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AUTOMATIC CONTROL AND MONITORING SYSTEM FOR THE DISTRICT HEATING SYSTEM AT THE UNIVERSITY OF ORADEA, ROMANIA

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ABSTRACT

The present geothermal installation system at the University of Oradea needs to be improved considerably; presently, the well potential is not utilized at maximum capacity, causing severe energy losses. Based on this situation, a project for modification of the existing system started. A part of these modifications is to implement an automatic control system for the whole installation system, which will ensure the optimum use of the energy of the geothermal water.

In this paper a control system for the well station and the pump station for the geothermal plant at the University of Oradea is developed. A programme for Allen Bradley programmable logic controller (PLC) that controls the system is presented. There is also implemented and presented a supervisory control and data acquisition (SCADA) system for the controlled system, using the InTouch SCADA programme. Finally, the overall operation of the PLC programme and the SCADA system is tested.

1. INTRODUCTION

Digital computers are increasingly being used in the implementation of modern control systems. Because of their development in the last years, the analysis, the design and the implementation of control systems has changed radically. Now, most of the industrial processes have a form of automatic control, one of them being even fully automatic. In most of them, anyway, the operator is a part of the control system.

The advantages which result from using a control system cannot be neglected. The main thing is that it ensures a more economical and safe operation of the process. Through the monitoring system, the state of the process can be monitored constantly, and therefore the reaction to failures or emergency situations is very fast. Also, an important factor is that less man power is necessary for controlling and monitoring the process.

Regarding these advantages, it was decided to implement such a system for the geothermal plant existing at the University of Oradea. The geothermal plant at Oradea consists of the following parts: The well station, the pump station, the heat station and the power station. The picture of the overall system is shown in Appendix I. In the present paper the implementation of a control system for a part of the geothermal plant, i.e. the well station and the pump station, is described.

In Chapter 2 a general overview of the present geothermal installation system at the University of Oradea is presented, with a detailed description of the well station and the pump station. Chapter 3 presents the main objectives that are expected to be achieved using this control system. Chapter 4 starts with some general information on control theory and then describes in detail the implementation of the process control system, as it was done. Finally, Chapter 5 deals with the description of the user interface of the implemented control system.

2. THE PRESENT GEOTHERMAL INSTALLATION AT THE UNIVERSITY OF ORADEA

2.1 General overview

At present well No. 4796, located in the campus area of the University of Oradea is used to produce hot geothermal water for district heating and for hot tap water. At the time being, there is no automatic control of the system, and therefore the well potential is not utilized at maximum capacity.

The present capacity of the well is 30 l/s artesian flow rate at a temperature of 85°C. The water goes directly into the heating system. When the heating system is operating, during the cold season, the necessary heat is regulated by modifying in steps the water flow rate through the plate heat exchangers, i.e. by placing diaphragms with different orifices on the geothermal water pipe. This operation takes place three or four times per season and does not provide a constant temperature inside the buildings. When the heating system is not running, during the summer, geothermal water is used only for producing hot tap water. After usage, the geothermal water is discharged at the relatively high temperature of 50-60°C into a river which is running close to the University. This means that the thermal energy from the geothermal water is utilized only partially.

The project scheme which involves the modifications that shall be done to the existing system is presented in Appendix I. For increasing the production capacity a deep well pump will be installed in the well station. The flow rate is expected to increase up to 50 l/s. The geothermal water then flows into a storage tank which is used both as an accumulator and as a degasser. After that, the water is pumped through the pump station to the heat station and to the binary power plant. In the binary power plant the geothermal water is the warm source in a binary thermodynamic cycle by which the thermal energy is transformed into mechanical energy and then into electrical energy.

In the heat station geothermal water is not used directly but through heat exchangers. The return water from these heat exchangers and from the binary power plant, being between 5-20 l/s and 30-40°C depending on the outdoor temperature, is proposed for a cascade usage which involves a greenhouse and a swimming pool. This assures the best possible utilization of the geothermal water. Finally, in order to compensate for the increase of the well production and to avoid pressure drop in the reservoir, a part of the geothermal water used will be sent through an accumulator to a reinjection well.

Besides the modifications mentioned above, an automatic control of the system will be implemented using programmable logic controllers (PLCs), sensors and actuators. All the system will be controlled and monitored using a Supervisory Control And Data Acquisition system, SCADA. Using this system, the utilization of the geothermal water will be permanently correlated with the demands, which will enable energy saving. Also, an automatic control of the system will be achieved.

In this project the automatic control system for a part of the system is presented and implemented, that is the well station and the pump station. The automatic control system is implemented using one Allen Bradley PLC (Rockwell Automation, 1994a) and InTouch SCADA MMI (Wonderware Corporation, 1994).

2.2 Well station

As was mentioned before, well No. 4796 is located in the campus area at the University of Oradea, and is used for producing hot geothermal water for heating and power generation process. The water from the well is sent directly into a 300 m^3 reservoir tank close to the geothermal well.

One of the functions of the reservoir tank is to separate the production of the well from the distribution network. Therefore, the well production does not have to follow the time variation in the process demand. Also, in this way the short time interruptions in the well production do not have an effect on the distribution network and the short time peak load production of the system is increased. Another function provided by the reservoir tank is to degass the geothermal water.

The geothermal well has an artesian flow capability of approximately 30 l/s. When the demand for hot water is more than 30 l/s, it is necessary to start the deep well pump P1 to increase the production. Figure 1 shows the schematic diagram for the well station and the reservoir.

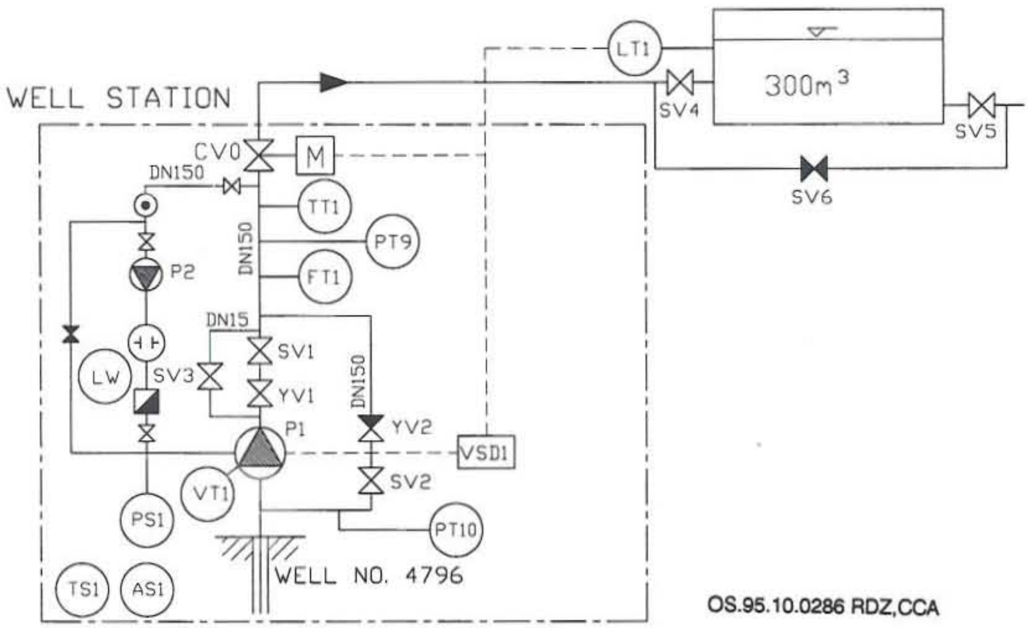

FIGURE 1: The well station and the reservoir tank

The objective of the well station is to keep the water level in the reservoir tank, measured by LT1, constant. Two regulators RG1 and RG2 and many sensors and control devices are utilized for this purpose. The complete list of all these sensors and control devices is presented in Appendix II. The regulator RG1 utilizes the control valve CV0 to regulate the flow rate from the well. The regulator RG2 utilizes the variable speed drive VSD1 to control the speed of the deep well pump P1. Pump P2 is a lubrication pump, which is used to increase the pressure of the lubrication water in the well pump line shaft bearing.

2.3 Pump station

The pump station is located close to the well station and the reservoir. The function of the pump station is to deliver geothermal hot water from the reservoir tank into the main distribution network, to the different processes, maintaining a constant pressure in the network, independent of their demand.

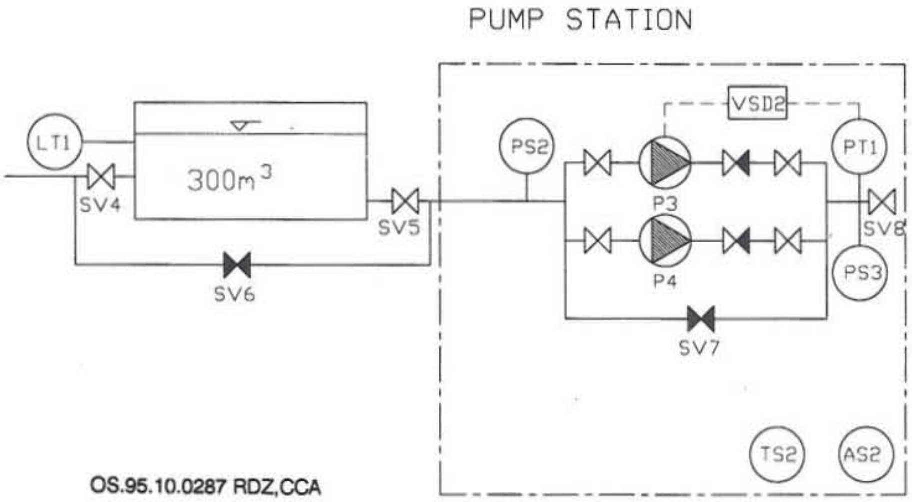

FIGURE 2: The pump station

The pump station comprises two booster pumps, one for reserve, as is shown in Figure 2. In order to avoid excessive pressure transient in the network and to save electrical energy needed for pumping, the booster pump is driven by a variable speed drive VSD2. Regulator RG3 utilizes the variable speed drive VSD2 to regulate the flow rate from the booster pump P3 or P4 by varying the speed of its motor. The sensors and control devices used are presented in Appendix II.

3. MAIN OBJECTIVES

3.1 Automatic control of the system (PLC and SCADA)

Almost all industrial processes need some form of control system if they are to run safely and economically. Very few industrial plants can be left to run by themselves, and most need some form of control system to ensure safe and economical operation.

The route towards increased productivity is through increased automation of processes and machines. This automation may be required to directly increase output quantities, or to improve product quality and precision. In any form, automation involves replacing some or all human input and effort required to both carry out and control particular operations.

To achieve process automation, the operator must be replaced by a control system, that has the ability to start, regulate and stop a process in response to measured variables within the process, in order to obtain the desired output. These objectives are obtained using a control system based on a PLC micro controller and using SCADA man-machine interface.

Although PLCs are similar to conventional computers in terms of hardware technology, they have specific features suited for industrial control. One important characteristic is that they are designed to survive in an industrial environment with all that this implies for temperature, dirt and poor-quality mains supply. Also they have a modular plug-in construction, allowing easy replacement or addition of input and output units. Another important feature is that they are easy to programme and reprogramme in a constantly changing plant. Finally, the most important characteristic may be, that they are fast enough to operate in real time, as most of the industrial processes need.

Connecting a PLC to the plant is how we achieve the automatic control of the plant. But, a PLC also has to be connected to the human operators, accepting commands from them and displaying the status of the plant in a form that can readily and easily be understood. This is called the man-machine interface or MMI. Using SCADA MMI provides a very user-friendly graphical interface that is very suggestive allowing the human operator to perform his duty efficiently.

3.2 Fault monitoring and protection of system components

There are many advantages in using the facilities of programmable controllers to carry out, monitor and record operations on items of the plant. First, a PLC is usually required to bring operator's attention to an alarm condition of the plant, or abnormal fault conditions. Second, most industrial equipment requires periodic routine maintenance, either after set lengths of operating time or after too many operations. Thus, a PLC is required to produce an event/alarm log for historical maintenance analysis. Conventional recording methods can be expensive and difficult to operate.

Another problem is that all process that may, through failure of some part, cause injury to human beings or cause damage to the equipment or the environment, should be equipped with a protective instrument system. Protective instruments are linked directly to the equipment, and are used only when the PLC fails. The protective instrument system is designed to override the normal control system. It can be manually or automatically initiated.

3.3 Data collection with SCADA MMI

SCADA is the technology that enables a user to collect data from one or more distant facilities and send control instructions to those facilities (Boyer, 1993). This means that SCADA is a two way system; it can both monitor the system and also control it.

The man-machine interface or MMI is the junction from which information travels from the SCADA system to the operator and from the operator to the SCADA system. There are several things that have to be monitored at the same time, such as alarms, status, graphics and trends. Because the picture on the screen cannot be too complex, these are usually grouped into several screens, depending on functions.

The control change screens are usually very simple. The control functions can be affected by moving the screen cursor with the mouse to a spot next to the desired control function and pressing the enter button. In case of other kinds of adjustments (speed, level, flow) the cursor movement would be followed by entering the appropriate value.

The status screens are used to monitor the status changes associated with ongoing control commands and also measured values and the status of all controlled devices. Series of well designed status screens allow the operator to do an electronic walkabout, and be well informed from information contained in a small number of screens.

SCADA MMI allows graphics and trends of the important parameters of the process to be obtained, which are more intuitive than other kinds of presentation. This can give a better image of the whole process, and also change the way processes are operated. Beside this, SCADA could provide several types of reports such as alarm logs, communication reports, etc. Some of these are printed automatically at a fixed time (daily communication reports, accounting related information, reports detailing the needs for process maintenance), but others are printed only when asked for or on demand (special alarm report, recent operation). For the alarm logs, a printer is usually dedicated to that task.

Keeping the operation running and restoring it to operation quickly, when it does shut down are two economic justifications for installing PLC and SCADA systems. To avoid accidental changes SCADA also provides some security measures such as passwords and restricted access in order to ensure that only those people who are authorized can effect changes.

4. PROCESS CONTROL SYSTEM

4.1 General considerations about control theory

In practice there are various and complex industrial processes, most of which can be simplified by dividing them into many small sub-processes. These sub-processes can generally be considered to fall into three distinct areas which are, monitoring sub-systems, sequencing sub-systems and close loop sub-systems (Parr, 1995).

The monitoring sub-systems display the process state to the operator and draw attention to abnormal or fault conditions which need attention. Digital sensors are used to measure conditions with distinct states (on/off, high level/normal/low level) and analogue sensors are used to measure conditions which have a continuous range (temperature, pressure, flow rate). The results of these measurements are displayed to the operator using different techniques. The most modern one is SCADA MMI, described above.

A monitoring system often keeps records of the consumption of energy and material for accountancy purposes, and produces an event/alarm log for historical maintenance analysis. The sequential sub-systems are those that follow a predefined sequence.

Many industrial processes require some plant variable (temperature, pressure, flow) to be kept at a fixed value or to follow some profile. Such sub-systems are denoted as closed control loop systems. Such systems can be represented by the block diagram of Figure 3. There, a particular characteristic of the plant denoted by PV (process variable) is required to be kept at a preset value SP (set point value). PV is measured by a suitable sensor and compared with the SP to give an error signal

$$error = e = SP - PV$$

The error signal is applied to a control algorithm. The output from the control algorithm is passed to an actuator which affects the plant. The algorithm will adjust the actuator until there is zero error, i.e. the process variable and the set point have the same value. Because the process variable PV is fed back to

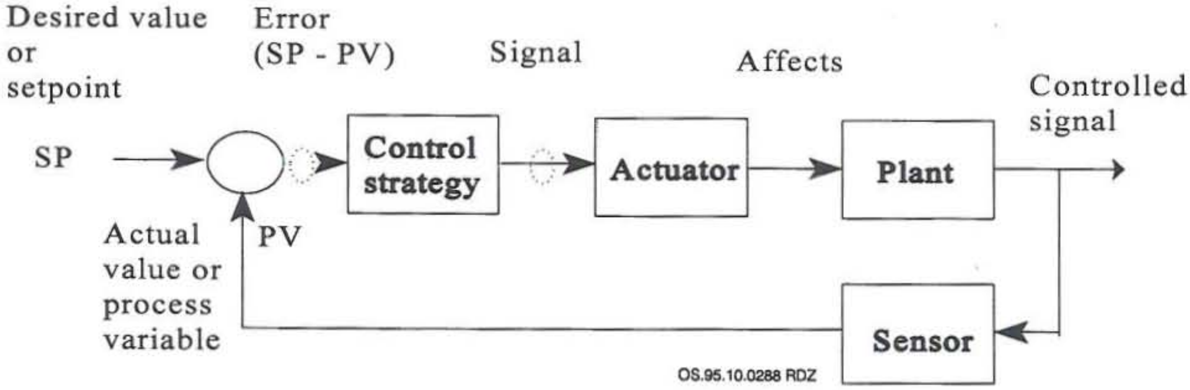

FIGURE 3: A closed loop control system

be compared with the set point SP, the term "feedback control" is used also to denote this kind of systems

(Åström and Wittenmark, 1984). The correction process is continuous, so the value of the controlled PV can also be made to track a changing set point.

The three types of control strategy outlined above can be achieved in many ways. Monitoring/alarm systems can often be achieved by connecting plant sensors to displays, indicators and alarm announciators. Sequential systems can be built from relays combined with timers, uniselectors and similar electromechanical devices. Closed loop control can be achieved by using programmable controllers (PLCs) or individual regulators. When a system deviation *e* is produced by a disturbance or due to a change in the reference variable, the controller intervenes by changing the manipulated variable so that the system deviation is kept as small as possible, the ideal case is zero. Depending on the type of controller, this elimination of the system deviation occurs at different rates and with different degrees of precision. The manner in which a controller eliminates the system deviation is called the response characteristic of the controller (Warnock, 1988).

The most commonly used continuous-action controllers are of the type PID. The PID controllers can be implemented in different ways: proportional P, integral I, proportional-plus-integral PI, proportional-derivative PD and proportional-integral-derivative PID. Proportional action of a transfer element means that the output variable of the loop element is in a fixed (proportional) ratio to its input variable. The proportional controller or P controller produces an output variable x_a proportional to the system deviation e. The relationship is as follows:

$$x_a = K_p \cdot e \tag{1}$$

The proportional gain K_p is the amount by which the output variable x_a changes when the input variable changes with e. The P controller reacts very quickly to a system error because its output variable acts instantaneously on the final control element. However, the P controllers cannot eliminate the disturbances completely, or correct the controlled variable to the set point. A steady-state deviation always remains.

For the integral controller or I controller it is not the output variable itself that is proportional to the input variable but the rate at which the output variable changes. The integral-action coefficient K_i indicates by how many units the output variable of the I controller changes during the period T, when a system deviation e is present in the input. It is common to use the integrating time $T_i = 1/K_i$ instead of K_i itself. Correction of system deviation takes longer than with a P controller. On the other hand, the I controller can eliminate the deviation precisely to zero. There is no offset or steady-state system deviation as there is with the P controller.

$$\frac{dx_a}{dt} = K_i \cdot e \tag{2}$$

By integrating this, the following expression for the output variable x_a is achieve$_d$:

$$x_a = K_i \cdot \int_0^t e\, dt + e_0 \tag{3}$$

The proportional-plus-integral controller or PI controller is a combination of both types, and can be regarded as P controller and I controller connected in parallel. The P component provides part of the controller output value immediately and the I component completely eliminates the system deviation. The output is the following:

$$x_a = K_p + \frac{1}{T_i} \cdot \int_0^t e\, dt \tag{4}$$

As the PI controller does, the proportional-plus-derivative action controller or PD controller incorporates two components, a proportional-action component and a derivative-action component. When there are rapid changes in the controlled variable, the derivative-action component has a strong effect on the controller, output variable, for a certain period of time. The controller input value is constant after the step change. As the derivative component depends on the rate of change of the controller input value, it no longer contributes to the output value of the controller:

$$x_a = K_p + T_d \cdot \frac{de}{dt} \tag{5}$$

In the steady-state condition, therefore, only the P component provides the controller output value, which means that the PD controller is also subject to steady-state system deviation.

A PI controller with an additional derivative-action component is called a PID controller. This type of controller combines the advantages and disadvantages of proportional, integral and derivative actions:

$$x_a = K_p + \frac{1}{T_i} \cdot \int_0^t e\, dt + T_d \cdot \frac{de}{dt} \tag{6}$$

The step response of the PID controller is governed by the three adjustable characteristic values K_p, T_i and T_d. By adjusting these components, we try to obtain a response of the system as quickly, as accurately and as oscillation-free as possible. This is called tuning of the regulator.

4.2 Description of Allen Bradley PLC

A programmable controller is a solid state device used to control machines or process operations by means of a stored programme and feedback from input or output devices. PLCs are standard units based on a hardware CPU, memory and I/O units (and eventually communication units or special function units for remote control or networking, if necessary) for the control of machines or processes. PLCs provide the ease and flexibility of control based on programming and executing simple logic instructions (often in a ladder diagram form). They have internal functions such as timers, counters and shift registers, making sophisticated control possible using even the smallest PLC.

Allen Bradley PLC consists of three basic functional areas, processing, memory and input/output. The controller operates by examining the input signals from process and carrying out logic instructions (which have been programmed into its memory) on these input signals, producing output signals to drive process equipment or machinery. This process of reading inputs, executing the programme and controlling the outputs is done on a continuous basis called scanning. The input and output systems form the interface by which field devices are connected to the controller. The purpose of the interface is to condition the various signals received from or sent to external devices. The standard interfaces built into the PLC allow them in most cases to be directly connected to process actuators and transducers without the need for intermediate circuitry or relays.

The Allen Bradley programmable logic controller is constructed on a modular basis with function modules slotted into the backplane connectors of the mounting rack. This allows simple expansion of the system when necessary. The individual circuit boards are easily removed and replaced, facilitating rapid repair of the system and easy further development.

The CPU controls and supervises all operations within the PLC, carrying out programmed instructions stored in the memory. An internal communications bus system carries information to and from the CPU, memory and I/O units, under control of the CPU. A SLC 5/04 processor is used in this project. The processor instruction set consists of 71 instructions including bit, timer and counter instructions, comparison, move and logical instructions, math instructions, I/O instructions, control instructions, and special instructions (PID). As a programming device a usual PC computer can be used. The programming language used is APS (Advanced Programming Software), in which the ladder programme is written (Rockwell Automation, 1994b; 1994c). The software takes care of down loading the ladder programme into the PLC.

20 K Words programme memory is used for initial programme development and testing. This consists of CMOS RAM (because it has very low power consumption) equipped with lithium batteries in order to maintain the contents when power is removed from the PLC system. This feature makes programmes stored in RAM virtually permanent. After a programme is fully developed and tested it may be down loaded into an EEPROM or UVPROM memory chip using the built-in facility. The PLC also provides up to 4 K additional data storage (Rockwell Automation, 1994a). The I/O capacity is 960 discrete and there are provided maximum 3/30 chassis I/O slots.

The I/O units form the interface between the microelectronics of the programmable controller and the real world outside, and must therefore provide all necessary signal conditioning and isolation functions. This often allows the PLC to be directly connected to process actuators and transducers, without the need of intermediate circuitry or relays.

By using PLCs it became possible to modify a control system without having to disconnect or re-route a single wire; it only needed a change in the control programme. Programmable controllers also require shorter installation and commissioning times than do hardwired systems.

4.3 Programming the PLC

4.3.1 Automatic operation of the well station

The scheme which the control programme is based on can be found in Appendix I. The complete list of sensors, actuators and control devices that are referred to below can be found in Appendix II.

The well pump P1 and the control valve CV0 control the level in the reservoir tank. Two different regulators are assigned to these two control devices, RG1 for the valve and RG2 for the well pump (Table 1). The regulators have a dead band corresponding to 2% of the level transmitter span, to avoid excessive wearing of the control devices.

TABLE 1: Regulator characteristics

No.	Name	Final control element	Process value	Set point
RG1	Water level in reservoir	CV0	LT1	2.6 m
RG2	Water level in reservoir	VSD1	LT1	2.5 m

The well station can be operated in two modes, i.e. a group mode on or in a group mode off. In group mode on, the PLC can automatically change between artesian and well pump production according to the demand rate for hot water. In this case, always when pump P1 is not running the PLC puts RG1 in auto and fetches its fixed set point. PLC sees that, in group mode on, the regulators RG1 and RG2 can never be simultaneously in auto mode; if RG1 is in auto then RG2 is in manual with output 0%; if RG2 is in auto then RG1 is in manual with output 100%. In group mode off, the PLC cannot automatically start the pumps P1 and P2. The mode selection can be done from SCADA system.

When group mode on is selected and the artesian flow rate delivers enough hot water for the system, then the regulator RG1 regulates the water level LT1 in the reservoir tank, using the control valve CV0. If the artesian flow from the well is sufficient to maintain the level in the reservoir tank, then the well pump P1 is not to be operated. The level in the reservoir tank is then controlled by modulating the opening of the control valve CV0. The RG2 is in manual mode with 0% output. In this case, the well pressure PT10 is approximately equal to the well head pressure PT9, and the control valve has to throttle (less than 100% position) the flow.

If the artesian flow rate is not enough for the system, even when the valve CV0 has reached the fully open position (100%) the water level in the reservoir LT1 is decreasing. When the water level LT1 has reached down to the L-alarm level, LT1_L, the PLC changes automatically over to the pump operation. It puts RG1 in manual and fixes its output to 100%, puts RG2 in auto and starts the pump P1. The pump P1 is operated using the variable speed drive VSD1. The automatic start of the pump P1 is implemented as bumpless transfer, using the process variable value at the start time as set point and ramping from this set point to the set point that is used for RG2. Every ramp is done from t_A to t_A seconds, and the ramp step is x_A cm. These values can be changed from SCADA system. Finally, the ultimate set point for RG2 will be reached. When the pump starts to operate, the well pressure PT10 will decrease below the well discharge pressure PT9 which indicates that it has increased the well's flow rate above the artesian flow rate. The values x_A, t_A can be changed from SCADA system.

The pump P2 is a lubrication pump that is used to increase the pressure of the lubrication water for the deep well line shaft bearings. If the bearings do not get enough lubricating water serious damage will occur in the pump assembly. In group mode on, PLC automatically starts and stops the lubrication pump P2. When there is an artesian flow from the well, the pump P2 is normally not operated. Prior to starting deep well pump P1, the lubrication pump P2 is started if the pressure, indicated by pressure switch PS1 is too low. If during operation of the P1 the PS1 shows too low lubrication pressure and P2 is not running, the PLC starts it. If during the operation of P2 the well discharge pressure PT9 is greater than x_D bars for more than t_F minutes, the PLC stops P2. When pump P1 is stopped the pump P2 will be stopped after t_X minutes. The values x_D, t_F and t_X can be changed from SCADA system.

When the demand for hot water decreases again it will gradually reach the state when the artesian flow becomes enough for the process. In this case, the PLC will change automatically over to artesian flow mode, i.e. stops the pump P1, puts the RG2 in manual with 0% output and puts RG1 in auto using its fixed set point, letting the valve control the level in the reservoir. The condition for stopping the pump P1 is when the well pressure PT10 has reached a value greater than or equal to PT9-x_B bar for more than t_B minutes.

A counter counts the number of times P1 is started, independent of which mode the well station is operating. If the well station is in group mode on and the number of starts of the P1 exceeds x_C times/hour, then the well station is put in group mode off and therefore automatic starting of P1 by the PLC is blocked. The value x_C can be changed from SCADA system.

When the well station is in group mode off, then the PLC cannot automatically start the deep well pump P1, even if the artesian flow rate from the well is insufficient for the process. The same is valid for the lubrication pump P2. The change over from artesian flow to pump operation has to be done by the operator of the SCADA system.

If the variable speed drive VSD1 is out of operation then the well station is forced into group mode off, and remains in that mode until it is put into operation again. P1 is stopped and RG1 is put in auto using its fixed set point. If the pump P1 is running and stops for any reason, the RG1 is put in auto with its fixed set point and RG2 is put in manual with 0% output. In group mode the operator can start the pump P1 independent of the position of the control valve CV0, but VSD1 must be in operation.

4.3.2 Automatic operation of the pump station

The objective of the pump station is to keep the supply pressure PT1 in the distribution network constant. The regulator RG3 is used for that purpose. The RG3 utilizes the variable speed drive VSD2 to regulate the flow rate from the booster pump P3 alternatively P4 by varying the speed of its motor, as is shown in Table 2.

TABLE 2: Regulator characteristics

No.	Name	Final control element	Process value	Set point
RG3	Geothermal water supply pressure	VSD2	PT1	2.5/4.0 bar-g

Two different fixed set points are used for the regulator RG3 in the PLC depending on whether the power station is running or not. When the power station is running, a set point of 4.0 bar-g is used. When the power station is not running, a set point of 2.5 bar-g is used. The regulator has a deadband corresponding to 2% of the pressure transmitter span, to avoid excessive wearing of the control device.

The pump station can be operated in two modes: group mode on and group mode off. In group mode on the PLC can automatically start and stop the booster pumps. PLC ensures that the booster pumps P3 and P4 can never be operated simultaneously. If the P3 or P4 pump is running and stops for any reason, the RG3 is put in manual with 0% output. In group mode off the PLC cannot automatically start the pumps P3 and P4. The mode selection is done from the SCADA system.

When group mode on is selected for the pump station, the PLC will automatically start and stop the booster pump P3 connected to the VSD2, put RG3 in auto and select/change its set point depending on whether the power station is running or not. When VSD2 is out of operation, the pump station cannot be in group mode. This means that the PLC can never start the booster pump directly on line.

Two counters count the number of times the P3 respective P4 are started, independent of which mode the station is operating in. If the station is in group mode on and the number of starts of the booster pump does exceed the value x_{1B} times/hour, then the station is put in group mode off and therefore further automatic starting of the pump by the PLC is blocked.

When the pump station is in group mode off, then the PLC cannot automatically start the booster pump, even if the supply pressure is not high enough. It can stop the booster pump if an alarm situation occurs. The starting of the pump must be done by the operator of the SCADA. In group mode off the operator can start the booster pump independent of the output of RG3, but depending whether VSD2 is in operation or not. If the variable speed drive VSD2 is out of operation then the pump station is forced into group mode off and remains in that mode until it is put into operation again. The relevant pump is stopped and RG3 is put in manual with 0% output.

4.3.3 Automatic restart after power failure

In case of disturbance in the electrical system with the pump P1 or P3 in operation (phase failure switch in panel A4 or A3 activated), an automatic restart of the pump is initiated when the system has recovered and the phase failure switch has been stable for t_Y minutes. The PLC stores the output signal and the set point of RG2/RG3 at the time of failure and puts the regulator in manual mode.

The automatic restart is implemented as bumpless transfer, using the process value at the restart time as set point and ramping from this set point to the set point that was used before the failure. The initial output signal of RG2/RG3 in the restart is the output signal of the regulator just before the failure.

4.3.4 Failure diagnostics and system reaction in case of failures

When a failure is detected in the system an appropriate failure message is relayed to the SCADA system. Each failure is latched, and it is unlatched only when the failure is not longer present and it has been acknowledged.

If one or more of the failures presented in Table 3 show up in the well pump or in the lubrication pump, then P1 and P2 are stopped, the well station is put into group mode off, RG2 put in manual operation and RG1 in automatic operation.

If a failure occurs in the level transmitter (line broken/over range) then the pumps are stopped and the control valve CV0 is fully opened in manual mode. An appropriate failure message is relayed to the SCADA system.

TABLE 3: Failures in the well pump P1 and lubrication pump P2

Failures	Notation
Overload protection for P1 tripped	P1_OL
Overload protection for P2 tripped	P2_OL
Pressure switch for lubrication water activated	PS1
Failure in VSD1	P1_CA
Excessive temperature in the motor windings of P1	TS11
Well pump thermal switch disconnected	P1_TD
Lubrication pump thermal switch disconnected	P2_TD
Excessive vibration of P1 for t_E seconds	VT1_HH
PT9 shows too high pressure for t_D seconds	PT9_HH
LT1 lower than LL limits for t_J minutes with 100% opening of RG2	LT1_LL
LT1 higher than HH limits for t_I minutes with 0% opening of RG2	LT1_HH

If one or more of the following failures show up in the control valve (Table 4), then RG1 is put in manual mode with unchanged output, and P1 and P2 are inhibited from running. An appropriate failure message is relayed to the SCADA system.

TABLE 4: Failures in the control valve CV0

Failures	Notation
Fault signal from the control valve CV0	CV0_CA
CV0 torque limit switch activated (open direction)	CV0_TL1
CV0 torque limit switch activated (close direction)	CV0_TL2
PT0 will not change its value while the valve is operated in either direction	-
End switch fully closed valve will not give signal within t_M seconds after the PLC has put the output signal to 0%	CV0_LC
End switch fully open valve will not give signal within t_M seconds after the PLC has put the output signal to 100%	CV0_LO

If one or more of the following failures show up in the booster pump (Table 5), then P3 is stopped and RG3 put in manual operation. An appropriate failure message is relayed to the SCADA system.

TABLE 5: Failures in the booster pump P3

Failures	Notation
Overload protection for P3 tripped	P3_OL
Excessive temperature in the motor windings of P3	TS12
Booster pump thermal switch disconnected	P3_TD
Failure in VSD2	P3_CA
Failure in the transmitter PT1	-
Failure in the transmitter LT1	-

If one of the failures from Table 6 show up in the well station, then all devices in the well station are shut down. In case of phase failure, an automatic restart is initiated in group mode on after power recovery, as described in Chapter 4.3.3. An appropriate failure message is relayed to the SCADA system.

TABLE 6: Common failures in the well station

Failure	Notation
Emergency switch in panel A4 activated	ES2
Phase failure switch in panel A4 activated	PFS2

The warnings from Table 7 are reported to the SCADA system:

TABLE 7: Common warnings in the well station

Warning	Notation
Well station ambient humidity too high (AS1)	AS1
Well station ambient temperature too high (TS1)	TS1
Low (L) well head pressure, lasting more than 5 s	PT9_L
High (H) well head pressure lasting more than 5 s	PT9_H
High (H) well flow, lasting more than 5 s	FT1_H
High (H) motor current for P1 lasting more than 5 s	P1_MC_H
Low (L) well temperature, lasting more than 5 s	TT1_L
High (H) well temperature, lasting more than 5 s	TT1_H
High (H) level in the reservoir tank, lasting more than 5 s	LT1_H
Low (L) level in the reservoir tank, lasting more than 5 s	LT1_L
Excessive flow for 2 minutes	FT1_HH
Excessive motor current in P1 for 5 s	P1_MC_HH

If one of the failures from Table 8 shows up in the pump station, then all devices in the pump station are shut down. In case of phase failure, an automatic restart is initiated in group mode on after power recovery, as described in Chapter 4.3.3. An appropriate failure message is relayed to the SCADA system.

TABLE 8: Common failures in the pump station

Failures	Notation
Emergency switch in panel A3 activated	ES1
Phase failure switch in panel A3 activated	PFS1
Suction pressure switch for booster pumps activated	PS2
Discharge pressure switch for booster pumps activated	PS3

The warnings from Table 9 are also reported to the SCADA system.

TABLE 9: Common warnings in the pump station

Warnings	Notation
Pump station ambient humidity too high	AS2
Pump station ambient temperature too high	TS2
Low (L) system pressure, lasting more than 5 s	PT1_L
High (H) system pressure, lasting more than 5 s	PT1_H
High (H) motor current for the booster pump P3 more than 5 s	P3_MC_H
Excessive motor current in P3 for 10 s	P3_MC_HH

4.3.5 Description of the PLC programme

The APS (Advanced Programming Software) software from Allen Bradley was used to develop a ladder programme which implements the operational description presented above. Basically, the programme is constructed on a modular basis, being divided into functional segments for both the well station and the pump station.

The first segment is the initialization segment. There, all the initializations needed for the programme variables are done. Also, in this segment, there is allocated memory into the PLC for the inputs and outputs and also for all the data that we are going to use further in the SCADA system. Then comes the segment in which the evaluation of the global state of the system, for both the well station and pump station, is done. Here the selection between the group mode (ON/OFF) is done, and also the case of stopping the system if necessary is treated.

Another segment deals with the evaluation of the regulator modes and calculation of the regulators. Each regulator is implemented using the PID instruction provided by the processor. Counters, timers flags and memory locations are used to process the output of the regulators so that they control the system in the way described above. Also, the settings for the regulators are established here for the first time (set point, deadband, output range, etc.), even if they can be changed further from SCADA.

The evaluation of failures and warnings, including evaluation of the limit conditions (analogue variables lower than L or LL limits, or higher than H or HH limits) is a separate segment too. All the failures are latched and are unlatched when the failure is no longer present and has been acknowledged. The warnings are not latched. Finally, the last segment treats the state (ON/OFF) of the controlled devices and activation of the digital outputs.

The ladder programme is fully documented, indicating clearly where each segment starts and ends. Also, there are many comments inside each segment, to make the programme easy to understand. All the addresses used in the PLC for inputs and outputs have a name which correspond to the name of the I/O described in Appendix II.

5. USER INTERFACE

5.1 SCADA - general overview and functional description

SCADA is the acronym that is formed from the first letters of Supervisory Control And Data Acquisition. A SCADA system allows an operator, in a location central to a widely distributed process to make set point changes on distant process controllers, to open or close valves or switches, to monitor alarms, and to gather measurement information. When the dimensions of the process become very large, the benefits in term of reduced cost of routine visits can be appreciated.

Typical signals gathered from remote locations include alarms, status indication, analogue values, and totalized meter values. Similar signals sent from the central location to remote sites are usually discrete binary bit changes or analogue values addressed to a device of the process. Combining all this, a very complex control could be achieved.

The SCADA system is configured using the InTouch SCADA package. InTouch is a software package used to create PC based man-machine interfaces (Wonderware Corporation, 1994). InTouch uses Microsoft Windows Version 3.1 or later as its operating environment. It is the development environment, where object-oriented graphics are used to create touch-sensitive display windows.

These display windows can be connected to industrial I/O systems (such as programmable controllers) and other Microsoft applications. The SCADA pictures are linked with the Allen Bradley programmable logic controller using Dynamic Data Exchange (DDE) communication protocol in order to transfer data (Wonderware Corporation, 1990). The Wonderware Allen Bradley Serial Server is used like a DDE server that allows InTouch to access data in Allen Bradley PLC.

5.2 Realization of the system

The structure of the control system can be found in Appendix III. It consists mainly of the following items: sensors and control devices (also described in Appendix II), the programmable logic controller PLC and the SCADA user interface. The SCADA system works based on the data stored into the PLC memory. Therefore, the first thing that was done in building the system was to prepare the data into the PLC, that means to allocate memory from the PLC memory for each datum that is used by SCADA (flags, addresses in B files, integers, addresses in N files, timers, counters and PID regulators).

Also, the SCADA has to communicate with the PLC so that it should be possible to read or write data to/from the PLC memory. This is achieved by installing the appropriate driver, the Wonderware Allen Bradley Serial Server, which ensures serial communication and takes care of the communication protocol.

Then the SCADA pictures were constructed, using the InTouch picture editor. The pictures show the schematic drawing of the system, containing reference to all inputs and outputs of interest. For the alarm picture, all the alarm texts were defined. Also, the definition of all trend curves and historical diagrams was done here.

The SCADA system is based on five main pictures, an overview picture of the well station, an overview picture of the pump station, a picture showing the state (ON/OFF) of all alarms and warnings and two pictures showing trend curves for all analogue values.

The overview picture of the well station (Figure 4) shows the state of all measuring transmitters and actuators. For both regulators (RG1 and RG2) a box showing the process variable PV is assigned, the set point SP, the output signal OUT and the regulator mode (MAN or AUTO). By selecting these boxes it is possible to change the regulator tuning constants (PID constants), the set point and the regulator mode (only on group mode off).

Pump icons shall be green when the motor is running, white when the motor is not running and not faulted, blinking red when the motor has an unacknowledged fault and red when the motor has an acknowledged fault. Same applies for the VSD1. The status of the control valve CV0 is shown using special icons for, fully closed, fully open, operated in opening direction, operated in closing direction, non-operated or faulted. The well station can be switched between "group mode on" and "group mode off" by clicking with the mouse at the appropriate place in the overview picture.

The overview picture of the booster pump (Figure 5) shows the state of all measuring transmitters and actuators. For the regulator RG3 a box is assigned showing the process variable PV, the set point SP, the output signal OUT and the regulator mode (MAN or AUTO). By selecting these boxes it is possible to change the regulator tuning constants (PID constants), the set point and the regulator mode. In MAN mode of RG3 it is possible to start and stop P3 manually by clicking with the mouse on the pump icon.

OS.95.10.0289 RDZ

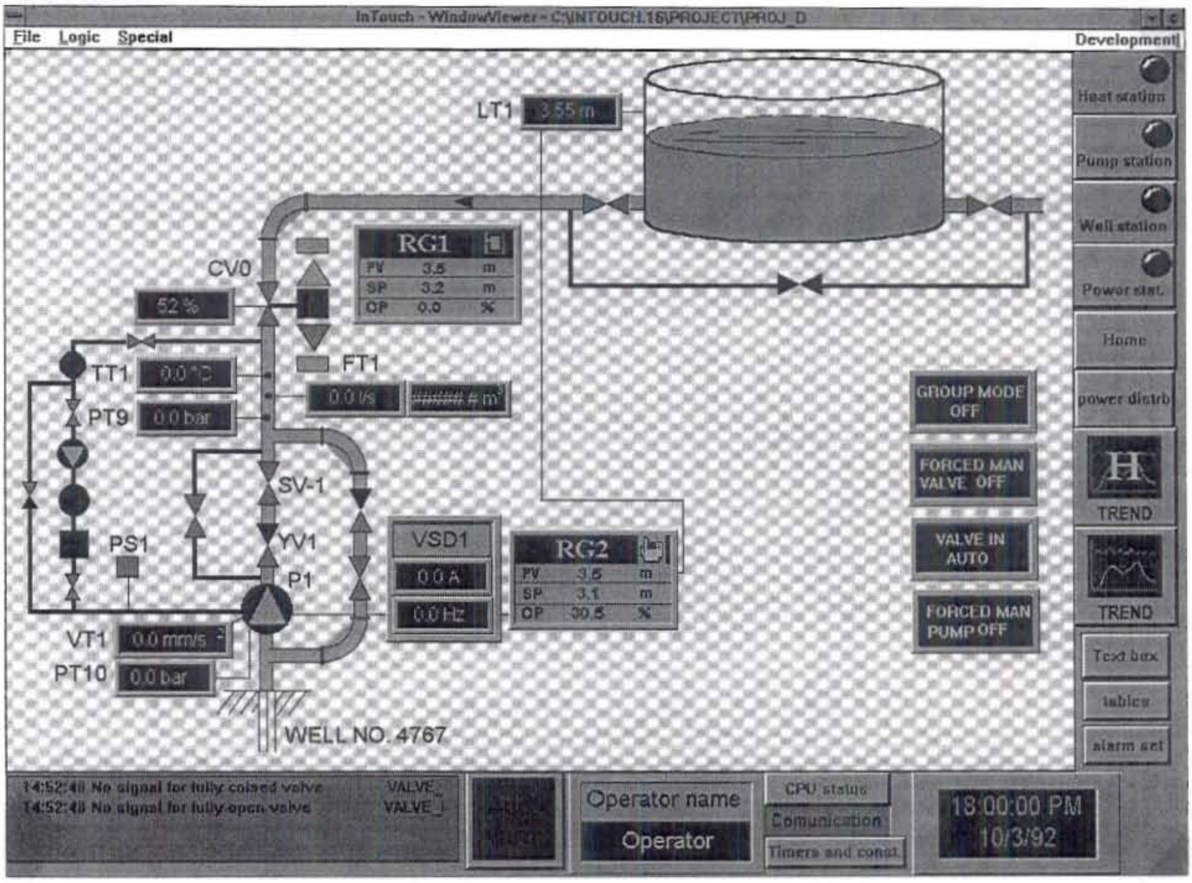

FIGURE 4: SCADA picture of the well station

The pump icon shall be green when the motor is running, white when the motor is not running and not faulted, blinking red when the motor has an unacknowledged fault and red when the motor has an acknowledged fault. By opening the appropriate boxes in both overview pictures it is possible to change all the reference values for the control limits that were referred to in Section 4.3.1 (such as time constraint).

The picture showing the state of the alarms and warnings is used to monitor the state of the system. When an alarm or warning shows up or disappears, it is reported to the SCADA system with a time tag. It is possible to change reference values for alarms and warnings from SCADA as shown in Table 10.

TABLE 10: Reference values for alarms and warnings

Analogue value	LL limit	L limit	H limit	HH limit
LT1	LT1_LL	LT1_L	LT1_H	LT1_HH
PT1	PT1_LL	PT1_L	PT1_H	PT1_HH
PT9	PT9_LL	PT9_L	PT9_H	PT9_HH
P1_MC	P1_MC_LL	P1_MC_L	P1_MC_H	P1_MC_HH
P3_MC	P3_MC_LL	P3_MC_L	P3_MC_H	P3_MC_HH
VT1	VT1_LL	VT1_L	VT1_H	VT1_HH
0	FT1_LL	FT1_L	FT1_H	FT1_HH
TT1	TT1_LL	TT1_L	TT1_H	TT1_HH

OS.95.10.0290 RDZ

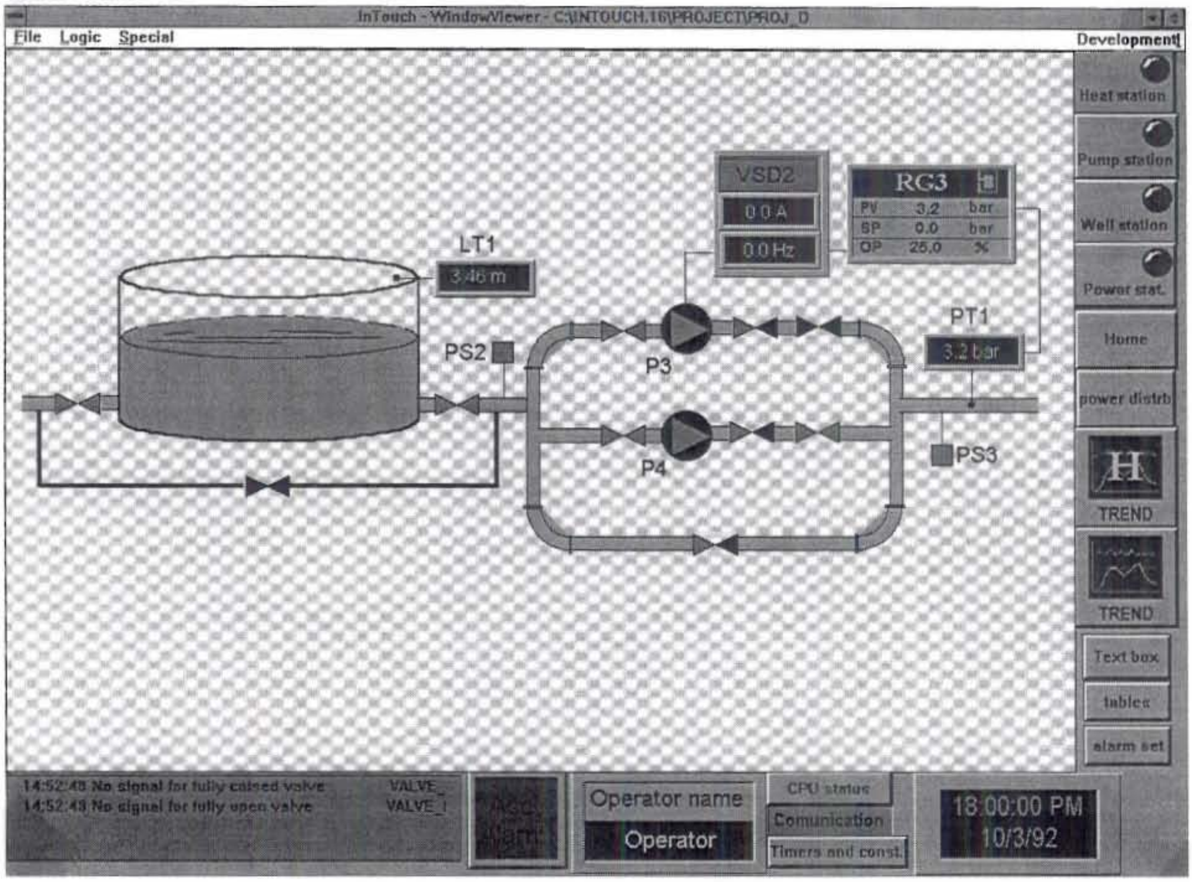

FIGURE 5: SCADA picture of the pump station

Also, all the regulator tuning constants can be changed from SCADA, as is shown in Table 11.

TABLE 11: Regulator constants that can be changed from SCADA

RG1	P, I, D constants, minimum valve opening and maximum valve opening
RG2	P, I, D constants, minimum pump speed and maximum pump speed
RG3	P, I, D constants, minimum pump speed and maximum pump speed

The pictures showing the trend curves for the analogue values (Figure 6) are used to monitor the variation in time of these values. It is possible to view also all analogue values on historical diagrams. The time scale for the historical diagrams can be changed as wished.

5.3 Testing the PLC programme and SCADA system

The functional operation of the whole system was tested using different test scenarios to simulate the real condition of the plant. The testing process follows an incremental scheme, first the PLC programme was tested separately, and after the desired behaviour was achieved it was linked and tested together with SCADA.

A simple simulation model in the PLC was used to simulate the level in the reservoir tank LT1 and the

OS.95.10.0291 RDZ

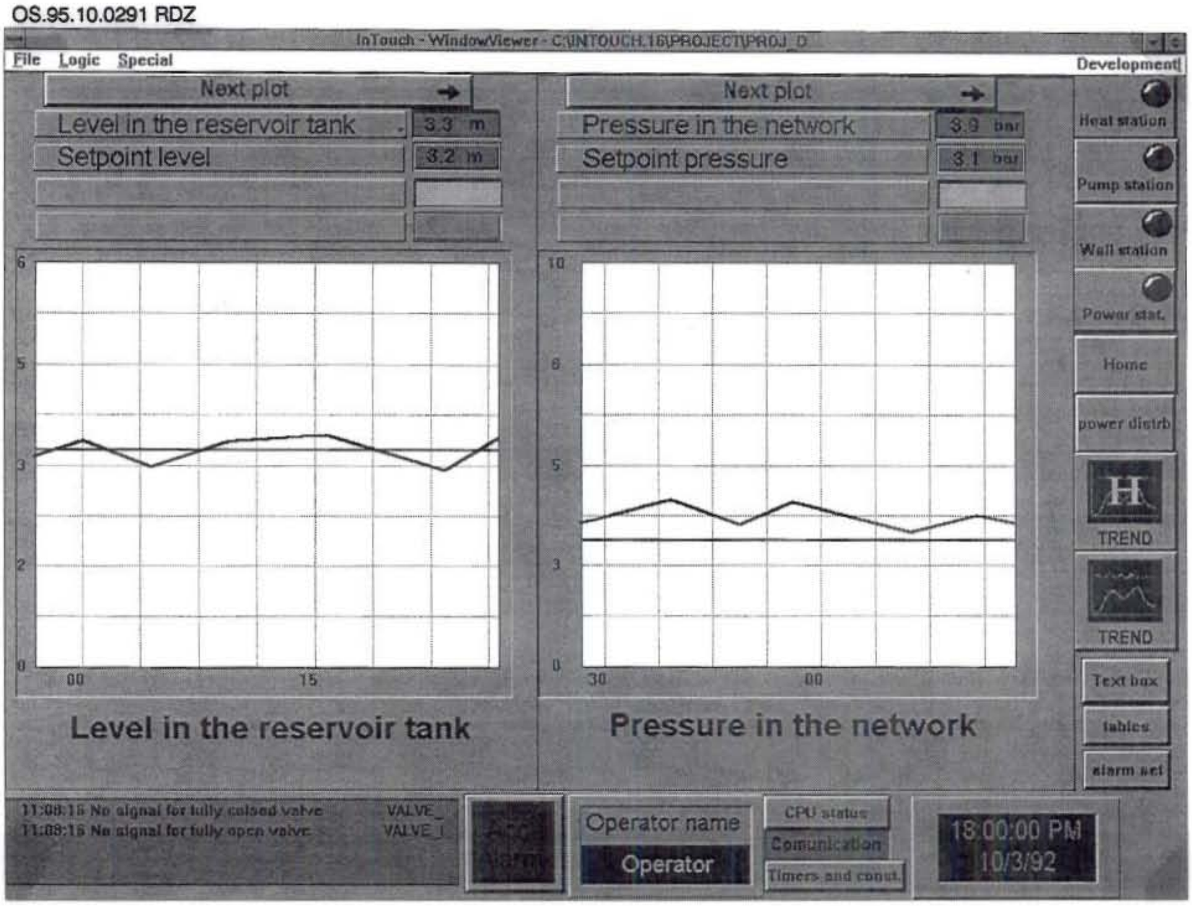

FIGURE 6: SCADA picture showing real trends of analogue values

system pressure PT1. During the testing process, all the digital and analogue inputs (except the tank level LT1 and the system pressure PT1) were simulated using simulated inputs and ordinary SCADA inputs. Both the normal operating mode (group mode on) and the manual mode (group mode off) were tested, and the system reaction was observed. The system reaction to each possible failure that can occur was also tested. When necessary, corrections were done.

6. CONCLUSIONS

There are a lot of advantages which result from implementing the described automatic control system. One of these is that it ensures almost fully automatic control and monitoring of the system that leads to a more economical and easier operation of the process. Also, the control system is designed so that it ensures the protection of the system components in case of failures that could damage the equipment, and the protection against failures that could cause damages to a member of the public or a worker. This leads to a safer operation of the system.

Finally, through the data collection facilities provided by SCADA MMI, we are able to monitor and record during long periods of time (months, years) the global state of the system. Using the graphical facilities of the SCADA MMI these data could be easily processed and presented in a graphical form, which is easier to interpret. On this basis, estimations of the system state (the well, the reservoir, etc.) could be done and also the optimal strategy in utilization of the geothermal energy could be found.

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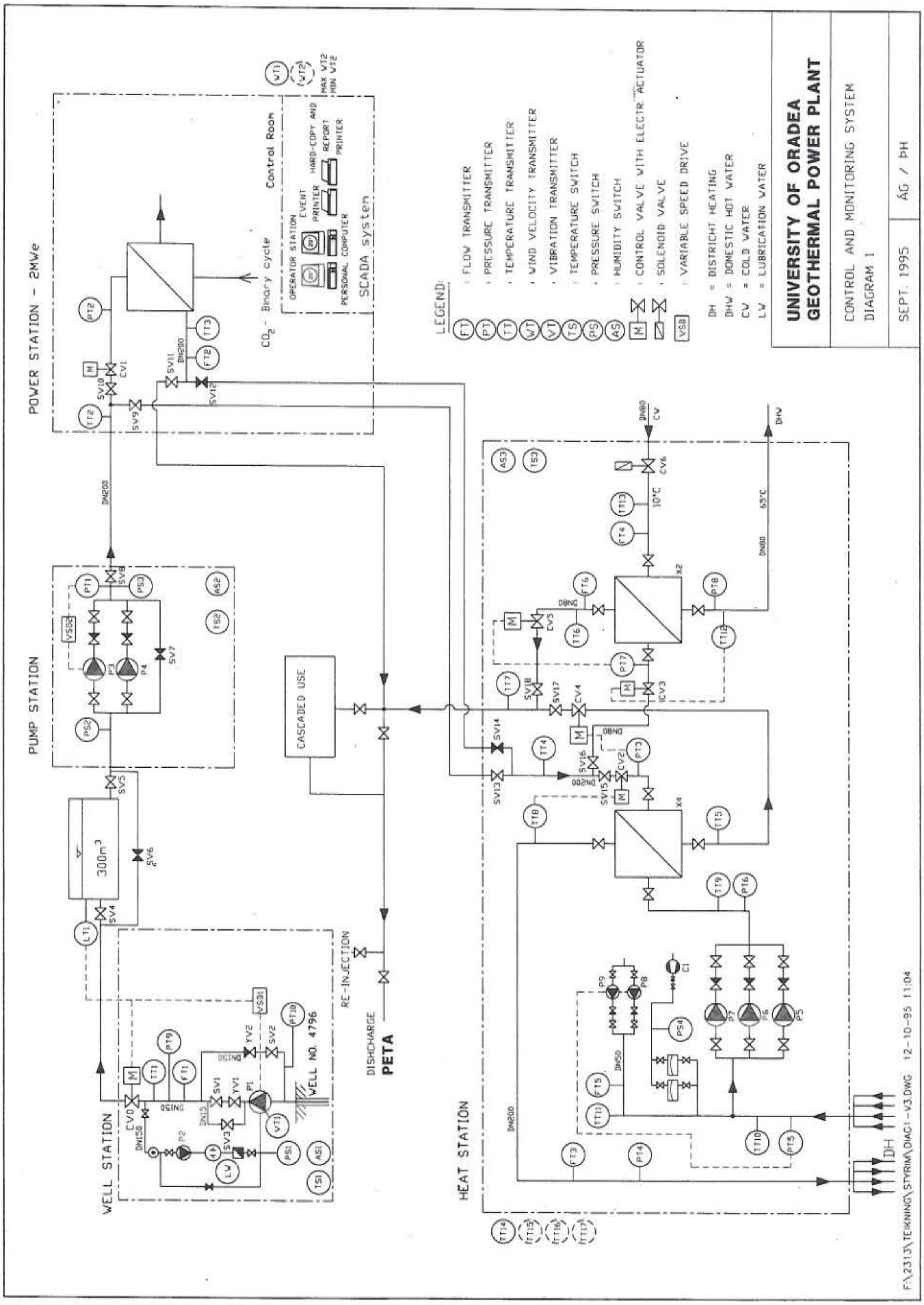
APPENDIX I: Control and monitoring system diagram



APPENDIX II: Sensors, actuators and control devices

The controlled devices are presented in the following table:

The controlled devices	Notation
Deep well pump associated with the variable speed drive VSD1	P1
Lubrication pump for the well pump	P2
Booster pump associated with the variable speed drive VSD2	P3
The reserve booster pump	P4
Well control valve associated with an electrical actuator (motor)	CV0

The pumps P1, P3 and P4 are controlled with a variable speed drive. The opening of the valve CV0 is controlled with an electrical actuator (ON/OFF in two directions) with opening/closing time equal to 40 seconds. The pump P2 is ON/OFF controlled. The following sensors and actuators are installed:

Digital inputs	Notation
Limit switch indicating fully open position of CV0, CV0_LO	CV0_LO
Limit switch indicating fully closed position of CV0, CV0_LC	CVO_LC
Limit torque switch for open direction, CV0_TL1	CV0_TL1
Limit torque switch for closing direction, CV0_TL2	CV0_TL2
Fault indication for the control valve CV0, CV0_CA	CV0_CA
Well pump power relay auxiliary switch, P1_ON	P1_ON
Overload/short circuit protection for P1 tripped, P1_OL	P1_OL
Well pump thermal switch disconnected, P1_TD	P1_TD
Overheat switch for P1, TS11	TS11
VSD1 ready, VSD1_RD	VSD1_RD
Fault in VSD1, P1_CA	P1_CA
Lubrication pump power relay auxiliary switch, P2_ONST	P2_ONST
Lubrication pump thermal switch disconnected, P2_TD	P2_TD
Lubrication pump pressure switch, PS1	PS1
Overload/short circuit protection for P2 tripped	P2_OL
Booster pump power relay auxiliary switch	P3_ON
Booster pump thermal switch disconnected	P3_TD
Overload/short circuit protection for P3 tripped	P3_OL
VSD2 ready	VSD2_RD
Overheat switch for P3, TS13	TS13
Fault in VSD2, P3_CA	P3_CA
Suction pressure switch, PS2	PS2
Discharge pressure switch, PS3T	PS3T
Phase failing switch in panel A3, PSF1	PSF1
Phase failing switch in panel A4, PSF2	PSF2
Emergency switch in panel A3 activated, ES1	ES1
Emergency switch in panel A3 activated, ES2	ES2
Too high indoor temperature in well station, TS1	TS1
Too high indoor humidity in well station, AS1	AS1
Too high indoor temperature in pump station, TS2	TS2
Too high indoor humidity in pump station, AS2	AS2

Digital inputs	Notation
Remote/Local switch in panel A3 for the pump station, RL1	RL1
Remote/Local switch in panel A4 for the well station, RL2	RL2
Well flow counter, FT1_CN	FT1_CN
Scaling, 1 pulse corresponds to 100 litres of water	
Well flow direction/error switch, FT1_ER	FT1_ER

Digital outputs	Notation
Start P1, pulse for 1.0 s	P1_RNRN
Stop P1, pulse for 1.0 s	P1_STST
VSD1 start/stop	VSD1
Start P2, pulse for 1.0 s	P2_RNRN
Stop P2, pulse for 1.0 s	P2_STST
Start P3, pulse for 1.0 s	P3_RNRN
Stop P3, pulse for 1.0 s	P3_STST
VSD2 start/stop	VSD2
Open valve	CV0_OP
Close valve	CVO_CL
Well pump vibration transmitter reset switch	VT1_RZ

Analogue inputs	Notation
Level transmitter for the reservoir tank	LT1
Scaling: 4-20 mA corresponding to 0-6.0 m height in the tank	
Opening of the valve CV0	PT0
Scaling: 4-20 mA corresponding to 0-100% opening of the valve	
Pressure transmitter for the system pressure	PT1
Scaling: 4-20 mA corresponding to 0-10.0 bar	
Pressure transmitter for well head pressure	PT9
Scaling: 4-20 mA corresponding to 0-10.0 bar	
Pressure transmitter for well pressure	PT10
Scaling: 4-20 mA corresponding to 0-10.0 bar	
Current transmitter for the well pump motor	P1_MC
Scaling: 4-20 mA corresponding to 0-200 A	
Current transmitter for the booster pump motor	P3_MC
Scaling: 4-20 mA corresponding to 0-200 A	
Flow transmitter for well fluid flow	FT1
Scaling: 4-20 mA corresponding to 0-50.0 l/s	
Well pump frequency rate	P1_HZ
Scaling: 4-20 mA corresponding to 0-100 Hz	
Booster pump frequency rate, P3_HZ	P3_HZ
Scaling: 4-20 mA corresponding to 0-100 Hz	
Vibration transmitter for the well pump	VT1
Scaling: 4-20 mA corresponding to 0-5.0 mm/s^2	
Temperature transmitter for well return water temperature	TT1
Scaling: 4-20 mA corresponding to 0-120°C	

Analogue outputs	Notation
Speed signal for VSD1, VSDP1_SP Scaling: 4-20 mA corresponding to 0-100% speed	VSDP1_SP
Speed signal for VSD2, VSDP32_SP Scaling: 4-20 mA corresponding to 0-100% speed	VSDP32_SP

APPENDIX III: Control system structure