles

separation process and incorporated into the general monitoring system.

Producing wells in Miravalles have important differences in their monitoring and control systems depending on if these are neutral or acid wells (Figure 2). Due to their complexity, the acid wells need an exclusive automatic control system for the neutralization process, whereas for the neutral wells only some alarms and wellhead pressure meters are included in the monitoring and control system. Even though all the neutral wells use inhibition systems to avoid carbonate calcite scaling, only well PGM-29 has an independent automatic control system for its inhibition system. This is because its production serves a small independent wellhead unit (WHU), which produces 5 MWe. The separation stations and producing wells in Miravalles are listed in Table 2.

FIGURE 2: An acid well in Miravalles

TABLE 2: Relationships between production units, producing wells and separation stations

Unit 1			**Unit 2**			**Unit 3**	**WHU 1**
Separation station 1	**Separation station 2**	**Separation station 3**	**Separation station 4**	**Separation station 5**	**Separation station 6**	**Separation station 7**	**Separation station 29**
PGM-05 PGM-31 PGM-65	PGM-03 PGM-17 PGM-66 PGM-19*	PGM-12 PGM-20 PGM-21	PGM-05 PGM-08 PGM-42	PGM-43 PGM-44 PGM-45	PGM-46 PGM-47 PGM-49	PGM-11 PGM-14 PGM-60 PGM-62 PGM-02* PGM-06* PGM-07*	PGM-29

* Acid well

Although ICE, is the only owner of the Miravalles geothermal field and of its entire works except for Unit 3, the operation and maintenance activities of Miravalles are divided administratively between the gathering system and the generation units. For this reason, there is an exclusive control and monitoring system for the gathering system, with separate monitoring and control systems for the generation units (power houses).

The Service Centre of Geothermal Resources – CSRG is the ICE division that performs exploration, development and exploitation activities of the geothermal resources in Costa Rica. Under its responsibility is the field instrumentation maintenance division which performs maintenance activities on the control and monitoring system of the steam gathering system in Miravalles. This research report is focused on the study of this system.

2. DESCRIPTION OF THE MONITORING AND CONTROL SYSTEM IN MIRAVALLES

In this report, the monitoring and control system is commonly referred to as the SCADA (Supervisory Control And Data Acquisition) system. It is assumed that the system includes software elements and control equipment. In order to get a better understanding of this system, the description will be divided in two main topics, the hardware and the software.

2.1 The hardware of the monitoring and control system in Miravalles

2.1.1 Network architecture

The monitoring and control system of the gathering system in Miravalles is provided with a network that includes 12 nodes with a tree type topology for the two branches, interconnected by a fibre optic cable approximately 20 km long in total. This cable is a mono mode type of 12 fibres and several fibre optic converters are used to interconnect the nodes. Every separation station or producing well connected to the network represents a node, as shown in Figure 3, which also shows the distance (m) in metres between the nodes of the optical fibre cable.

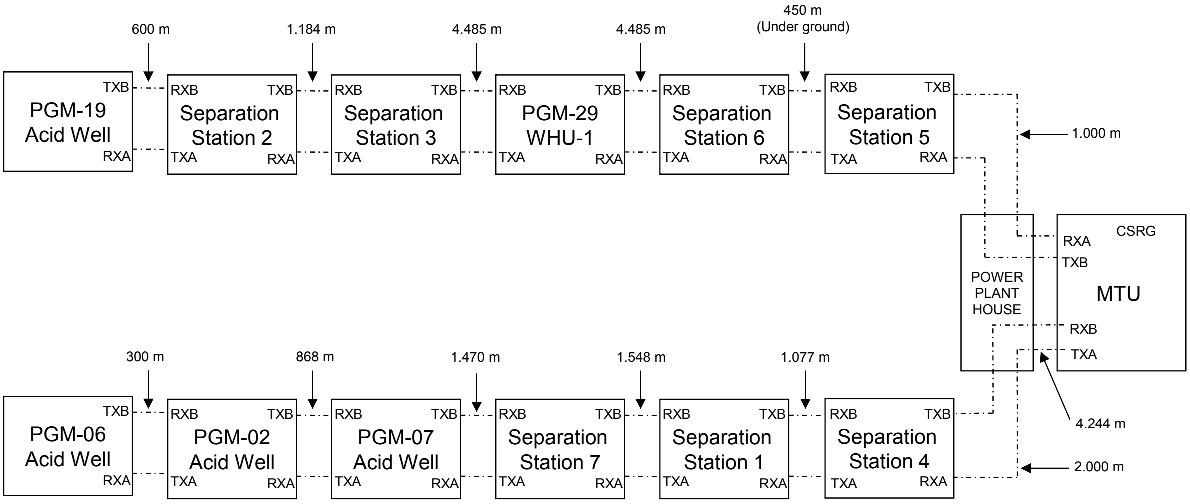


FIGURE 3: Monitoring network in Miravalles and interconnected nodes; MTU is Master Terminal Unit

FIGURE 4: Master Terminal Unit – MTU located at the CSRG

The Master Terminal Unit, MTU, is the main location point of the SCADA system. From this point, there are two net branches towards each of the nodes. Every branch has 6 nodes and both branches go through the power plant house to the MTU. However, the signals are not displayed in the control room of the power plant house. They are displayed in the MTU, which is located in the monitoring room within the CSRG, by the operation staff of the gathering system (Figure 4).

The development of the gathering system in Miravalles was done in 5 stages. First was the construction of separation stations 1, 2 and 3 together with their production wells for Unit 1. The second stage included the construction of separation stations 4, 5 and 6 together with their production wells for Unit 2. The third stage saw the building of separation station 7 intended for the production wells for Unit 3. The fourth stage was the construction of the station for the 4 acid wells together with their neutralization system. Finally, the moving of WHU 1 in 2006 (from well PGM-09 to PGM-29) with an inhibition system for well PGM-29 required an addition to the monitoring system.

As production from the geothermal field increased in stages, the monitoring and control systems were also increased. Separation stations and production wells were added to the monitoring system to supervise and better control the steam production for the producing units. As each one of the additional stages of the monitoring system was handled as an independent project, sometimes different control equipment and instrumentation were used during different stages. During the buying process for each new project, similar equipment was acquired (but with some different features due both to manufacturer's design and to inevitable changes with time), to be used for the same purposes. For this reason, efforts were made to achieve a good interconnection between the equipment developed or acquired at different time.

2.1.2 Automatic control equipment

Automatic control equipment at separation stations consists mainly of a PLC (Programmable Logic Controller), a series of interfacing screens or HMI (Human Machine Interface) and two or three PID (Proportional-Integral-Derivative) controllers. Automatic control equipment for the neutralization system in acid wells consists mainly of a PLC and a HMI. The system for the acid well PMG-19 also includes a PID controller.

The use of the automatic control equipment together with the measurement equipment and all the auxiliary systems allows the unattended operation of separation stations and some dosage systems installed in the geothermal wells. This means that it was not necessary to have full time permanent operational staff at these places to maintain the steam production. As explained previously, due to the different stages at which the gathering system in Miravalles has been developed, there are some differences in the installed control equipment. This is listed in Table 3.

TABLE 3: Automatic control equipment of the steam gathering system in Miravalles

	PLC	**HMI**	**PID Controller**
Separation stations 1, 2 and 3	Manufacturer: Omron Model: C200HS	Manufacturer: Omron Model: NT-631C	Manufacturer: Foxboro Model: 762C
Separation stations 4, 5 and 6	Manufacturer: Omron Model: CS1	Manufacturer: Omron Model: NT-631C	Manufacturer: ABB Model: MOD30ML
Separation station 7	Manufacturer: Omron Model: C200HS	Manufacturer: Omron Model: NT-620C	Manufacturer: Omron Model: E5EK
Acid well PGM-19	Manufacturer: Omron Model: C2000H	Manufacturer: Omron Model: NT-620C	Manufacturer: Foxboro Model: 762C
Acid well PGM-07	Manufacturer: Omron Model: CQM1	Manufacturer: Omron Model: NT-20S	Not used
Acid wells PGM-02, PGM-06	Manufacturer: Omron Model: CQM1	Manufacturer: Omron Model: NT-20S	Not used
Well PGM-29	Manufacturer: Omron Model: CQM1	Manufacturer: Omron Model: NT-20S	Not used

PLC: Programmable logic controller; HMI: Human machine interface
PID controller: Proportional-Integral-Derivative controller

A PLC was installed in every control room located at the separation stations or interconnected wells. These PLCs are used to collect all the data from the measurement equipment and to perform some of the control functions of the steam production process (Figure 5). There is also a HMI installed in every control room. One of its main functions is to show the operational staff all the variables related to the steam production process and operational information of the auxiliary systems. Also, using the HMI, the operator can select between automatic and manual operation of the separation station or interconnected wells. In manual condition, the HMI can be used to execute operational commands.

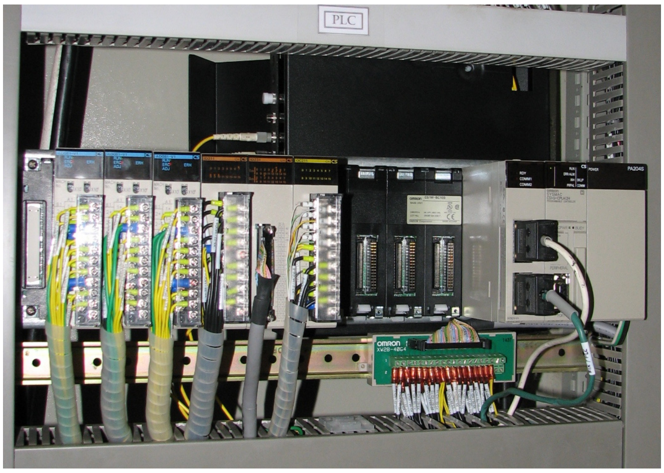


FIGURE 5: Omron PLC, model CS1

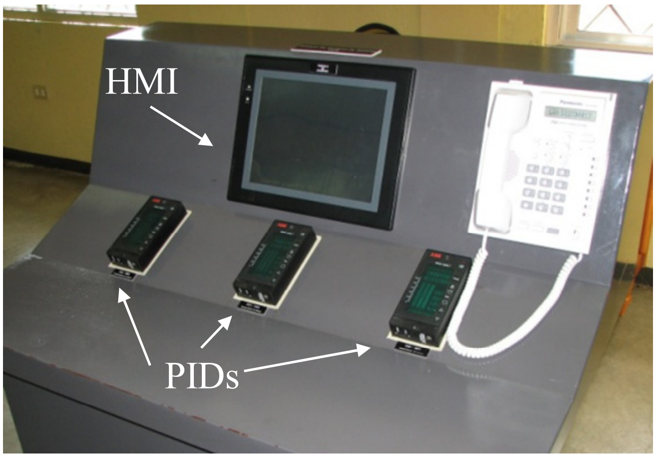


FIGURE 6: Separation station control panel with a HMI, type Omron NT-631C, and ABB PID controllers. MOD 30ML

PID controllers are used in the automatic control systems of each separation station and some acid wells. The main function of these controllers is to lead the automatic control of some critical variables of the steam production process. Every PID is configured specifically for the assigned variable and according to the conditions of the process. A HMI and a PID controller can be seen in Figure 6.

2.1.3 Measurement equipment

Instrumentation in Miravalles is used to measure many kinds of physical variables such as pressure level, temperature, steam flow, valve positions, etc., related to the steam production. Efforts have been made to acquire high level and high performance equipment in order to get optimal reliability of the measurements made. Some examples of the measurement instruments are shown in Figure 7.

Durability is considered another important issue due to the highly corrosive environment around the geothermal field. Due to the very wet tropical weather of Costa Rica, the installed equipment might rust and get damaged quickly. Therefore, high performance materials such as aluminium, stainless steel types 304 or 316, polyurethane were selected.

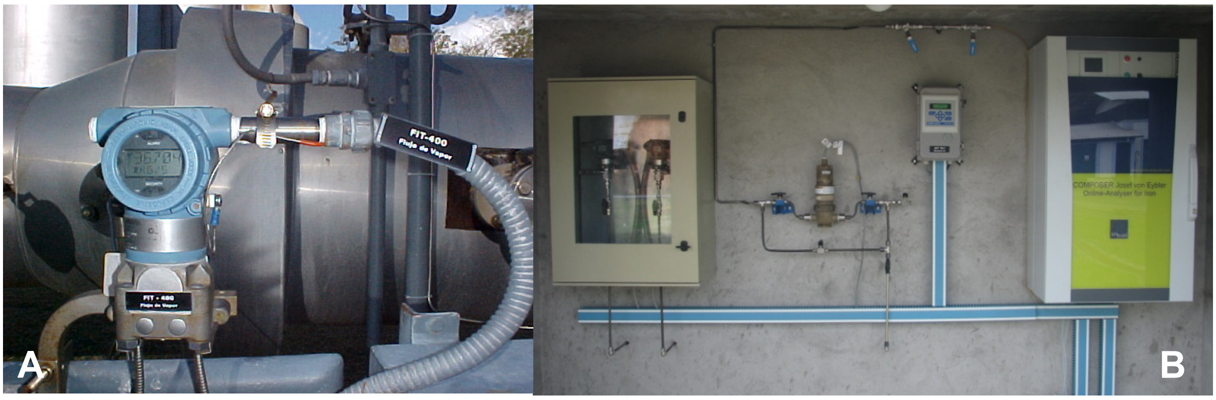


FIGURE 7: a) Differential pressure transmitter; b) Acid well instrumentation (to the left: pressure transmitter, centre: pH meter, and to the right: online-analyzer for iron)

Environments containing gases like hydrogen sulphide, which reacts with copper and silver, are likely to cause corrosion in electronic equipment. About 20% of all electrical and electronic failures are caused by corrosion problems. In H_2S environments, an even higher ratio of failures due to corrosion problems may be expected (Rivera, 2007). Even though the outside mechanical structures in separation stations and producing wells in Miravalles show accelerated corrosion, the hydrogen sulphide corrosion of the electronic equipment and electrical installations is not a big problem. An environmental monitoring programme exists for the surroundings of the geothermal field; measurements of hydrogen sulphide have always been very low (within the error range of the instrument used). This confirms the small impact that this gas has had. Table 4 lists the measurement equipment of the monitoring system used at the separation stations and wells in Miravalles.

TABLE 4: Measurement equipment used in Miravalles

Type	Variables	Main characteristics	Manufacturer
Separation stations			
Pressure transmitter	Steam line pressure Separation pressure	Output 4-20 mA + HART, typical range 0-50 bar, transient protection, accuracy 0.075% of span, display LCD, electronics housing: low-copper alumin. or CF-3M, NEMA 4X, IP 65	Rosemount 3051TA Rosemount 3051TG Siemens 7MF4332 ABB 621PF
Differential pressure transmitter	Steam flow	Output 4-20 mA + HART, typical range 0-600 mbar, transient protection, accuracy 0.075% of span, display LCD, electronics housing: low-copper alumin. or CF-3M, NEMA 4X, IP 65	Rosemount 3051CD Siemens 7MF4432 Yokogawa EJX910A
Temperature transmitter	Separation temperature Brine temperature	Output 4-20 mA + HART, RTD PT100 4 wires, transient protection, accuracy 0.15% of span, display LCD, electronics housing: low-copper alumin. or CF-3M, NEMA 4X, IP 65.	Rosemount 3144DI ABB 658TH Kamstrup Flextop HPT
Level transmitter	Water tank level	Magnetic level gauge with 4-20 level transmitter	Promag PM-260V
Position transmitter	Release valve position Emerg. valve position Water level control valve position Main steam valve position	Output 4-20 mA, typical range 0-90° counter clock, switch limits SPDT, visual indicator, NEMA 4X.	Stonel QZM7VE2C Stonel MQ7VE2C Westlock 2007-CS-RS Proximity 15VD6
Acid wells and well PGM-29			
Pressure transmitter	Well head pressure Separation pressure Pumping pressure	Output 4-20 mA + HART, typical range 0-100 bar, transient protection, accuracy 0.075% of span, display LCD, electronics housing: low-copper alumin. or CF-3M, NEMA 4X, IP 65	Yokogawa EJA503A Yokogawa EJA503A Rosemount 3051
Flow meter	Pumped fluid flow	Output 4-20 mA + HART Range 0-1360 l/h Precision 0.5% in Liquid	Micro Motion 1700I11AECSZZZ Yokogawa Rota Mass RCCF31-AH2A/FF1
pH meter	Brine pH	Output Two 4-20 mA Measurement Range 0-14 Three alarm relays for process measurement or temperature	Rosemount Analytical 1055-01-10-22
Iron meter	Brine iron content	Analogue: 4-20 mA Measuring range 0.1..20 mg/l Fe Accuracy better than +/- 3% (based on full scale) Measuring method: Colorimetric	Seibold Online-Analyser for iron 2008-FE-003A

2.1.4 Data transmission

In order to incorporate all the important variables into the monitoring system, it was necessary to interconnect each one of the nodes to the net using 3 communication protocols for 3 independent channels (ports). Each channel is dedicated to one protocol. The distribution of ports and communication protocols related to the equipment that use them can be seen in Table 5.

TABLE 5: Distribution of ports and protocols of the monitoring system in Miravalles

Port	Protocol	Equipment	Location
0	Host Link	Omron PLCs	Separation stations 1 to 7, acid wells PGM-02, PGM-06, PGM-07 and PGM-19. Well PGM-29
1	Modbus RTU	ABB MOD 30, PID Controller	Separation stations 4 to 6
2	Foxboro	Foxboro 762C, PID Controller	Separation stations 1 to 3 and acid well PGM-19

FIGURE 8: The fibre optic multiplexer used in Miravalles

For each node of the network, one, two or the three of these channels are connected using RS-232 or RS-485 standards with a fibre optic converter, FOC, which at the same time is a fibre optic multiplexer (TC Communications model TC29000S-04-25FC-1-24) (Figure 8). Every fibre optic converter has four available input channels which are multiplexed and transmitted by a pair of optic fibres towards another fibre optic converter in each of the nodes and finally to the Master Terminal Unit.

Related to port 0 and the Host Link protocol, all the instruments used for measuring the variables involved in the steam production process send a signal of 4-20 mA proportional to the variable measured. These signals are led to an analogue input module of the PLC. The connection between each measurement instrument and the PLC is made through a copper multi-conductor control cable. Then the PLC is configured to send all these variables through a module with a RS-232 port to the fibre optic converter and finally to the MTU using the Host Link protocol.

Port 1 and the Modbus RTU protocol are only used for the ABB PID controllers located at 3 separation stations (Unit 2). Modbus is a common protocol used by these PID controllers and the SCADA system. The three PID controllers are interconnected by a RS-485 subnet (typical for this PID model) which is connected with the fibre optic converter (FOC) using a RS-485 to RS-232 converter. Finally, the FOC sends the information related to these PID controllers to the MTU using the Modbus RTU protocol.

Port 2 and the Foxboro protocol is used only for the Foxboro 762C PID controllers located at 3 separation stations (Unit 1). Foxboro is a particular protocol used by these PID controllers but can also be used for the SCADA system. The three PID controllers are interconnected by a RS-485 subnet (typical for this PID model) which is connected with the FOC, using a RS-485 to RS-232 converter. Finally, the FOC sends the information related to these PID controllers to the MTU.

Using the same communication method, the PLC transmits several alarm-signals from the automatic control process and the operations of the separation station or acid well. Many of these alarm-signals come from measurement instruments, switch type, that send a digital signal in case of any alarm activation. Some others are generated according to the operational conditions programmed into the PLC.

2.2 SCADA software of the monitoring and control system in Miravalles

The SCADA software used for the monitoring system of the gathering system in Miravalles is FIX software from Intellution®, version 6.14 developed for Windows 95 or Window NT. The same version has been used from the very beginning, eleven years ago. Two licenses were acquired, one for the SCADA server, that allows SCADA programming development with no limitation of I/O (input/output) points in its database; the other license was for MMI (Man-Machine Interface) which accesses all the data placed at the SCADA server.

Since 1998, it has been necessary to change computer equipment when software is installed due to operating problems. Currently, a SCADA PC Pentium 4, 3 GHz, 512 MB RAM with a 40 GB hard disk using a Windows XP operating system is being used as a server. In addition, as MMI, a PC Pentium 3, 866 MHz, 512 MB RAM with a 20 GB hard disk, using Windows 2000, is being used.

2.2.1 Database

The SCADA database in Miravalles has no limitations in the quantity of variables or I/O points. Its configuration is made by block programming for each variable where the variable type is defined and its characteristics (range, alarms, addresses, etc.) are configured. Several variable types have been used such as analogue, digital, boolean, totalizer, etc. A sample of the variables listed in the database in the SCADA FIX can be found in Table 6.

TABLE 6: Separation station database overview

REC#	Tag Name	Type	Node	Description	Channel	I/O Address	Scan	Curr. Value	Curr. Mode
1	S2_A/M_UPH	DA	S2,	Estado A/M de UPH	OMR	S2:HR:0:1	ON	AUTO	AUTO
2	S2_ABR_VA	DO	S2,	Mando apertura de VA	OMR	S2:IR:221	OFF		AUTO
3	S2_ABR_VE	DO	S2,	Mando apertura de VE	OMR	S2:IR:221	OFF		AUTO
4	S2_ABR_VPV	DO	S2,	Mando apertura VPV	OMR	S2:IR:221	OFF		AUTO
5	S2_ABR_VR	DO	S2,	Mando apertura de VR	OMR	S2:IR:221	OFF		AUTO
6	S2_ALM_ROBO	DA	S2,	Alarma Robo/Incendio	OMR	S2:IR:3:1	ON	NORMAL	AUTO
7	S2_AUT_VA	DR	S2,	Estado A/M de VA	OMR	S2:HR:8:2	PON	AUTO	PAUT
8	S2_AUT_VE	DR	S2,	Estado A/M de VE	OMR	S2:HR:8:1	PON	AUTO	PAUT

Currently, the database has 1,098 programmed variables in total for its 12 nodes. Even thought this SCADA system was commissioned by an external company of automation development, ICE personnel are qualified to perform changes in the SCADA database. This advantage allows ICE to develop improvements of the current monitoring system as well as to include new variables and new nodes to the network.

2.2.2 Operator interface screens

The SCADA system in Miravalles is provided with screens developed according to the process. There are more than 300 screens already programmed. Some of them are of general information type where drawing diagrams appear with different variables of the steam field process. Some others are for specific functions such as operating a unique PID controller or the steam production in detail. Also, special screens were developed to show alarms or to execute control functions, as will be described in further sections. An operator interface screen can be seen in Figure 9.

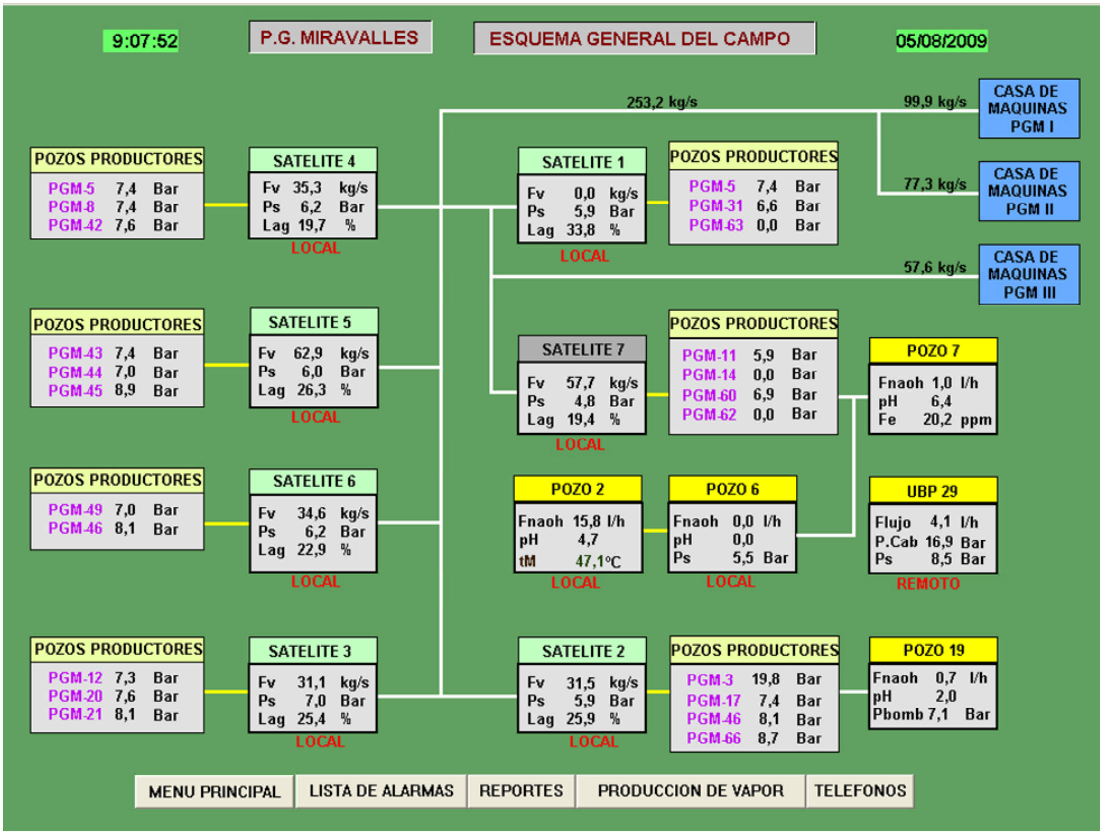


FIGURE 9: Operator interface screen of the SCADA system in Miravalles

2.2.3 Control functions

One of the main characteristics of any SCADA system is to allow the users to remotely execute some control functions to equipment located in the field from the MTU (Boyer, 1999). In Miravalles, several of these functions are programmed for both the separation stations and producing wells. Some of the most important control functions that can be executed by the SCADA system in Miravalles are shown in Table 7.

TABLE 7: Available control functions of the Miravalles SCADA system

Separation stations	Geothermal wells
Remote / Local (separation station control) Open / Close (geothermal valves) Auto / Manual (geothermal valves) On / Off (auxiliary equipment) Auto / Manual (PID controllers)	Auto / Manual (PID controllers) On / Off (dosage equipment)

2.2.4 Historical charts

The data storage facility is one of the most valuable characteristics of the monitoring SCADA system in Miravalles. The data for each variable can be stored for many years, making it possible to generate historical charts for several variables in order to compare tendencies between them. Also it allows behaviour analysis of any variable over time. Using the historical graphs, it is also possible to analyse special events of the steam production process. A behavioural analysis of each variable is shown in the historical chart at the moment when contingencies appear, thus pointing out possible causes of changes or losses in steam production.

2.3 Problems with the existing monitoring and control system

The monitoring and control system of the gathering system of Miravalles was installed in late 1998. From the very beginning some communication problems, from Remote Terminal Units (RTUs) to the MTU, partially affected operation of the system. Therefore, a few years later the system was updated with new fibre optic base communication equipment. These changes were successful. Since then, the system has worked without any new problems with the communication equipment.

Regarding the monitoring network operation, problems are mainly caused by external factors. Some of these factors are breakages of the fibre optic cable in aerial lines due to the climatic conditions of the zone (strong winds) and damages caused by rodents biting cables (non-armoured cables). When the network fails there is a data loss from where the fault occurs. This is because the network has two independent branches and there is no redundancy in data acquisition or storage.

The most important problem of the monitoring and control system considered by the author of this report regards the compatibility between the SCADA licences and the computer equipment (CPU) that runs the SCADA software applications. Some of the CPU internal devices, such as the hard disk, memory RAM and motherboard, have presented functional problems and consequently CPU replacements have been made. The new hardware has called for upgrades in software, both in its operating system and auxiliary programmes or drivers. Some problems with the last replacement of the SCADA server hardware (CPU) are as follows:

- Due to the new hardware with modern technology it was necessary to upgrade from Windows NT (recommended by the manufacturer) to Windows 2000 (based on NT technology).
- New hardware did not allow the installation of a multiport board (RS-232) used by the SCADA system for access to each of the communication ports (Hostlink, Modbus, and Foxboro). Therefore, a new modern multiport board together with its software was installed.
- Furthermore, some separation station control equipment that used Foxboro and Modbus communication channels had information gaps in the database. So, it was also necessary to upgrade drivers used by the SCADA FIX for these channels.

Although it was possible to solve the problems mentioned above, there are others which still persist – mainly software problems. The SCADA server often presents run time errors; with some damaged system files having to be recovered. Also, the SCADA server was formatted after some period of time, because it became slower and unstable, presenting errors in some applications.

Because of all these problems, it is quite clear that it is necessary to update the licensed FIX software which was not designed for both modern hardware CPUs and modern operating systems. Another problem is that ICE is facing an absence of a local provider in Costa Rica for the FIX software. A new provider and maybe some other SCADA system must be found to acquire new licenses and also carry out the required updating changes. Finding a good local provider is very important for ICE. Not only does it simplify the buying process, but access to local technical support is also more reliable.

3. DESIGN OF A MODERN MONITORING AND CONTROL SYSTEM FOR A GEOTHERMAL STEAMFIELD

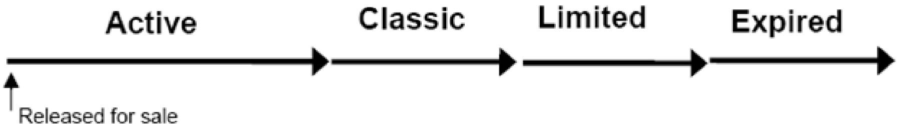
3.1 Monitoring and control systems upgrades

Modern geothermal projects often use a sophisticate system for monitoring and control, while older plants are often operating with many individual analogue systems and older software too. These plants usually need excessive maintenance and many components are becoming obsolete.

Consequently, the reliability of the plant goes down and upgrading is required. Usually such updates are also used to expand the quantity of monitored variables and to improve the control processes.

The life-cycle of a control system can be used to explain more about the needs for a system upgrade. It is often shorter than that of the plant itself. For a geothermal power plant with a life time longer than 30 years, it may be expected that the control system will be renewed at least once during the life of the plant (Magnússon, 2003).

The life-cycle of a product has different phases, as shown in Figure 10. More specifically, the *active* period in the automation level (PLCs, etc.) is often a period of 10-15 years (in some cases 20 years) and in the operator level (HSI: Human System Interface, SCADA) only a period of 3-7 years. This is because the automation level is much more stable than the operator level due to the information technologies (IT) (which SCADA is based on) being subject to shorter product cycles than the automation level (Magnússon, 2003). Once it reaches the stage of *limited,* it is time to start a migration strategy for upgrades. It is important to know that without a highly developed migration strategy it is not possible to guarantee the success of upgrades. The lack of this strategy can result in incompatibility problems between new and old equipment, high difficulty in operating the plant (different types and often badly conceived HSI), and control system components may become prematurely obsolete (due to lack of support or incompatibility with new control system additions). All of these represent economic losses for the plants.



- **Active**: The product is marketed and developed further.
- **Classic**: The product is maintained and developed to a very limited degree.
- **Limited**: Service and support for the product is available, but may be hard to find. Price of spare parts increases sharply.
- **Expired**: Ad-hoc service. If part fails, no service may be available.

FIGURE 10: The product life-cycle (Magnússon, 2003)

When performing a system upgrade, it is necessary to consider that the geothermal projects often make special requirements on control systems (Magnússon, 2003):

- Complex regulation of a largely custom-made process often spreads over a large geographic area;
- Communication system often based on many generations of equipment and protocols due to the evolution of the geothermal project during its lifetime;
- Varying and often non-standardized equipment sizes due to adaptation to well output;
- Due to the above variations, the automation software is most often custom-made and project specific;
- Due to the frequently remote location of geothermal projects, remote monitoring and control of the plant is often preferable;
- H_2S corrosion of electrical systems and electronics in high-temperature fields places special requirements on air conditioning and control system design.

Another aspect to take into account when upgrading the monitoring and controlling system is the importance of purchasing products of recent design and strong market position. If old design automation products are purchased, then their life-cycle and the expiration date will be shorter, meaning the equipment may need to be replaced in just a few years. Besides, products with a small market are likely to have much shorter life-cycles than products that have a stronger market position. Products that are widespread often have strong third-party support that prolongs the service life. A recent design and market position should, therefore, be looked at when choosing key control system components.

When implementing a new monitoring and control system it is necessary to consider some planning aspects (Magnússon, 2003), such as:

- *Software common-mode failures*: Redundant software based components are especially vulnerable to common-mode failures during software upgrades than can introduce the same failure to both parts of a redundant system.
- *Human-system interface (HSI)*: Upgrades without a good migration strategy can result in implementing a not well integrated and harmonized HSI, for example where equipment from several vendors are used frequently, resulting in inconsistent HSI characteristics. Any incoherent modifications are a significant source for human factor related hazards in power plants.
- *Design of the HSI*: When designing a new HSI it is important to consider whether or not the old existing graphical HSI can be used as a basis for tools and base picture elements in the new HSI. In addition, an interactive process between HSI specialists and the customer is essential for a good design of displays including picture elements, dialogues and other display conventions. Thus, it is possible to ensure that the design is according to HSI conventions of the existing plant and, thus, the amount of operator re-training is reduced.
- *Naming conventions:* When naming system changes are necessary as part of a plant upgrade, only one person or a small group of persons should assign names for new signals, objects, equipments, etc. This is to ensure that the naming conventions are applied consistently.
- *Staff participation:* The participation of plant staff in upgrading work has several advantages. It can bring to the project extensive knowledge on the existing plant and its operation. Direct participation in the upgrading project is perhaps the best way of training and educating operation and maintenance personnel. The problem is that the staff often has to perform all its normal duties in addition to the project work. This may lead to conflicts with other tasks and has the potential for delays or undesired technical solutions. The staff should, therefore, be relieved of most or all of their normal duties and preferably assigned to the upgrade project on a full-time basis.

3.2 Migration to TCP/IP and Ethernet networking

Modern monitoring and control networks are most of the time based on the Transmission Control Protocol/Internet Protocol or TCP/IP. It has become the de facto international standard. The advantages of TCP/IP networking are (Kwok-Hong and Barry, 2002):

- Worldwide adoption (e.g. the Internet);
- Very well developed hardware and software market;
- Simplicity and choice of application layer protocols;
- Inherent resilience of the IP routing concept;
- Strong network management, including remote control and monitoring.

Using TCP/IP and the commonly associated Ethernet technology will give power plant operators access to a wide range of standards-based inexpensive hardware and a large pool of trained staff.

TCP/IP networking supports several different services that can be used by plants:

- General plant data (administrative functions);
- SCADA data and automation control;
- Video transmission (CCTV for remote security monitoring of the plant surroundings);
- Voice communications (IP telephone).

3.2.1 Network security

One aspect to consider for TCP/IP networks is network security. To manage threats from external sources most (if not all) operators of private TCP/IP networks use a secure gateway to manage the connection. This gateway is usually called a "firewall". SCADA traffic is effectively segregated from other networked applications when it is carried on analogue circuits. When all traffic is carried on TCP/IP, it will be necessary to provide specific security controls to prevent unauthorised staff from accessing data. The simplest method for achieving segregation is to use the facilities of Multiprotocol Label Switching (MPLS) to build Virtual Private Networks (VPNs). MPLS VPN is a family of methods for harnessing the power of Multiprotocol Label Switching (MPLS) to create Virtual Private Networks (VPNs). MPLS is well suited to the task as it provides traffic isolation and differentiation without substantial overhead. MPLS VPNs are easy to administer and provide any-to-any communication within a community group (Kwok-Hong and Barry, 2002).

3.2.2 Interconnection media technology

There are three basic media Ethernet types: coaxial, twisted pair and optical fibre. The most common type found today is twisted pair. The use of coaxial networks has declined due to their connection cost and installation complexities. New high-speed networks will primarily use copper twisted pair and optical fibre as the physical layer media (Lounsbury, 2008).

As a part of modern networks, optical fibre technology is the most powerful and versatile communication medium due to its high bandwidth capability and immunity from electromagnetic interference. The use of optical fibre has become commonplace in most monitoring and control systems for electrical plants (Kwok-Hong and Barry, 2002).

3.2.3 Industrial Ethernet

Today's industrial network focus has extended the Ethernet network into control applications. This new network will not, however, supplant the existing fieldbus networks in the near term. Currently, there are several industrial Ethernet networks defined by various consortia, including EtherNet/IP™, Modbus-IDA (Interface for Distributed Automation), and PROFINET (Lounsbury, 2008).

Industrial Ethernet is a specialized, rigorous application of standard "office Ethernet" technology that adds some other requirements like downtime reduction, harsh environment resistant, electrical noise and vibration resistant, redundant power supply (including battery backup systems), high security (data protection), wide interconnection options (must link other LANs, serial protocols, legacy networks, and fieldbuses), levels of priority and high performance (in physical equipment, software drivers, routers, and switches). Figure 11 shows an example of an industrial Ethernet network configuration using Siemens equipment for a process control system.

3.3 A centralized system

There is a trend to concentrate the operation of different power plants in centralized control rooms (dispatch centre). This is of concern to power companies operating geothermal power plants since in the majority of cases they are operating more than one power plant and perhaps also a district heating system. This often leads to the problem of connecting the different power plant control systems to the Supervision Control and Data Acquisition System (SCADA) in the central control room.

Geothermal power plants are mostly located in remote and inconvenient areas. It is, therefore, of interest to install remote control and monitoring from a remote control centre, which is conveniently located. In recent years, remote monitoring and control in geothermal projects has been used to an

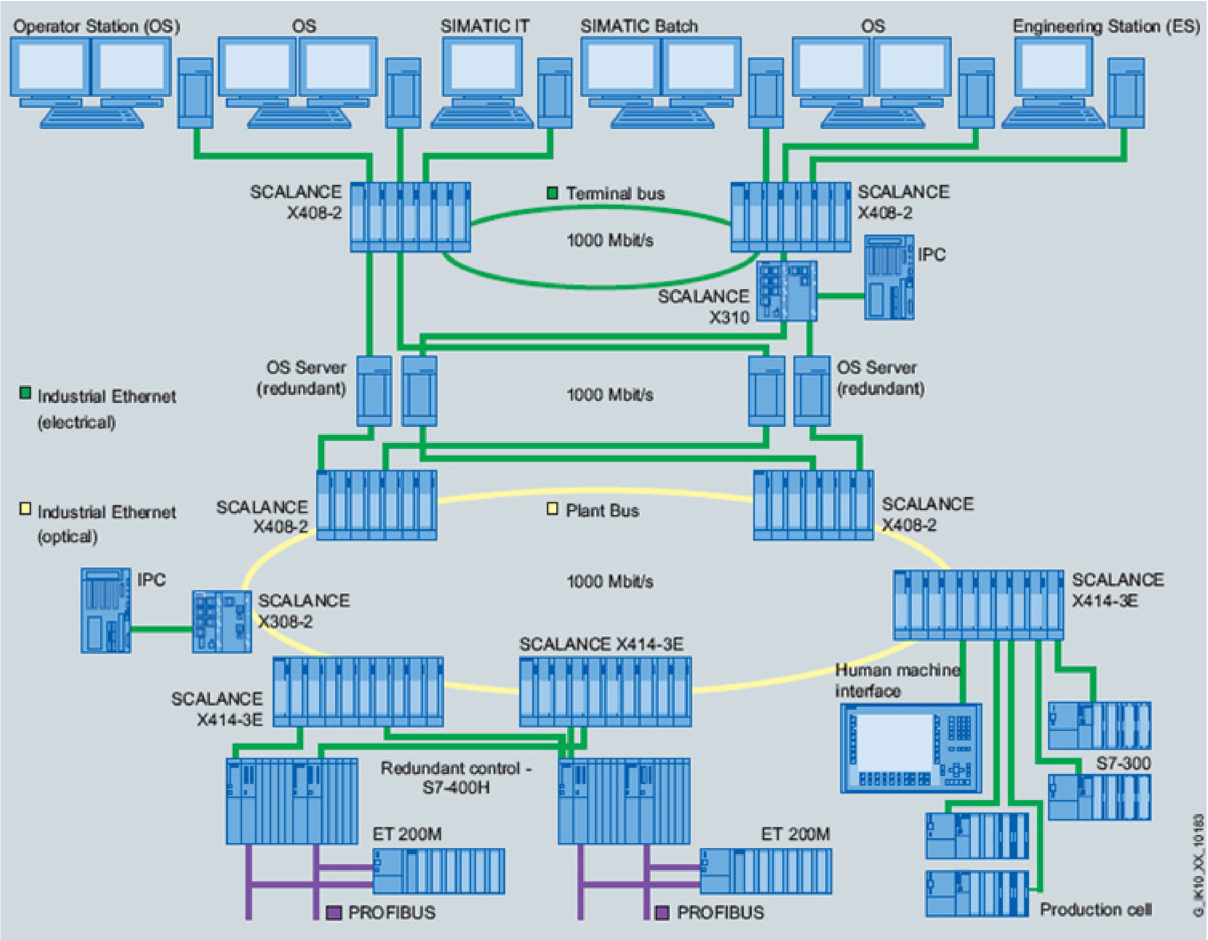


FIGURE 11: An example of an industrial Ethernet network (Siemens, 2009)

increasing degree worldwide often leading to considerable savings in manpower. Closed Circuit TV (CCTV) is becoming popular for remote monitoring of the surroundings of the geothermal plant.

Remote control and reduced staffing on-site can affect plant availability. With reduced staffing on-site, it may take longer to get the required maintenance staff on-site in case of equipment failure. Plant outage time may, therefore, in some cases be longer. To compensate for this, redundant control equipment such as backup pumps that start automatically may have to be installed. Modularisation of the process may also be applied to reduce the risk of one failure stopping the whole plant. The decision to monitor and control the plant remotely does, thus, usually have a significant effect on the design of new plants and their control system. In some cases, remote monitoring can facilitate the diagnosis of a failure and, thus, reduce the time needed for repair. A careful consideration of all the factors affecting plant availability is needed when planning for remote control (Magnússon, 2003).

As an example, at the Nesjavellir power plant, PLCs control every sub-system in the power plant. The control system for the electric power production includes a redundant PLC for each unit. Printers and the engineering station are connected to the systems. The PLC network is connected to the station SCADA system through gateways. The station SCADA system is a part of the Reykjavik Energy (Orkuveita Reykjavíkur) SCADA system. The dispatch centre is in Reykjavík where the daily operation of the plant is monitored and controlled. Normally, the control room at Nesjavellir is unmanned and the operators at the plant take care of the daily maintenance on a daily shift basis (Ballzus et al., 2000). Figure 12 shows the dispatch centre of Reykjavik Energy, as an example of a centralized system in Iceland.

3.4 Redundant SCADA system

Generally SCADA systems are highly reliable; however, they will break down entirely if one piece of the hardware fails. Granted, most modern computers are designed for reliability, but breakdowns still occur, especially with computers located in harsh environments. Considering that all of the geothermal plant processes are critical and the downtime costs are high, redundancy must be incorporated into the system to eliminate failures due to equipment failure. It is possible to greatly reduce lost data and downtime by planning the proper system design, and by choosing a SCADA system with built-in redundancy (Flannagan, 2007).

FIGURE 12: Dispatch centre of Reykjavik Energy in Iceland

In a simple application, the computer connected to the control and monitoring units becomes the server that is dedicated to communication with the plant control devices, while the display nodes are clients. When a client computer requires data for display, it requests data from the server and processes that data locally. To provide redundancy, a second standby server can be added that is also dedicated to communication with plant control devices. If the primary server fails, the client's requests for data are channelled to the standby server.

In some cases, host pairs of servers are used with one host pair dedicated as a standby in a separate location from the primary host pair. The standby server does not duplicate the primary server's functions. In that scenario, both servers would have to communicate with the PLCs, thus doubling the load on the PLC network and reducing system performance. A better solution for a client/server system is one in which only the primary server communicates with the PLCs. The primary server also communicates with the standby server, continually updating the plant's status. If communication is interrupted, the standby server assumes the primary server has failed and takes over the role as the primary server. When the primary server is repaired and returned to service, it reads the plant's status from the standby server and resumes its role as the primary server. Data are automatically backfilled and the two servers become synchronised again as the standby server reverts to its former role.

If a dedicated file server is also added to the SCADA system, the user can centralize the databases and display screens; continuity is then maintained if the primary server fails. Another benefit is that centralized databases are easier to manage and maintain. Changes only need to be made to one database and are then automatically updated everywhere else. In addition, it is possible to support dual network paths to the centralized database, allowing dual file servers if required. On the other hand, if the LAN in a newly configured system fails, then control and monitoring by the display nodes is lost. In view of this, a second LAN and file server are crucial to help ensure system stability, even in the event of a network failure.

Beyond duplicating hardware, the plant can employ split-task redundancy. This goes further than simply maintaining continuous communication with the plant-floor devices; it also ensures that all alarm and trend data are maintained in the event of a failure. Split-task redundancy is aimed directly at the centralised part of the processing, and guarantees that all processing power is employed. It is achieved by splitting the server's task into four subtasks: I/O (input/output); alarms; trends and reports. Each of these tasks manages its own database independently of the other tasks, enabling the system user to handle redundancy differently for each task. In addition, to ensure maximum system stability, redundant PLCs can be employed. This ensures that any hardware component in the system can fail without disrupting the control and monitoring of the plant. Finally, a SCADA system can be provided with two independent power sources, usually battery backed. Each system device (computers, Ethernet switches, etc.) can also have redundant power supplies.

3.5 Contract characteristics

The process of acquiring a new monitoring and control system for a geothermal plant is a laborious and delicate process. The plant must assign qualified personnel to prepare the purchase contract which should have all the conditions and specifications governing the procurement process. A good definition of the aspects governing the contract will be essential to ensure that the plant will get materials and equipment at the desired quality standards as well as the desired operability, including the aspects mentioned above.

It is recommended to use a reference document as a guide for defining both the specific and general aspects of the purchase contract. For example, the electric company Reykjavik Geothermal of Iceland has recently used the document: *Conditions of Contract for Electrical and Mechanical Works Including Erection on Site, 3rd edition 1987*, edited by the International Federation of Consulting Engineers, FIDIC. Based on this document, the most important sections that should be defined as a part of proposal specification documents are discussed in the next sections.

3.5.1 Procurement – Tender documents

Tender documents include the general information related to the purchase process such as tender submission date and address, purpose of the proposal specification documents, interpretation of proposal specification documents prior to tender submission, addenda (modifications), alternative tenders, evaluation of tenders, etc.

3.5.2 Special conditions

All kinds of special conditions related to the project must be defined here. Some of them are engineer's duties, performance bond or surety, contractor's equipment, electricity, delay in completion, consequences of failure to pass a test upon completion, terms of payment, insurance of works, labour, materials and transport, customs and import duties, disputes, governing law, etc.

3.5.3 Tender and contract forms definition

There are many forms that should be used during a purchase process. This section defines the charts or tables to be used in tenders. Some of them are a form of tender, schedule of prices, hourly rates for labour, hourly rates for equipment, submitted drawings and documentation, guarantees, name of contractors and subcontractors, statement of qualifications, maintenance equipment, etc.

3.5.4 Technical specifications

As a part of the proposal specification documents, the technical specifications section is one of the most important as it describes in detail the characteristics of the equipment to be acquired. As an example, the following is a summary of the most important technical specifications of a contract for a monitoring and control system. This information is based on the "*Control and protection system of contract documents of Hellisheidi geothermal power plant"* (Reykjavík Energy, 2004).

SCADA network: The SCADA network should interconnect all the station SCADA system equipment in the plant on a redundant SCADA network, suitable for the harsh environment of a power plant. The communication in the station SCADA system network will be through Ethernet TCP/IP double network. The SCADA network will be 100 Mbit/s Ethernet. All switches and other active equipment needed should be furnished. All interconnections should be fibre optical, except within the same cubicle or same cubicle row. Two independent LANs or LAN backbones (or a ring connected LAN) should be provided and the SCADA equipment should be divided between the LANs in such a way that a single fault in either LAN will not render the SCADA inoperable.

SCADA hardware: The hardware configuration should be flexible and of a distributed design, centred around the LAN interconnected computer equipment. The user interface should be based on computer workstations. All hardware furnished should be new and the latest version of hardened design, intended for industrial use. The SCADA system hardware should basically be divided into two redundant parts, the main and reserve systems that are physically separated. The systems should be centred on the operator consoles in the control room (see Figure 13). The main equipment of the two redundant SCADA systems, except for workstations, will be placed in separated computer rooms.


FIGURE 13: Operator consoles in the SCADA control room of Hellisheidi power plant in Iceland

All key components, such as servers and workstations, should be identical and interchangeable to facilitate maintenance, in case of hardware failure. The proposed solution is to split the SCADA system into a main and reserve system. The reserve system should be used in case of a failure in the main system. The reserve operator console will be used for maintenance work and training when the main operator console is in operation. Two or more operator consoles (OCs) should be located in the control room and in the dispatch centre. The OCs are independent from each other in such a manner that it should be possible to use each of the OCs as a reserve OC for the other in the case of failure in one of them.

Scada software: The software should be standard-based, distributed, LAN-based, and allow hardware platform independence. Any SCADA equipment could experience a power failure, and then an automatic restart of the system or the relevant equipment should be initiated when the power comes back on.

The real-time SCADA database with the data coming from the PLCs, historical data logging, etc. should be stored in a logical data structure. All access to the database should be through well defined access routines. For each SCADA system, two identical copies of the database, on separate computers, the main and reserve database server, should exist at all times. A failure in one of the database servers should thus not affect SCADA system operation or access to the database from the office LAN. Upon restoration of the faulted database server, the database should be restored and database synchronization resumed.

To protect the security of the SCADA system, external access should be through a LAN gateway or a LAN router. The gateway or router should give adequate protection, including passwords, to guard the SCADA system against any attempt to access the SCADA system without permission. In addition, the SCADA security system should provide its own password protection.

It should be possible to edit database data, modify displays, and perform other common maintenance operations on-line on the SCADA without disturbing the normal operation of the SCADA. Facilities for testing and checking the effects of system changes before they are fully incorporated should be provided. This applies to, for example, display and database editing.

Only one operator console at a time should be given authority to send commands to a specified controllable object. Preferably, it should be possible to configure the system in such a way that certain sub-processes can only be commanded by certain operators (as decided with login privileges) or from certain workstations. The control of a system should only be permitted from one site at a time, i.e. the station control or remotely from the dispatch centre. It should be clearly indicated on the display whether an object is controllable, see Figure 14.

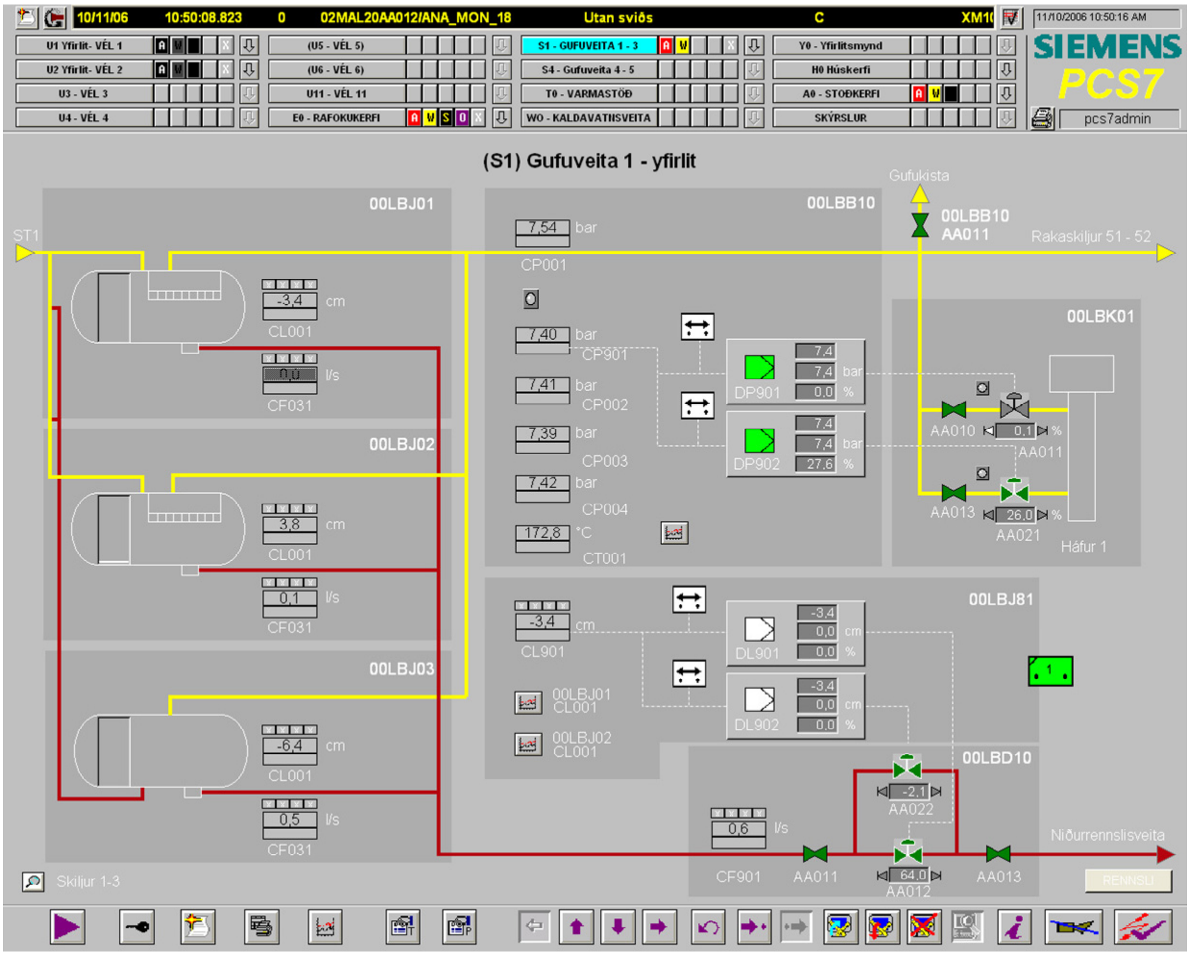


FIGURE 14: Screen of the separation process of the SCADA system in Hellisheidi power plant in Iceland

PLC network: The connection from the PLC network to the SCADA network will be through OPC/gateways, based on OPC (OLE for process control) interfaces. These interfaces are based on Microsoft's OLE/COM (Microsoft Component Object Model) technology, and DCOM (Distributed Component Object Model) technology, which are based on open software application interoperability between the automation/control applications, field systems/devices and business/office applications. For the PLC network, two independent LANs or LAN backbones (or a ring connected LAN) should be provided and the PLC equipment should be divided between the LANs in such a way that a single failure in any LAN will not render the SCADA system inoperable.

Programmable logic controller (PLC) systems: Each PLC system should be an independent control system able to operate independently of the station's SCADA system and other PLC systems. Each

PLC system should control the processes of its system and collect measurements, indications and alarms for local and remote indications to the station SCADA system. The PLC systems in normal operation should be controlled from the station SCADA system. A fault on a single PLC unit should not disturb the service of the other PLC units.

All the control functions, such as start/stop, raise/lower, open/close, set-point adjustments and essential monitoring functions such as alarm listing should be accessible from the station SCADA system operator consoles OCs. The station SCADA system should include the necessary number of graphical process diagrams to give a good overview over the status of all equipment in the respective PLC system and include all control functions in the systems in a clear way.

Programmable logic controllers (PLC) should be of an appropriate type for power plant applications and their design should be modular, with easily replaceable units. The PLC should fulfil the reliability and availability requirements of these specifications. A redundant CPU configuration should be used throughout to enhance availability. Figure 15 shows an example of a PLC SIMATIC S7-400 from Siemens, with redundant CPU, used in Hellisheidi power plant.


FIGURE 15: Redundant programmable logic controller, PLC

All hardware and software, programming, software configuration and testing necessary for a complete and appropriate function of the respective control systems should be included. All PLCs should be from the same manufacturer and be of the same product line. Programming devices provided should be able to access all PLCs, using the same software package central from the engineering station in the control.

4. MEASUREMENT INSTRUMENTS FOR THE SCADA SYSTEM OF A STEAM GATHERING SYSTEM

In monitoring and control systems used for geothermal plants, a lot of information related to the steam production process is required. To get all this information, it is necessary to apply different types of measurement instruments. These instruments are used for every one of the variables of interest at the separation stations and producing wells of the geothermal field. In this way, the information gathered from the measurement instruments is used by the monitoring and control system to keep the steam production process working properly.

Later in this report, some important aspects of design for the instrumentation used in the separation stations and producing wells will be included. A correct design is necessary to ensure the SCADA system receives the right information.

4.1 General and special requirements

The monitoring and control system requires that the information coming from the measurement instruments be highly reliable, as plant production depends upon it. For that reason, all the measurement instruments from the separation stations and producing wells (the same for the rest of the plant) require special features that must be specified during the purchasing processes. These special requirements must be according to the special conditions in the geothermal field and also to the high quality standards that guarantee the reliability needed. For a steam gathering system the following measurement instruments are the most commonly used:

- Temperature transmitters;
- Pressure transmitters;
- Level transmitters;
- Flow transmitters.

Some of the general requirements that all these instruments should meet are:

- All equipment should be of the manufacturer's standard production and should be in accordance with the provisions of the applicable IEC (International Electro-technical Commission) recommendations and other national standard bodies.
- The atmosphere in close vicinity of separation stations and producing wells contains a high concentration of hydrogen sulphide (H_2S). Therefore, no equipment in direct contact with the atmosphere may contain copper, silver or their alloys. All copper, silver and their alloys in electrical circuits must be tinned or protectively coated against hydrogen sulphide.
- All surface treatment of the equipment, type and thickness of coatings should be documented.
- For all sensors, the output signal should be 4-20 mA, except Pt100 temperature sensors that are directly connected to 4 wire Pt100 inputs on Programmable Logic Controllers. The 4-20 mA signals should be in accordance with IEC 60381-1. Also, 4-20 mA signals with superimposed HART protocol for additional information may be considered in order to facilitate maintenance.
- The enclosure rating should be IP 54 or better for indoor applications and IP 65 or better for outdoor applications.
- It is also important to state some aspects such as kinds of markings, official language, inspections and testing certificates, and technical documentation.

A short description of various types of the above mentioned measurement instruments, and their advantages or disadvantages, is given in the following sections.

4.1.1 Temperature transmitters

Temperature measurement is an important part of geothermal operations, typically accomplished by a temperature sensor in contact with a solid surface or immersed in a fluid. Thermocouples and resistance temperature detectors (RTD) are the two most common sensors types. Although these sensors have overlapping temperature ranges, each has certain application-dependent advantages. Several factors must be considered when selecting the type of sensor to be used in a specific application: temperature range, accuracy, response time, stability, linearity, and sensitivity. An RTD is the sensor of choice when sensitivity and application flexibility are the most important criteria, as in the case of geothermal plant applications.

RTDs operate by exhibiting an increase in resistivity with an increase in temperature. RTDs are most commonly made from platinum, nickel, or copper. Copper and nickel versions operate at lower temperature ranges and are less expensive than platinum. Platinum (Pt) is the most versatile material because of its wide temperature range (–200 - 850°C), excellent repeatability, stability, and resistance to chemicals and corrosion.

FIGURE 16: Temperature transmitter with an RTD sensor

RTDs are available in 2-, 3-, and 4-wire configurations. The 2-wire version is well suited to applications where the sensor is directly connected to the receiver to prevent lead length resistance errors, a problem that led to the development of more accurate 3- and 4-wire configurations. When there is a significant distance between the sensor and the receiving instrument, 3-wire units are used; their accuracy, although less than that of a 4-wire detector, is sufficient for many industrial applications. In the 4-wire configuration, one pair of leads supplies the excitation current to the RTD and the other pair measures voltage across it. This technique significantly minimizes lead voltage drop and provides high accuracy.

Temperature transmitters with RTDs type Pt100 4-wires are recommended in the separation stations and for producing wells (see Figure 16). They can be used to measure the geothermal fluids in its different phases: vapour, brine or two-phase fluid. An appropriate installation method is using thermo-wells which are welded to the pipe line. Thermo-wells allow maintenance activities such as sensor replacements without cooling down of the pipe.

4.1.2 Pressure transmitters

Three types of pressure measurements: absolute, differential and gauge pressure, are available. Absolute pressure is measured relative to a perfect vacuum (i.e. atmospheric pressure). Differential pressure is the difference in pressure between two points of measurement (this is commonly used for level and flow measurements as describe later in the report). Gauge pressure is measured relative to ambient pressure. Gauge pressure transmitters are used in separation stations and producing wells for variables' measurement such as wellhead pressure, separation pressure and steam line pressure. A common transmitter type used is 2 wires, 4-20 mA with a pressure rating dependent on the piping system design (ASME class).

4.1.3 Level transmitters

Level transmitters are used to measure the level of a liquid within a specified space. Level transmitters can operate through a wide range of temperatures, pressures, vapour gas mixtures, and processing conditions. Level transmitters can use many different technologies to sense or measure levels. Some include capacitive or RF admittance transmitters (use a radio frequency technique based on differing dielectric constants), differential pressure level transmitters (measure head pressure in a vessel due to height of liquid in vessel), electrical conductivity or resistance devices (use a low-voltage power source applied across separate electrodes; a conductive liquid contacting both probes completes the conductive circuit), mechanical or magnetic floats (have sealed reed switches in their stems with a permanent magnet installed in the float, when the float rises or falls, the switch is activated), optical level transmitters (use optic sensors and principles of optical refraction to detect the presence or absence of fluid), radar or microwave (driven devices that emit a microwave pulse toward the process material; the pulse is reflected back by the surface of the material and picked up by receiver) and sonic or ultrasonic level transducers (measure the length of time it takes for a reflected sound wave to return to a transducer and the transmitted time is proportional to the level).

For geothermal applications, level transmitters are used mainly in the separation stations for level measurement in the separated water tanks or separators. Due to the high temperature, high pressure and the proprieties of geothermal brine, there are two types of level transmitters commonly used: differential pressure and magnetic float.

For geothermal plants in Iceland, a common differential transmitter type is 2 wires, 4-20 mA with a pressure rating dependent on the piping system design (ASME class). As shown in Figure 17, differential pressure between P1 and P2 depends on the liquid level changes; the transmitter sends an electrical signal proportional to the level within the tank.

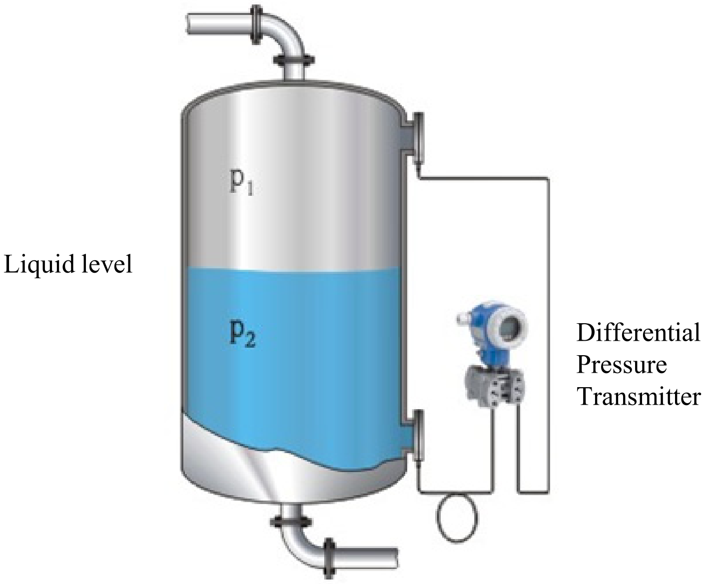


FIGURE 17: Differential pressure level measurement

Magnetic float sensors have been used for many years in Miravalles geothermal field with very good results. This type of level transmitters has better performance than the differential pressure transmitter type but it is more expensive. Figure 18 shows how magnetic sensors are used to level measurements. A specially designed and engineered float is housed in a non-magnetic chamber. The float is weighted to the specific gravity of the process fluid and is equipped with a series of magnets which generates a sufficient flux so as to attract another magnetic assembly on the outside of the chamber. This external magnetic assembly has an array of magnetic relays in a special container attached to the external wall of the float chamber. As the float moves with the changes in the liquid level of the vessel, the strong magnetic attraction between the relays and the float will ensure the activations of the relays. These relays are used to produce an electrical signal that varies with the position of the float exactly and thus, in turn, the liquid level precisely.

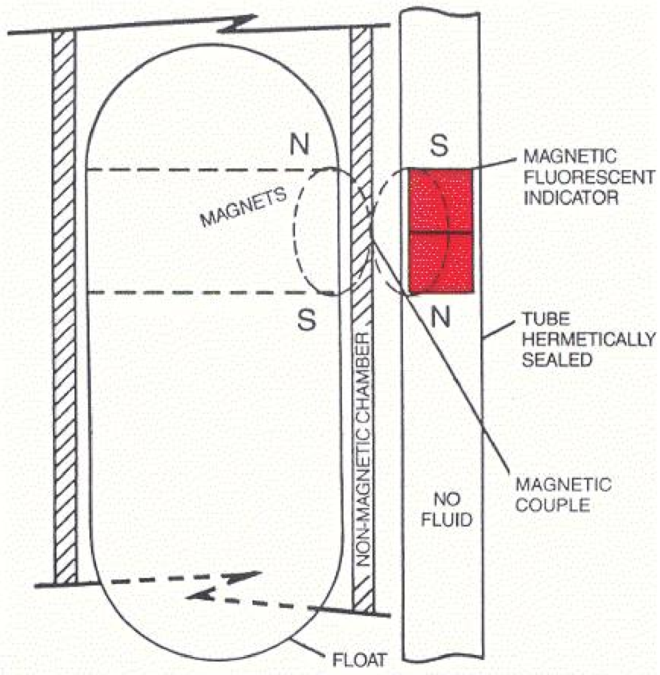


FIGURE 18: A magnetic float sensor for level measurement

4.2 Geo-fluid flow meters

Mass flow rates of two-phase geo-fluids are best measured directly by first separating the two phases and measuring the flow rates of the liquid and vapour individually by means of venturi meters or calibrated orifices. Venturis are very accurate for determining volumetric flow rates. If the fluid density is known, then the mass flow rate can easily be calculated. A sharp-edged orifice plate may also be used for these measurements. They are much less expensive than venturi meters and are more suitable for field measurements. Venturi meters are more appropriate when accurate measurements are needed for steam flow rates being delivered to a power station (DiPippo, 2008).

Manufacturers of measuring instruments offer several options for flow meters that can be used in separation stations and producing wells. In Iceland three options have mostly been used, which have performed well. These are discussed in the following sections.

4.2.1 Electromagnetic flow meter

The operation of a magnetic flow meter or mag meter is based upon Faraday's law which states that the voltage induced across any conductor as it moves at right angles through a magnetic field is proportional to the velocity of that conductor (Omega Engineering Technical Reference, 2009a).

Faraday's law:

$$E \text{ is proportional to } V \times B \times D$$

Where E = The voltage generated in a conductor;
V = The velocity of the conductor;
B = The magnetic field strength;
D = Distance between electrodes.

To apply this principle to flow measurement with a magnetic flow meter, it is necessary first to state that the fluid being measured must be electrically conductive for the Faraday principle to apply. As applied to the design of magnetic flow meters, Faraday's Law indicates that signal voltage (E) is dependent on the average liquid velocity (V) the magnetic field strength (B) and the length of the conductor (D) (which in this instance is the distance between the electrodes). In the case of wafer-style magnetic flow meters, a magnetic field is established throughout the entire cross-section of the flow tube (Figure 19a). If this magnetic field is considered as the measuring element of the magnetic flow meter, it can be seen that the measuring element is exposed to the hydraulic conditions throughout the entire cross-section of the flow meter. With insertion-style flow meters, the magnetic field radiates outward from the inserted probe (Figure 19b).

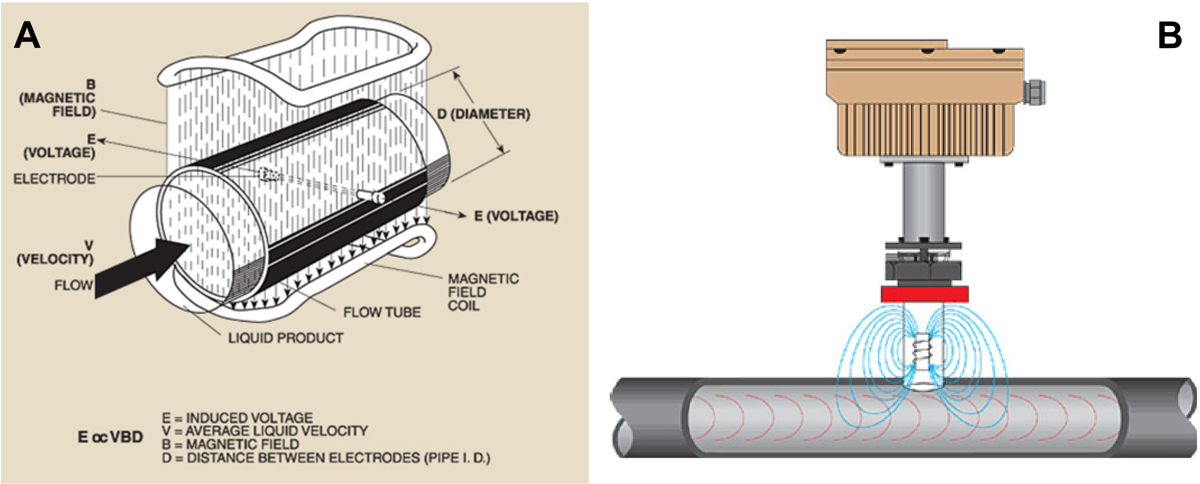


FIGURE 19: Magnetic flow meters; a) Wafer-style; b) Insertion-style

Electromagnetic flow meters have been used successfully in Iceland for applications in geothermal plant, mostly used for cold and hot clean water. The accuracy required of this type in Hellisheidi power plant is ±0.25% or better. If pipe lines are bigger than DN400 and accuracy is not very important, ultrasonic flow meters are used instead (see Section 4.2.2). Condensate fluid is never measured with an electromagnetic flow meter because of the low conductivity associated with this fluid.

4.2.2 Ultrasonic flow meter

The basic principle of operation employs the frequency shift (Doppler effect) of an ultrasonic signal when it is reflected by suspended particles or gas bubbles (discontinuities) in motion. This metering technique utilizes the physical phenomenon of a sound wave that changes frequency when it is reflected by moving discontinuities in a flowing liquid. Ultrasonic sound is transmitted into a pipe with flowing liquids, and the discontinuities reflect the ultrasonic wave with a slightly different frequency that is directly proportional to the rate of flow of the liquid, see Figure 20 (Omega Engineering Technical Reference, 2009b).

Ultrasonic flow meters have been used successfully in Iceland for applications in separation stations and others sites of the geothermal plant. They are mostly used for brine and condensate fluid, but also in pipelines bigger than 400 mm in diameter if an accuracy of ±2% is accepted.

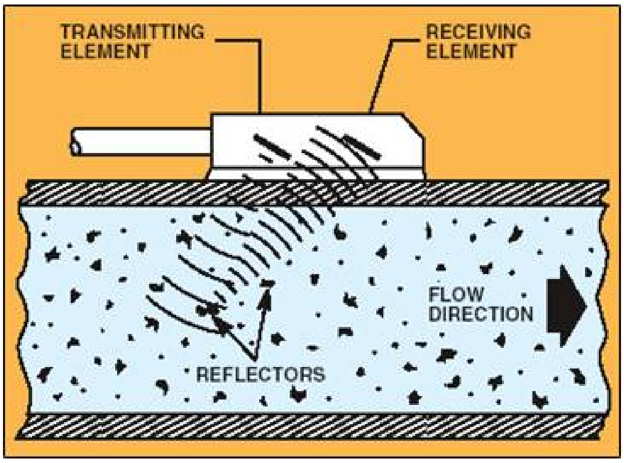


FIGURE 20: The ultrasonic Doppler flow sensor

4.2.3 Differential pressure-based flow meters

Steam flow can be measured with several types of flow meters. The most commonly used ones for geothermal steam are those based on differential pressure measurements like orifice plates and venturi tubes. Orifice plates have become the most important type in Iceland because of their good performance and low cost. Venturi tubes are also highly used by geothermal power plants but for applications when high accurate and reliability are required as they are more expensive than orifice plates.

Differential pressure-based flow meters measure steam flow by using a primary element to cause a pressure drop. Flow rate varies with the square root of the pressure drop across the primary element. Pressure drop is measured with a differential pressure transmitter. Orifice plates contain a hole or orifice through which flow passes (see Figure 21). Upstream and downstream piping are required to condition the flow and provide for accurate measurement. Pressure is measured upstream and downstream from the orifice plate with a differential pressure transmitter, which then calculates the flow rate.

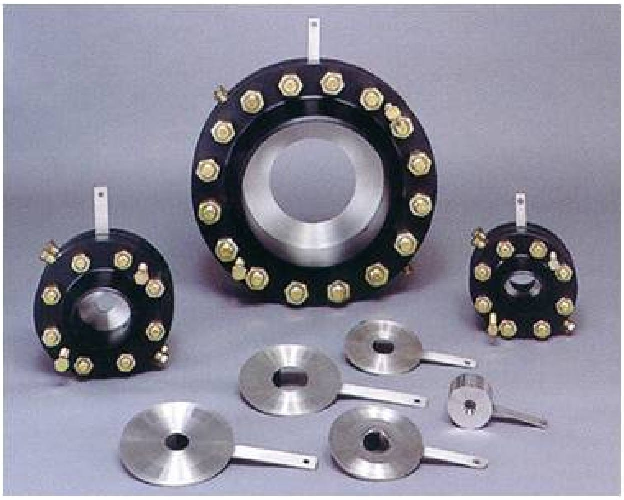


FIGURE 21: Typical orifice plates

Venturi tubes consist of a tapered inlet and outlet with a straight section in the middle that is narrower than the pipe diameter (see Figure 22). They have a length of about eight pipe diameters. Pressure drop is lower than with orifice plates. Upstream pipe requirements are less stringent than those for orifice plates, and they do not require straightening vanes. On the other hand, venturi tubes are more difficult to manufacture with precision than orifice plates, which makes them more expensive. Their size makes them difficult to inspect and change (Yoder, 1998).

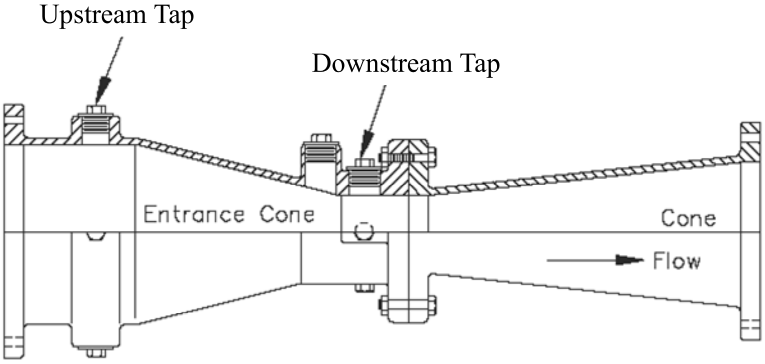


FIGURE 22: Venturi tube

5. CONTROL FOR THE SCADA SYSTEM OF A STEAM GATHERING SYSTEM

A geothermal gathering system has end users requiring steam at specific pressure, temperature or flow. Therefore, it is important to control these parameters. For example, in Hellisheidi power plant the steam supply system ensures a certain pressure to the turbine, as well as protects equipment in case of an emergency. Control loops are integrated into the SCADA system and use monitoring and control elements described by this document.

5.1 Pressure loop

The main aim of the pressure loop in the steam supply system is to protect the pipeline and other equipment as well as to adjust the steam pressure to the turbine. A pressure transmitter is usually located close to the turbine and sends the measured value to the Programmable Logic Controller (PLC) of the control system. The PLC compares that value with its previously defined set point and sends back a signal to the positioner of the steam relief control valve. Thus, the control valve opens or closes in order to maintain the separation pressure as required by the designed plant conditions. The main feature is to protect equipment, i.e. if a turbine trips then the control valve releases all excess steam into the atmosphere temporarily until the turbine starts again.

5.2 Water level loop

The main aim of the water level loop in separation stations is to optimize the performance of a separator. A water level transmitter is located at the separator and sends the measured value to the PLC of the control system. The PLC compares that value with its previously defined set point and sends back a signal to the positioner of the level control valve. Thus, the control valve opens or closes in order to maintain the water level as required by the designed conditions of the separators.

5.3 Control valves

ISA S75.05 offers a formal definition of a control valve: It is a power operated device which modifies the fluid flow rate in a process control system. It consists of a valve connected to an actuator mechanism that is capable of changing the position of a flow controlling element in the valve in response to a signal from the controlling system. This definition, a distillation of several other formal definitions, is extremely broad, even including off-on valves. The control valve is integral to, and inseparable from, the control system. Control begins when the valve is actuated. The valve is chosen to be reasonable in cost, requiring minimum maintenance, using the least amount of energy, and compatible with the control loop (Globalspec, 2009). Figure 23 shows a typical control diagram which includes these elements.

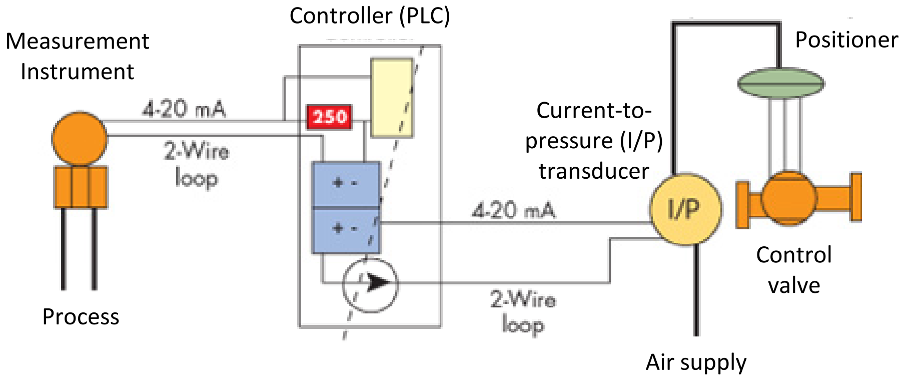


FIGURE 23: Typical control valve process

Control valves play an important role inside the automatic control and monitoring of a gathering system in a geothermal plant. These valves are used by the control system (SCADA) to fulfil the control functions inside of a separation station. It means that the automatic control of variables such as the steam pressure and the separator water level is made through the control valves under the commands of the SCADA system. The correct operation of these valves is basic under the point of view of the automatic control, in general, for they are located as final elements in the control process.

There are many different types of control valves for industrial processes. Some of them are globe valves, butterfly, eccentric disk, ball, etc. The most commonly used for geothermal applications in Iceland are: the globe valve with rotating plug for wellhead applications, the butterfly valve for brine control applications and ball valves for pressure relief steam applications. As an example, one special valve used for relief steam applications at Hellisheidi power plant is the R-Series V-port segment valve with Q-Trim (from Metso Company). Q-Trim valves (Figure 24) optimize noise attenuation, pass impurities, provide very high range ability and keep the valve dimensions, weight and cost reasonable.

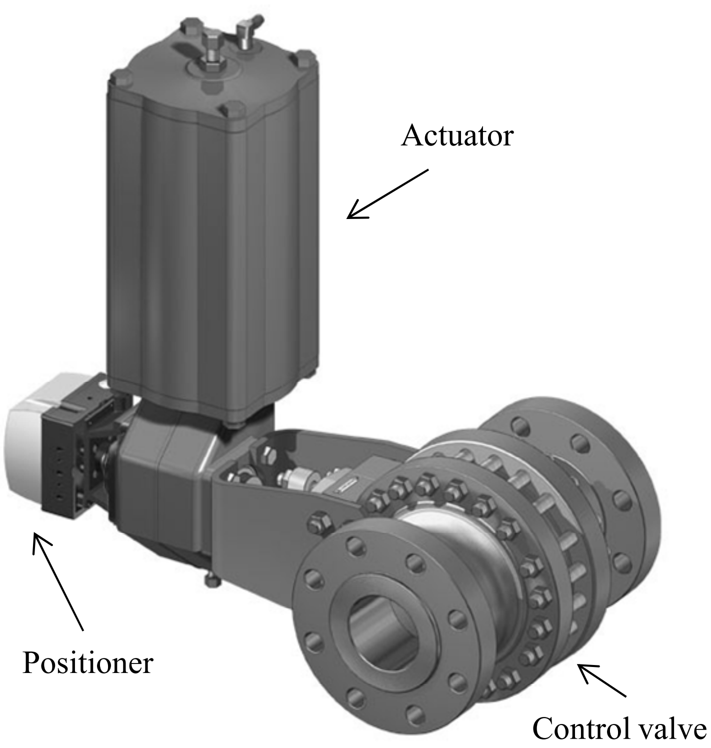


FIGURE 24: Q-Trim control valve, actuator and positioner

5.3.1 Actuators

Due to the high pressure in geothermal power plants, a high torque is required for control valves. Therefore, a mechanical actuator (Figure 24) is necessary for moving the valve. There are three main types of actuators: pneumatic, hydraulic and electric. All of them can be used for geothermal applications but advantages have been found for pneumatic actuators in Iceland, such as low maintenance, higher regulating abilities and being more economical.

Another important feature of the pneumatic actuators used in Iceland is that they use a clean air source with positive pressure to maintain mechanical chambers of actuators over pressure. This will prevent environment air entry into actuators to avoid corrosion problems caused by moisture and hydrogen sulphide gas (H_2S), typically found at the surroundings of geothermal fields.

5.3.2 Positioners

Similarly, there are some special electronic devices required for positioning control valves. Different types of positioners (Figure 24) can be found, such as conventional pneumatic, conventional electro-pneumatic, smart positioners, etc. The most frequently used for geothermal applications in Iceland are the electro-pneumatic (with 4-20 mA control signal) and smart ones.

Positioners are protected from corrosion in the same way as for the actuators. This is the reason why a positioner design which allows over pressure for its internal parts is used. Also, all copper, silver and their alloys in electrical circuits of positioners must be tinned or protectively coated against hydrogen sulphide.

5.3.3 Technical specifications

When purchasing control valves, it is very important to specify the responsibility of the manufacturer in order to optimise the performance of the control valves. In Iceland, when purchasing control valves, some of the following requirements are made:

- The valves should be manufactured and tested according to local and international standards (depending on location of the project).
- Tightness test of the shell and the main seal should be performed on the completed valves with water at a test pressure according to local and international standards (depending on location of the project).
- The valve's seller should undertake full responsibility for all parts of the valves including additional equipment, e.g. actuators, etc.
- The valve's supplier should undertake full responsibility regarding sufficient actuator torque and characteristics required for the operation of the valves. The actuator should be sized according to the closing time and the maximum pressure difference defined for the project.
- The tenderer should state all surface treatment of the valves and additional equipment and type and thickness of coating.
- Material for valve parts should be suited for each fluid type (depending on fluid characteristics of the project). Material should be chosen with the high risk of silica scaling as well as high cavitations environment in mind. Due to silica precipitation (SiO_2) and throttling, hard facing of attacked parts (i.e. seats) is required. No copper alloys should be used for any parts of the valves and their accessories e.g. actuators, etc.
- All equipment should be of the manufacturer's standard production and should be in accordance with the provisions of the applicable International Electro-technical Commission (IEC) recommendations.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- With this research work, it is clear that some elements of the monitoring and control system of the gathering system in the Miravalles geothermal field are in the final phase of their life-cycle and have become obsolete. Some others can be improved to achieve greater reliability of the steam gathering system and improve control processes.

- The SCADA software currently used in the Miravalles geothermal field should be updated and this should be based on a highly developed migration strategy previously developed. It should follow the recommendations given in this research paper such as for purchasing products of recent design and strong market position, good compatibility between human-machine interfaces and giving a wide participation to the staff.

- In order to ensure maximum system stability, the SCADA network currently used in the Miravalles geothermal field can be improved using an Ethernet Industrial network including the concept of redundancy for both software and hardware elements. It should include a design that takes into account the fibre optical net currently operating, the compatibility with existing communication equipment and the communication features of Programmable Logic Controllers. Perhaps a gradual migration to a new SCADA system is most feasible, starting with new wells or wells that need to be refurbished.

- Due to the widespread location of separation stations and producing wells in the Miravalles geothermal field, the SCADA system has achieved considerable savings in manpower using a remote control room conveniently located within the concept of a centralized system. New plant extensions can be added to this system, including the new steam gathering system for the Las Pailas geothermal field.
- Measuring equipment for temperature, level, pressure and flow used in the gathering system of Miravalles geothermal field have demonstrated, and in some cases have exceeded the quality standards and specifications of the equipment suggested in this paper, therefore, no improvement in instrumentation is required.
- Automatic control of the gathering system in the Miravalles geothermal field can be improved using control valves with pneumatic actuators and smart positioners. The hydraulic actuators currently used have problems in accuracy of positioning, requiring extensive and expensive maintenance and have environmental problems due to the use of hydraulic oil.

6.2 Recommendations

- Once the new SCADA software is working, it is recommended to have the contractor make a minimum of one software version update per year, in order to keep it up to date.
- A practical way to achieve redundancy in the monitoring and control net in Miravalles is to make the connection between the two branches already existing and to get a ring type topology configuration.
- Inside the improvement process of the monitoring network it is recommended to include a Closed Circuit TV (CCTV) system for remote monitoring of the surroundings of the gathering system in the Miravalles geothermal field.
- It will be necessary to make an economic study to determine the profitability of replacing the current hydraulic system used by the actuators of the control valves on the separation stations of Miravalles geothermal field with a pneumatic system which would be more profitable, precise and environmentally friendly.

ACKNOWLEDGEMENTS

I want to give my sincere gratitude to all staff of United Nations University – Geothermal Training Programme in Iceland, especially to Dr. Ingvar B. Fridleifsson and Mr. Lúdvík S. Georgsson for giving me the opportunity to participate in this programme. Special thanks to my supervisors Jóhann Thór Magnússon and Elín Hallgrímsdóttir for their invaluable guidance which made this project possible.

I would like to extend my gratitude to my employer, ICE, especially to Dr. Alfredo Mainieri, Mr. Antonio Yock, Mr. Paul Moya, my colleagues and the staff of field instrumentation maintenance area, for their support during this 6 month training.

I am deeply grateful to Sonia, Gloriana and Rodrigo Andrés for their patience and unconditional love. Also, I warmly thank my dear parents, Rodrigo and Élida, for their guidance and support throughout my life.

Finally, I thank the Almighty God who makes all things possible.

REFERENCES

Ballzus, C., Frímannsson, H., Gunnarsson, G.I., and Hrólfsson, I., 2000: The geothermal power plant at Nesjavellir, Iceland. *Proceedings of the World Geothermal Council 2000, Kyushu-Tohoku, Japan*, 3109-3114.

Boyer, S.A., 1999: *SCADA: Supervisory Control and Data Acquisition* (2nd edition). ISA – The Instrumentation, Systems, and Automation Society, USA, 215 pp.

DiPippo, R., 2008: *Geothermal power plants. Principles, applications, case studies and environmental impact* (2nd ed.). Elsevier Ltd., Kidlington, UK, 493 pp.

Flannagan, S., 2007: *The importance of redundancy in Scada systems.* Engineeringtalk, website: http://www.engineeringtalk.com/news/aud/aud158.html.

Globalspec, 2009: *Chapter 1 - Introduction to control valves*. Globalspec, website: http://www.globalspec.com/ reference/13606/179909/Chapter-1-Introduction-to-Control-Valves.

Kwok-Hong, M., and Barry, H., 2002: *Migrating electrical power network SCADA systems to TCP/IP and Ethernet networking*. Parsons Brinckerhoff, website: http://www.pbworld.com/ news_events/publications/network/ issue_53/53_21_makk_migratingtcpip.asp.

Lounsbury, R., 2008: *Industrial Ethernet on the plant floor: A planning and installation guide*. ISA – The Instrumentation, Systems and Automation Society, USA, 159 pp.

Magnússon, J.Th., 2003: Operational simulators and automatic control systems. In: Fridleifsson, I.B., and Gunnarsson, M.V. (eds.), *Lectures on sustainable use and operating policy for geothermal resources.* UNU-GTP, Iceland, publication 1, 185-194.

Moya, P., 2008: *Geothermal energy in Costa Rica (in Spanish)*. Costa Rican Electricity Institute, ICE, Guanacaste, Costa Rica.

Omega Engineering Technical Reference, 2009a: *Introduction to magnetic flow meters*. Omega Engineering Inc., website: http://www.omega.com/prodinfo/magmeter.html.

Omega Engineering Technical Reference, 2009b: *Introduction to ultrasonic Doppler flow meters*. Omega Engineering Inc., website: http://www.omega.com/prodinfo/ultrasonicflowmeters.html.

Reykjavík Energy, 2004: *Hellisheidi geothermal power plant – Control and protection system - Contract documents*. Reykjavík Energy, Reykjavík, report, 1/2.

Rivera, M.A., 2007: Design considerations for reliable electrical, control and instrumentation systems in geothermal power plants with emphasis on hydrogen sulphide related problems. Report 20 in: *Geothermal training in Iceland 2007.* UNU-GTP, Iceland, 461-490.

Siemens, 2008: *Industrial communication. Catalog IK PI – 2009.* Siemens, Germany.

Yoder, J.L., 1998: Using meters to measure steam flow. Flowresearch Inc., website: http://www.flowresearch.com/articles/Plant_Engineering_0498.PDF.