DEEP WELL ELECTRIC MOTOR PUMP CONTROLLER FOR OVERHEAD WATER TANK USING PLC

By

ZWELAKHE PATRICK KUBHEKA

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

Universiti Teknologi Petronas
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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2007

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Zwelakhe Patrick Kubheka

ABSTRACT

Rural areas are less exposed to environmentally hazardous chemicals and are therefore more suited to groundwater extraction for human consumption. Traditionally, windmills or hand operated lever pumps are used to extract water from a well. The problem with these techniques is that they do not provide a means of preventing storage tank overflows, which results in a waste of water. This project suggests a viable strategy of eliminating such waste. The system uses a motor-driven pump to suck up water from a deep well to the overhead reservoir tank. An electric motor runs on command by a Programmable Logic Controller (PLC). The automation – afforded by program in a PLC – ensures that water from the tank does not overflow.

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ABBREVIATIONS AND NOMENCLATURES

A	Internal cross sectional area of a water pipe
BALB	Bekalan Air Luar Bandar Project
D	Internal diameter of a water pipe
FYP1	Final Year Project, Phase 1
FYP2	Final Year Project, Phase 2
g	Acceleration due to gravity
GSM	Geological Survey of Malaysia
h	Number of homes in a typical large village
H	Head loss of the pumping system
H_d	Differential head
H_f	Friction head
H_s	Static head
H_v	Velocity head
KPLB	Kementerian Pembangunan Luar Bandar
L	Length of a water pipe
LD_L	Level Detector for 'water low' condition, i.e. empty tank
LD_H	Level Detector for 'water ligh' condition, i.e. full tank
Lestari	Malaysian Institute for Environment and Development
P	Power handling capacity of a motor-pump
PLC	Programmable Logic Controller
ρ_w	Density of cold water
r	Daily rate of water consumption per home
Q	Flow rate of water
t	Time (seconds) elapsed while the pump is running
T	Time (days) between two successive run sessions of a pump
v	Linear velocity of water in a pipe
V	Volume of the overhead water tank

CHAPTER 1
INTRODUCTION

Water is a limited natural resource upon which all life on earth is sustained. Groundwater is rainwater that has seeped into the ground. Some is absorbed by plants, what remains sinks to depths that range from one meter to hundreds of meters, and settles in-between layers of permeable soil, sand and rocks, called aquifers. Groundwater is a free and drinkable source and comes without the hassle of nature-unfriendly plastic bottles, bulky water filters and cumbersome water bills.

Background of Study

Despite a resurgence of this age-old practice of drawing water from the ground in many rural communities in Malaysia, a serious concern is with regards to the impurities in the environment, especially the urban environment, which can ultimately contaminate this type of water. The Institute for Environment and Development (Lestari) warns that pollution is a serious issue and a common harmful chemical found in groundwater is arsenic. Other harmful chemicals that have been found in groundwater in Malaysia are magnesium, iron and ammonia. The surrounding environment should be clean and pollution-free if groundwater is to be extracted for consumption.

Two types of wells are common in Malaysia for the extraction of groundwater: The dug well and the tube well. The dug well, which is common in rural areas, can be quite hazardous, especially as children could fall in. The tube well caters largely to the industrial sector and can go as deep as 120 meters underground. The dug well is usually less than 10 meters deep.

Problem Statement

Rural areas are less exposed to environmentally hazardous chemicals and are therefore more suited to groundwater extraction for human consumption. Traditionally, windmills or hand operated lever pumps are used to extract water from a well. The problem with these techniques is that they do not provide a means of preventing tank overflows, which results in a waste of water.

This project suggests a viable strategy of eliminating such waste. A motor-driven pump will be used to suck up water from a deep well to the overhead reservoir tank. An electric motor will run on command by a Programmable Logic Controller (PLC). The automation – afforded by a PLC – will ensure that water from the tank does not overflow.

Objective and Scope of Study

The objective of this project is to ensure that groundwater is retrieved and consumed without waste in rural communities. The scope of the project is limited to the following: Simulating the entire automated pumping process; evaluation of the motor specifications; specifying pump technical parameters for a typical tank size; programming the PLC for level monitoring and control; and building the prototype. Water quality testing and treatment will not be covered. Detailed mechanical designs and pressure monitoring/control on pipes is also outside the scope.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Groundwater stations in Malaysia

Water supply from deep wells is common practice in many rural communities in the country, especially in East Malaysia. However, a recent survey conducted by Property Times (New Straits Times, 2004) revealed that urban communities still have not caught on to this option, despite the increasing complaints of muddy and discolored tap water. While some urbanites simply are unaware that groundwater can be a free and drinkable source, others are wary of the impurities that abound in the urban environment, which they believe can ultimately contaminate this type of water.

In the rural areas of Sarawak, groundwater is an important supplementary source for every village and school. During prolonged dry seasons, the significance of groundwater as an alternative source becomes clear. During this time, rainwater stored in the tanks could not sustain the daily requirement and the nearby streams and rivers either dry up or are affected by saline water intrusion particularly in the coastal areas of Sarawak.

To systematically overcome this problem, the Geological Survey of Malaysia (GSM) started its hydro-geological investigation in 1975 with the objective to determine the possibilities of getting a groundwater source from the shallow aquifers. By the early 1980s, the importance of groundwater as a conjunctive source of domestic water had gained its pace in Sarawak. Nowadays, groundwater in various hydro-geological environments is exploited for domestic water supply.

The Minerals and Geo-science Department of Malaysia - as a result of merger between the Geological Survey of Malaysia and Mines Department - has to date identified and developed groundwater source in hard rocks and unconsolidated sediments which has benefited 60,000 rural population in 35 villages and 7 longhouses mainly in the coastal areas of Sarawak.

The department is also assisting the Kementerian Pembangunan Luar Bandar (KPLB) to implement the Project Bekalan Air Luar Bandar (BALB) – Alternative System, and also the Ministry of Education under Project Pembangunan Pendidikan Luar Bandar – Bekalan Air.

Under the Project BALB – Alternative System, the department has completed 30 tube wells mainly for rural villages. Examples of these are at Kpg. Sebat, Kpg. Segong, and Kpg. Krokong in Kuching Division, Kpg. Penasu in Sarikei Division, Kpg. Bungai, Kpg. Bakam dan Kpg. Beraya in Miri Division, and Kpg. Meritam, Kpg. Siang-Siang and Kpg. Lintang in Limbang Division.

Under the Project Pembangunan Pendidikan Luar Bandar – Bekalan Air, the department has completed 25 tube wells for the rural schools. Examples of these are at SK Kambug in Kuching Division, SK Sg. Nyiar in Sri Aman Division, SK Penasu in Sarikei Division, SK Batu 36 Oya and SK Batu Luking in Sibu Division, SK Poyut, SK Long Lapok and SK Sg. Biar in Miri Division, SMK Medamit and SK Siang-Siang in Limbang Division, and SK Ng. Temalat, SK Ng. Kain, SK Ng. Merit and SK Ng. Oyan in Kapit Division. The natural yield of the wells commonly range from 1,000 to 10,000 liters per hour and is able to meet the local consumption.

As far as automation is concerned, rural wells are manually operated. However, using a PLC for groundwater pumping is not an entirely new idea. Oil rigs and industrial firms isolated from the piped water grid have been using these devices for decades. The application of this technology to domestic water wells is innovative and not a widespread idea. The primary reason for such reluctance is that these controllers and their associated accessories do not come cheap; bearing in mind that water supply to rural communities is usually a local government service.

2.2 Control System Theory

A control system is a feedback algorithm that senses changes in the present state of a physical process and then make control decisions that determine the new state of the process. There are various devices for implementing such a feedback algorithm; a Programmable Logic Controller (PLC) is one of them. PLCs have been around since the mid 1970s and standard design protocols for PLC based control systems are now well established. These rules vary depending on the nature of the system to be controlled. Appendix D shows steps of the protocol for programming a PLC for flow process control.

Before the invention of PLCs, control circuits were based entirely on hard-wired circuits using bulky electromagnetic relays consisting of coils, contacts and solenoids. In typical modern control, a PLC replaces all these components with a single programmable module, offering various advantages, these include:

- Flexibility: PLCs are programmable and reprogrammable.
- Ease of maintenance: They are easier to install and troubleshoot
- Low cost: Fewer parts are used in a PLC control system
- Reliability: They do not fail as often as electromagnetic relays
- Faster control: PLC microprocessors respond very fast compared to relays

PLC programming software was originally developed with relay logic in mind so that anyone with electromagnetic relay experience could easily learn the PLC language. As a result, it is necessary to understand relay circuits to be handy with PLCs. These circuits are called ladder diagrams.

CHAPTER 3
METHODOLOGY AND PROJECT WORK

3.1 Methodology

Figure 1 shows steps undertaken to complete the project. The corresponding gaunt charts are shown in appendix A and B.

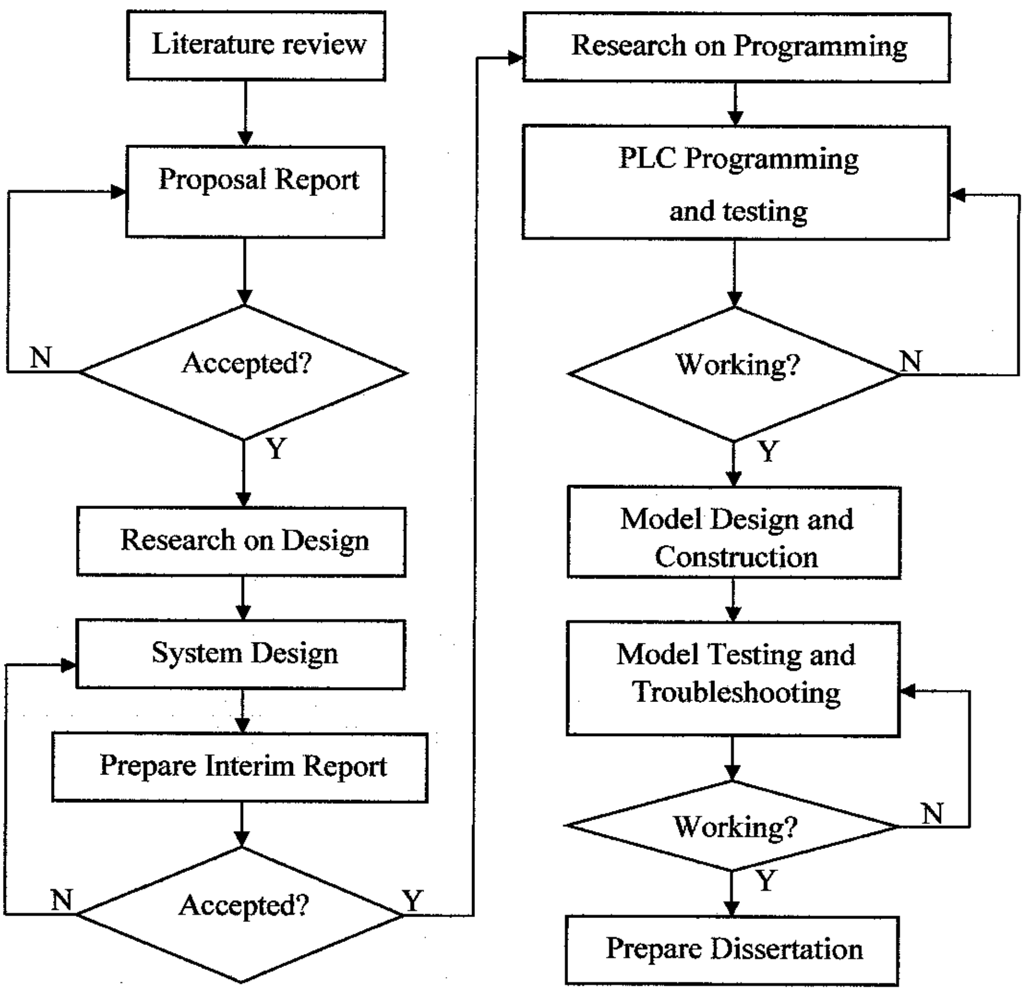

Figure 1: Flowchart of Methodology

3.2 Real System Design

3.2.1 Overview of the System Design

The actual system consists of the following major components:

- Overhead tank and deep well
- Electric motor-pump
- Programmable Logic Controller
- Level sensors
- Water Piping

Appendix H shows the process schematic diagram. The system operates as follows:

When the start button is pressed, the PLC will check if the High Level Detector (LD_H) is ON (i.e. if the tank is full). If so it will not start the motor. Otherwise the PLC will turn the motor ON and the driven pump will start extracting water from the well to the overhead tank. The PLC, motor and pump will continue to run until the tank reaches its maximum capacity, marked by the position of High Level Detector (LD_H). At this point, LD_H will be activated and send a stop signal to the PLC. The PLC will then stop the motor and the pump accordingly.

As the tank water is consumed, the level will drop until it reaches the tank minimum capacity, marked by the position of Low Level Detector (LD_L). At this point, LD_L will be activated to send a start signal to the PLC. The PLC will then start the motor and the pump accordingly, and the tank will begin to fill up again.

3.2.2 Design Calculations

The power handling capacity (P) of the pump and motor depends on the size of population the system would serve, and the energy (head loss, H) the pump must supply as it sucks water from the deep well and discharges it into the overhead tank. The population size dictates what size (V) of the overhead tank is appropriate. Once V is known, it can be used to evaluate the required flow rate (Q) of the system. After calculating the system head loss and flow rate, the power rating of the pump and motor can be easily determined. Therefore in summary, designing steps are:

- Find the capacity (V) of the overhead tank
- Determine the required flow rate (Q)
- Evaluate appropriate sizes for water pipes
- Calculate the total pressure head loss (H) of the system
- Calculate the power rating (P) of the pump and motor

Appendix C shows all calculations in detail. Table B shows design results. The procedure followed to determine parameters mentioned above is as follows:

Knowing the number of homes (h) in a target community and the average daily consumption rate (r liters/day) per home, the tank size was calculated using equation B1. The calculated tank volume could be used to evaluate the flow rate (Q) required to fill the tank in optimum time. However, research revealed that deep wells in Malaysia are operated at around 100 m^3/hr.

The diameter (D) of water pipes was evaluated from the flow rate and linear water velocity (v). This was done using equation B3 and B4. To minimize turbulence and friction losses, the linear velocity of water was kept at 3 m/s.

Pressure head loss is the energy that the pump must supply to the water as it drives this liquid from the deep well to the overhead tank. Total pressure head loss (H) of the system is the sum of static head (H_s); the differential head (H_d); the velocity head (H_v) and the friction loss (H_f), as dictated by equation B5. Illustrations of pressure heads are shown as figure 10 and figure 11. Once the flow rate and the total head loss were known, the power rating of the motor-pump was calculated from the equation B7.

3.2.3 PLC Programming

Appendix E gives details of steps that were followed to design and code the ladder program. Figure 6 in chapter 4 shows the flowchart that was used as a starting point. The PLC chosen is an Omron CPM1A and the final working program is shown in figure 7.

It was neither practical nor efficient to work out the ladder layout and actual code using only the flowchart. Several tools were incorporated sequentially, as guided by appendix E. These tools are:

- The required process operation (Section 3.2.1 and Appendix H)
- Memory addressing tables (Table D and Appendix G)
- Basic ladders used as building blocks (e.g. figure 5)
- The CPM1A PLC Instruction Set (Appendix F)

The first two points above covered step 1 and step 2 of the PLC programming protocol (Appendix E). The last two points – combined with some creativity – took care of steps 3 and 4. The last step (troubleshooting) was undertaken on the Omron CPM1A Training Kit. The kit was connected to a personal computer to download and debug the program, using the Syswin™ software.

3.2.4 Technical Details of Omron PLCs

Control and Instrumentation Laboratory uses PLCs manufactured by OMRON PTE LTD. Two models are available for small scale applications, viz. CPM1A and CPM2A. Each of these is actually a category of controllers, with the CPM2A range being slightly superior in size, power and performance than the CPM1A group. A physical size of a PLC is proportional to the number of inputs and outputs (I/O) it can handle, consequently the term 'size' is used to simply refer to the number of I/O points. On the basis of I/O points, the CPM1A is classified as a micro PLC whereas a CPM2A is referred to as a mini or midi PLC. The Omron manual (1999 release) gives elaborate details on the specifications, features and functions for the CPM1A and CPM2A range. Table A summarizes main features of these controllers.

Table A: Main Features of CPM1A and CPM2A Omron PLCs

Features and Specifications	CPM1A Range	CPM2A Range
Number of I/O points	10 to 40	30 to 60
I/O Expansion	up to 100 points	up to 120 points
Supply Voltage	20.4 to 26.4 VDC	85 to 264 VAC 50/60Hz
Inputs	24 VDC 5mA	24 VDC 5mA
Output Relays	Volt free, 2A, 250VAC, 2A 24VDC	Volt free, 2A, 250VAC, 2A 24VDC
Programmed using	Console or Syswin software	Console or Syswin software

A key feature that dictates a choice of a PLC for a particular control application is the number of inputs and outputs required for that application. This project requires 4 inputs and 1 output, so a basic CPM1A from table A - with 10 I/Os - will suffice.

A programmer has two choices for writing and downloading a program to an Omron CPM1A PLC, these are: a handheld calculator-sized programming console or, a software program - called Syswin™ - that runs on a Windows™ operating system on a PC. Each of these can be used to write, edit, download and debug a program in a PLC.

A programming console is a stand-alone portable device that does not need a PC to write and send a program to a PLC; it connects directly to the controller via the RS232 cable. Figure 2 shows two models of consoles that can be used to program a CPM1A PLC.

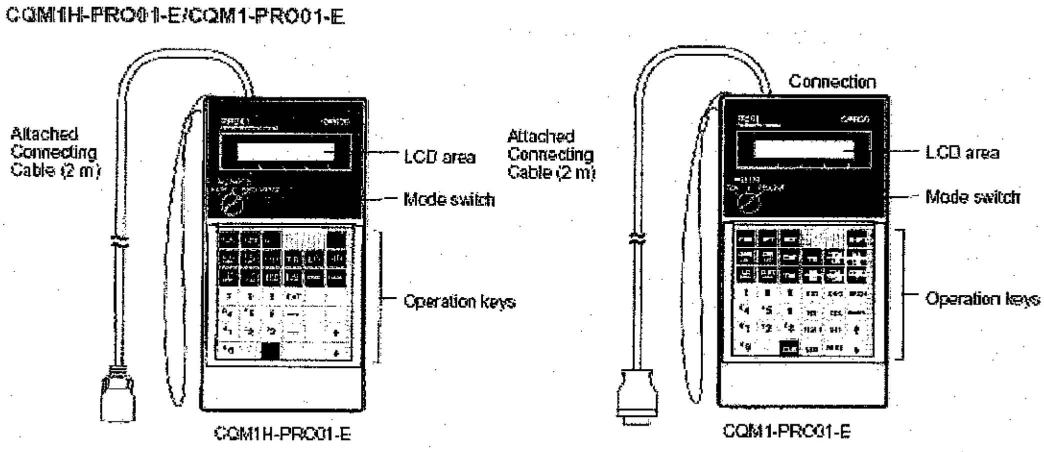

Figure 2: Programming Consoles for a CPM1A PLC

When using a console, the program must first be written in mnemonic code. Then it is entered on the console by sequentially typing commands - using the operation keys - and loading them into the PLC memory.

Syswin™ is a ladder programming software written to give programmers ease of using a Windows platform. Connection between a PC and a PLC is through an RS232 cable. Figure 3 shows a Syswin™ window with an empty ladder programming workspace.

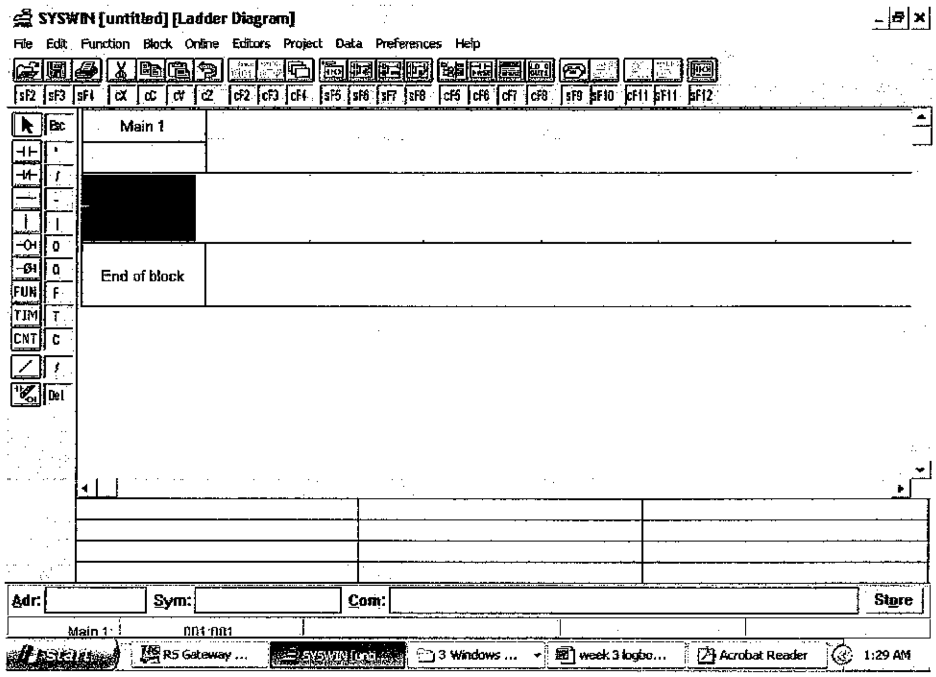

Figure 3: Syswin™ Window

When using Syswin™, there is no need to write the program in mnemonic code first - as is the case with a programming console. All that is necessary is to convert a ladder diagram obtained from simulation to a 'Syswin™ version'. The conversion process includes assigning appropriate addresses for each contact and coil in the ladder diagram.

The CPM1A instruction set is categorized into 14 groups, viz.

1. Sequence Instructions
2. Data Movement Instructions
3. Shift Instructions
4. BCD/Binary Calculation Instructions
5. Logic Instructions
6. Increment/Decrement Instructions
7. Data Conversion Instructions
8. Special Calculation Instructions
9. Subroutine Instructions

10. Interrupt Control Instructions

11. Step Instructions

12. Peripheral Device Control Instructions

13. Damage Diagnosis Instructions

14. Special System Instructions

Details of each group are in Appendix F.

3.2.5 Memory Structure and Addressing Modes of the Omron CPM1A PLC

In a ladder diagram, each element is assigned a memory address. This is a reference to a space in a PLC memory that stores the state (ON or OFF) of that particular element. Elements of the ladder diagram are simply symbols for contacts (capacitor symbols), coils (circles) and functions (squares). These represent inputs and outputs (I/Os). They include external hardware I/Os outside the PLC (e.g. level sensors, motors, etc) and internal I/Os. Internal I/Os are software type specified by the programmer in the ladder diagram. They are activated inside the program, and return their results within the program. The use of PLC memory to refer to I/Os and store their states is called addressing.

It is the responsibility of the programmer to decide how to allocate memory addresses to input and output elements, both internal and external. However, there are rules to be strictly observed: Memory is segmented into function-specific areas; some areas are accessible only via particular instructions; certain areas are reserved and the programmer access is completely forbidden. Appendix H shows the areas of a CPM1A PLC memory and their functions.

Of primary interest to the programmer is the IR area. This area is used to address inputs and outputs - IR stands for input/output register. As shown in Appendix H, addresses starting with IR00 refer to external inputs and those starting with IR01 refer to external inputs. Internal I/Os are referred to by addresses starting with IR2. It is a norm not to write the IR prefix in a ladder diagram, e.g. address 00000 is actually IR00000, meaning: first bit in the IR area addressing an external input. For all other areas, a prefix must be stated.

An example that follows further clarifies concepts of memory usage and addressing. It also introduces one of the basic building blocks of ladder logic – a self-holding circuit – that is used in the final ladder program of this project.

A self-holding ladder, figure 5, can be used to retain the START signal in the program when the pushbutton is released. It is customary to use a pushbutton to provide a START signal to a PLC-controlled process. Such a button is only ON while pressed and goes OFF when released, see figure 4. This may not be convenient, for instance one may want to start and keep the motor running even after releasing the START pushbutton.

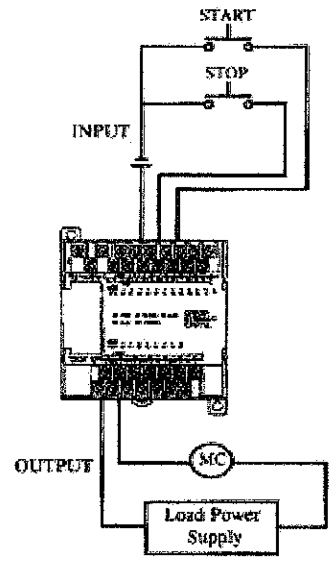

Figure 4: START and STOP Circuits for a PLC

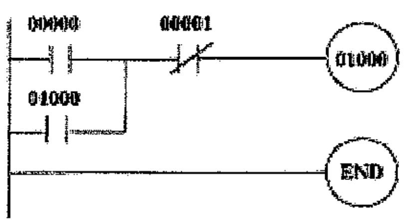

Figure 5: Self-Holding Ladder

With reference to figure 5, the number on top of each element is a memory address. Address 00000 refers to a START pushbutton, 00001 to a STOP pushbutton, 01000 to the output. END instruction identifies the end of the program.

Each ladder element is actually a program instruction written in graphic form, the address then specifies where the instruction fetches its operand, i.e. data to operate on. For instance, a circle at the end of the first rung is an output (OUT) instruction, getting its data at address 01000. Such data is a bit specifying if the output should be turned ON (data = logic HIGH) or OFF (data = logic LOW).

A self-holding action is made possible by the contact parallel to the START contact: When START pushbutton is pressed; contact 00000 closes and turns output coil 01000 ON. The output coil energizes contact 01000 parallel to START. So now even if START contact opens, the output remains ON through this parallel output contact. The output holds itself ON, until the STOP (00001) button is pressed.

3.3 Model Design and Construction

The size of the model was chosen by scaling down the volume of the overhead tank by a factor of 100 000, resulting in a 6 liter container. All other dimensions were then scaled down accordingly. Appendix I shows dimensions and pictures of the model. Materials used for construction are listed in Table B.

TABLE B: Parts for the model

ITEM	QUANTITY	SIZE	PRICE (RM)
Dolphin P-708 motor pump	1	23 W,1380 L/hr	36
Plastic containers	2	6L and 13L	20
Plastic lever arm	1	26cm long	4.2
Plastic hangers	11	38.5cm X 17cm each	6
Plastic tube	1	3 m, 2cm diameter	18
Plastic faucet	1	12cm X 10cm	5
Wood	1	1cm thick, $0.83m^2$	N/A
Water sealant	1	85.2g	6.5
Glue	10	235g total	101.8
Fastening rope	1	5cm X 10cm roll	1.2
PVC tape	1	5cm roll	2
Insulated copper wire	1	2m long	N/A
Spray paint	2	500mL each	11.5
Pushbutton switches	2	Diameter: 3cm each	N/A
Limit switches	2	Omron SS-5GL	8
Normally open Omron relay	1	24V	N/A
Omron CPM1A PLC	1	24V 10 point I/O	N/A
Power supply	1	24V	N/A
		TOTAL	**220.2**

Note: N/A implies that the material(s) were acquired from the Design or Control Laboratory.

3.3.1 Pump, Overhead Tank and Deep Well

The pump used was submersible type for aquarium tanks, and could be damaged if not installed and operated in water. This implied that the reservoir modeling the deep well had to be larger than the upper storage container (overhead tank). Therefore, the size of this reservoir was chosen to be at least twice that of the upper container. The stand for the overhead tank was designed to be triangular in shape. This geometry gave the most stable structure while using minimum materials. The overhead tank, float, float lever, tank stand and reservoir are all made from plastic. This material was chosen because it is easy to find, easy to cut and drill, and does not corrode – therefore best suited for water storage and handling.

3.3.2 Level Sensor Implementation

Commercially available level sensors far exceeded the budget allocated for building the prototype. A cost effective level sensing mechanism of a float was chosen as a viable alternative, see appendix I. The float mechanism works as follows: A float was constructed from a plastic material capable of floating in water. This float was glued to a pivoting lever that activates the two level sensors (Omron SS-5GL limit switches). One switch is turned ON by the float reaching the top of the tank, and sends a signal to the PLC about the 'full tank' state. Similarly, the other switch sends a signal to the PLC to report the 'empty tank' condition as the float reaches the bottom of the tank.

3.3.3 PLC-Motor Interfacing

A PLC – being a control device, not a high power switching element – typically operates on low currents and voltages. Consequently, when driving heavy loads like electric motors, it is necessary to include an interfacing circuit between a controller and the load. The interface circuit protects a controller from high-level signals while ensuring that a motor receives the high level signals to turn it ON and OFF as required. The circuit used in the model is a 24V relay, shown in figure 12 of appendix I.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Results on Real System Design

Table C summarizes results obtained from design calculations for the actual system. Appendix C shows all calculations in detail.

TABLE C: Results from Design Calculations

PARAMETER	SYMBOL	UNIT	VALUE
Overhead tank size	V	m^3	600
Flow rate	Q	m^3/hr	100
Suction pipe diameter	D	cm	15
Suction pipe total length	L	m	86.1
Discharge pipe diameter	D	cm	10
Discharge pipe total length	L	m	39.12
Head loss of the system	H	m	122.2
Power rating of the pump and motor	P	kW	33.47

4.2 Ladder Diagram

Figure 6 shows the flowchart that was used as a starting point for developing the ladder diagram. Input and output memory allocations are as shown in Table D.

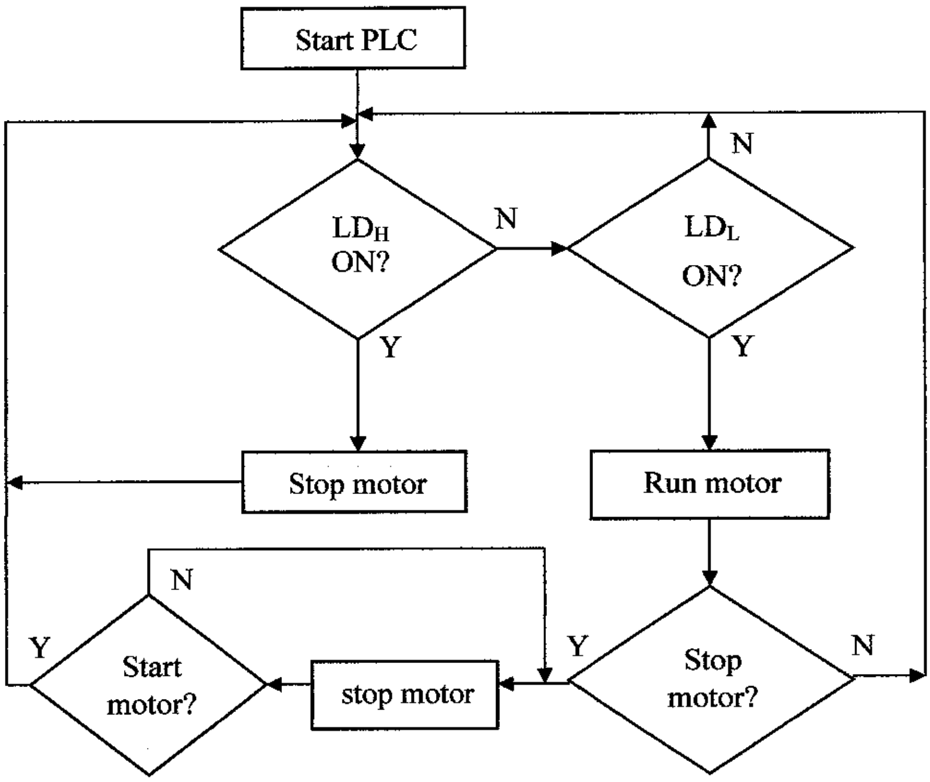

Figure 6: Flowchart for Developing the Ladder Program

Table D: I/O Memory Assignments

INPUT	DEVICE	OUTPUT	DEVICE
00000	START pushbutton	01000	MOTOR
00001	STOP pushbutton		
00002	Low Level Detector (LD_L)		
00003	High Level Detector (LD_H)		

Testing the initial program exposed two minor flaws. The first one was that when the tank level got to empty position while the system was on standby – i.e. STOP button pressed – the motor started. The second problem was that when the START button was pressed while the tank level was in full position, the motor started again. Adding two more contacts in network 1 of the ladder, and additional networks that drive these contacts, successfully eliminated these bugs.

Figure 7 is the final ladder program, with elaborate comments included. It contains a total of 9 networks. Each network performs a specific function dictated by the flowchart and process schematic. These functions are fully explained next to each network title in the ladder diagram.

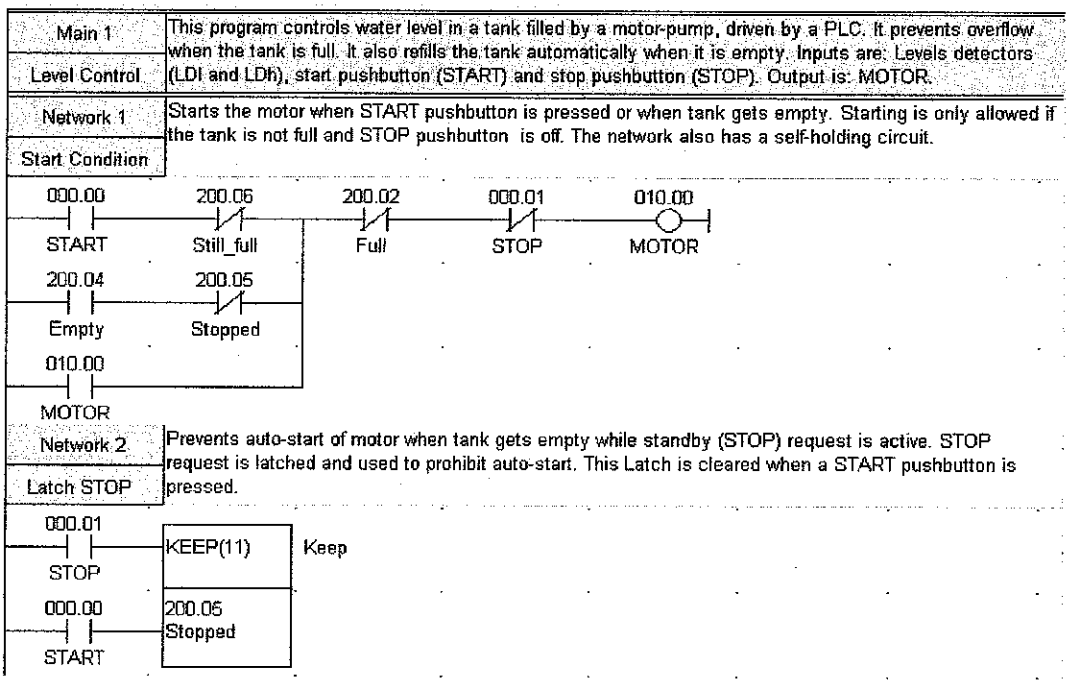

Figure 7a: Ladder Diagram

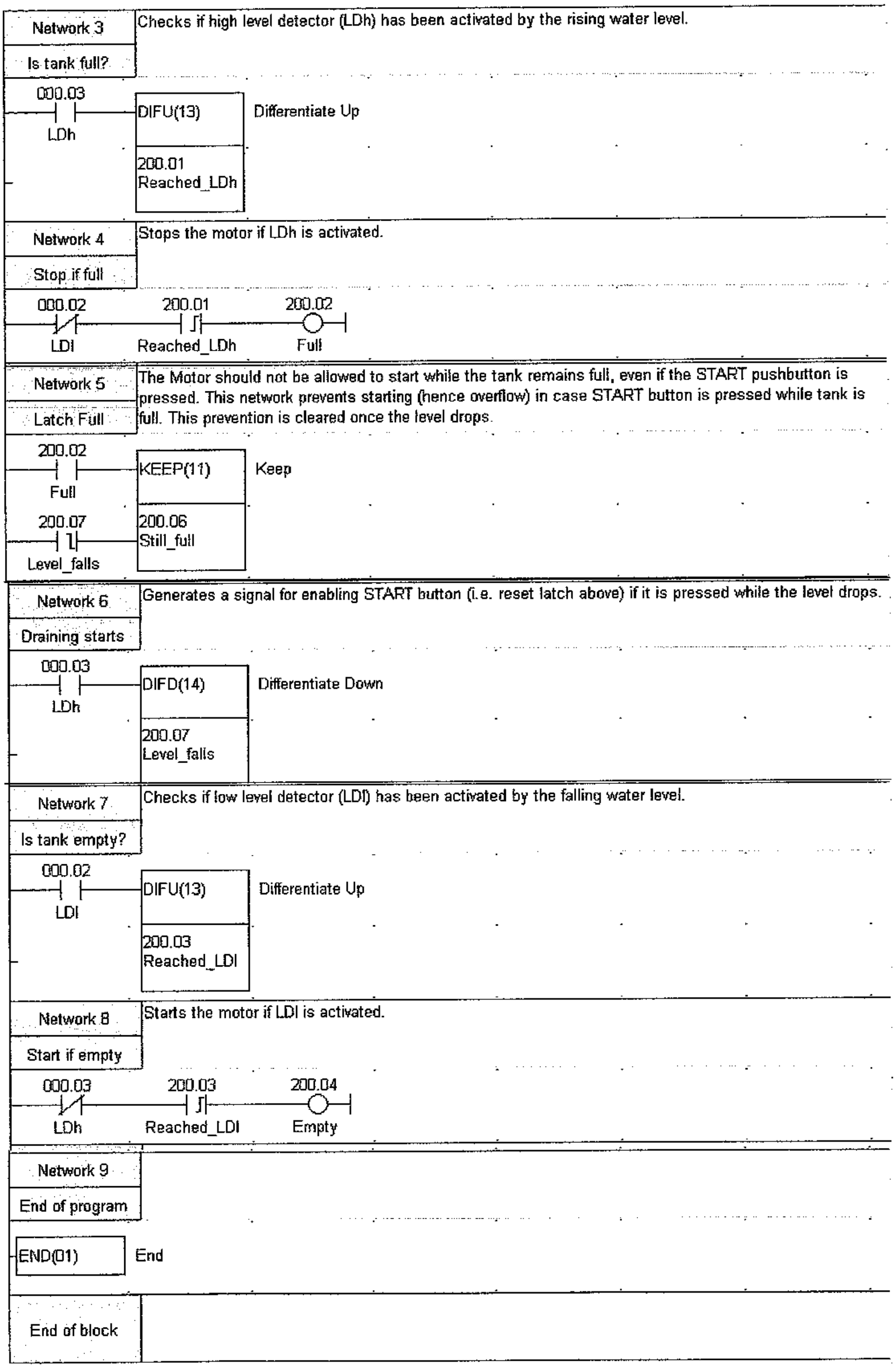

Figure 7b: Ladder Diagram, continued

4.3 Model Testing and Troubleshooting

The model was initially constructed with a 2W motor-pump, with a net head of 0.6m. This pump was found to be too slow during tests, taking up to 10 minutes to fill up the tank. The first suspect for this unacceptable observation was that perhaps losses in the pipe from the pump to the overhead tank were excessive. Therefore the pipe was shortened. However, there was no improvement in performance.

Ultimately the motor-pump was replaced with a more powerful 23W machine, which worked well and proved adequate. Apart from this alteration, the model worked perfectly after a series of adjustments on PLC connections and sensor positions.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Testing the final level control program on the model confirmed that there were no flaws, it worked as required. The design process also met the requirement of specifying the technical parameters of the actual system. Therefore the project work has met the objectives.

The use of a float for level sensing provides the most cost-effective solution, especially considering the fact that the system is designed for rural communities. The use of high-tech industrial sensors – e.g. non-contact level transmitters – is neither financially justifiable nor technically warranted, bearing in mind that the measurements are required at only two positions of the tank.

5.2 Recommendations

Recommendations for an upgrade include deep well level detection and maintenance tests. Deep well detection is necessary to protect the pump from cavitation damage once the well runs empty. Since water is trapped in between rocks (aquifers) in a well, a direct method of level sensing would not work. A viable strategy would be to detect the moisture content of aquifers. As water content in a well drops, the topmost aquifers will loose moisture. Therefore their percentage moisture content can be used as a measure of the well's remaining capacity.

Maintenance tests will check for the failure of high level detector (LD_H) or low level detector (LD_L) or the motor. There should be a failure alarm for each of these devices. If any of them is faulty, the program should set an appropriate alarm and stop the fill-up process, until the fault is rectified. Two ideas will be suggested for each device. They include software and hardware approaches. They are as follows:

High Level Detector (LD_H)

1) By a solenoid: While the tank is empty (i.e. LD_L ON), activate LD_H by a short pulse from a solenoid. Then check if LD_H responds to the solenoid command, both in closing and opening. A closing test will be conducted by checking for the rising edge of LD_H (using DIFU instruction), an opening test by the falling edge (DUFD). If any of the two checks fail, set an alarm and stop the motor.
2) By a software timer: Start a timer when the motor auto-starts (tank empty). A timer preset value should be just greater than the time it takes for the water level to reach LD_H . If the timer reaches its preset value before LD_H turns ON, then LD_H is faulty and its alarm must be turned ON and the motor must be stopped.

Low Level Detector (LD_L)

1) By a solenoid: While the tank is full (i.e. LD_H ON), activate LD_L by a short pulse from a solenoid. Then check if LD_L responds to the solenoid command, both in closing and opening. A closing test will be conducted by checking for the rising edge of LD_L (using DIFU instruction), an opening test by the falling edge (DIFD). If any of the two checks fail, set an alarm and stop the motor.
2) By software: Using a DIFD instruction, sense the falling edge of LD_L after the motor starts from the low level position of the tank. If the falling edge is not detected and the motor is not faulty, then LD_L is faulty. Its alarm should be turned ON and the motor must be stopped.

   Note: This approach will not work (for LD_L exclusively) if the motor is faulty.

   However, it can be used to indicate that either LD_L or the motor has a fault.

Motor

1) By a software timer: Start a timer when the tank gets empty (LD_L ON). A timer preset value should be a few seconds. If the timer reaches its preset value before the motor starts.

   Note: This approach will not work (for the motor exclusively) if LD_L is faulty. However, it can be used to indicate that either LD_L or the motor has a fault.

2) By software: Using a DIFD instruction, sense the falling edge of LD_L – which should occur when the motor starts from the low level position of the tank. If the falling edge is not detected and LD_L is not faulty, then the motor is faulty. Its alarm should be turned ON.

   Note: This approach will not work (for the motor exclusively) if LD_L is faulty.

   However, it can be used to indicate that either LD_L or the motor has a fault.

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APPENDICES

APPENDIX A

Project Gantt Chart, FYP1

No.	Details/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Topic Selection	—														
2	Preliminary Research															
	-Intro reading on PLCs, pumps, motors		—	—												
	-Research on local groundwater stations			—												
	-Preliminary Report draft and writing				—											
3	Submission of Preliminary Report				●											
4	Project Work															
	-Check softwares available in Control lab					—										
	-Select one and get familiar with it					—										
	-Research on PLC Ladder programming					—	—	—	—							
	-Simulation work						—	—	—	—	—	—				
	-Progress Report draft and writing							—	—							
5	Submission of Progress Report								●							
6	Project work continues															
	-Troubleshoot simulation									—	—	—				
	-Research on pumps and motors						—	—	—	—	—	—				
	-Design: Calculate for pump/motor selection									—	—	—				
	-Interim Report draft and writing											—	—	—		
7	Submission of Interim Report Final Draft													●		
8	Submission of Interim Report														●	
9	Oral Presentation															●

● Deadline

— Task Process

APPENDIX B

Project Gantt chart, FYP2

No.	Details/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Study Week	Post Exam
1	Task Planning and plotting the Gantt Chart	—															
2	Continue with Simulation																
	-Modify the simulation until it works well		—	—	—												
	-Extend the ladder diagram if necessary			—	—												
	-Progress Report 1, drafting and writing			—	—												
3	Submission of Progress Report 1				●												
4	PLC Programming																
	-Check PLCs available in the Control lab		—														
	-Select one and study its manual		—	—	—	—											
	-Write the PLC Program				—	—	—	—									
	-Test and Debug the Program						—	—	—								
	-Progress Report 2, drafting and writing							—	—								
5	Submission of Progress Report 2								●								
6	Prototyping and Exhibition																
	-Cost Analysis: Level sensors & PLC interface				—	—											
	-Buy parts if within budget						—										
	-Construction and Test Runs							—	—	—	—	—					
	-Pre-EDX												●				
7	Prepare and Submit Dissertation												—	—	—	●	
8	Oral Presentation																●
9	Prepare and Submit Extended Abstracts																— ●

● Deadline

— Task Process

APPENDIX C

DESIGN CALCULATIONS

Parameters to be evaluated are as follows:

a. Appropriate overhead tank size (V)
b. Flow rate (Q) required to fill up the overhead tank in reasonable time
c. Appropriate sizes for water pipes
d. Total pressure head loss (H) of the system
e. Power rating (P) of the pump and motor

a) <u>Appropriate overhead tank size (V)</u>

The size of a water storage tank depends mainly on the population size and consumption rate of the community it serves. Assume a large village of 200 homes, each consuming 100 liters on average a day. In rural areas of Malaysia, groundwater stations may be used as standby supplies in certain villages, the primarily supply being rainwater. However, during prolonged dry seasons, groundwater becomes the only source. During this time, rainwater stored in the tanks cannot sustain the daily requirements and the nearby streams and rivers either dry up or are affected by saline water intrusion, particularly in the coastal areas of Sarawak. It is therefore necessary for groundwater stations to cater for extended time durations. This calls for large storage to last for several weeks. It also implies that the pump should preferably run less frequently (say once a month) to fill a large tank, as opposed to running more often to fill the same tank at a higher flow rate.

For a pump to run once a month, the inner volume of the overhead storage tank should be:

$$V = hrT \quad \text{...(B1)}$$

$$V = (200 \text{ homes})(100 \text{ L/day})(30 \text{ days})$$

$$= \underline{600\ 000 \text{ liters}} \quad (600 \text{ m}^3)$$

This volume can be realized by a cylindrical tank of diameter 7.4m and height 3.5m.

b) Flow rate (Q) required to fill up the overhead tank in reasonable time

If the pump must fill the tank volume (V) to its maximum capacity in time t seconds, the required flow rate can be calculated from:

$$Q = V / t \quad \text{...(B2)}$$

However, deep well water stations in Malaysia are operated at around $\underline{100 \text{ m}^3/\text{hr}}$ ($0.0278 \text{ m}^3/\text{s}$, 440 GPM).

c) Appropriate sizes for water pipes

The diameter of water pipes is evaluated from the knowledge of fluid flow rate and its velocity. The velocity of a liquid in most systems is kept at lower than 3 m/s. This ensures that friction losses are insignificant. In the calculations that follow, the velocity at the discharge line of the pump will be limited to 3 m/s.

If a liquid flows with velocity v through a cross sectional area A, its flow rate is:

$$Q = Av \quad \text{...(B3)}$$

Where $$A = \pi D^2 / 4 \quad \text{...(B4)}$$

Therefore $D = \sqrt{(4Q) / (\pi v)}$

$= \sqrt{(4 X 0.0028) / (3\pi)}$

$= 0.109m$

$= 11cm$ (4.3 in)

Standard design tables (Friction Loss Tables) provide select diameter values in inches, viz. 1in; 15in; 2in; 3in; 4in; 6in; 8in; 10in and 12in (unit conversion factors are in table H). The value closest to the calculated one is 4in. Therefore the discharge pipe diameter is taken as 4 in (10cm). Table I on Appendix D shows sample values from Friction Loss Tables for a 4 in steel pipe. For the suction pipe, traditional pump system design practice recommends that the suction pipe diameter be chosen (from Table I) one size larger than the discharge pipe, viz. 6 in (15cm). The lengths of pipes are as shown in Figure 8 on the next page.

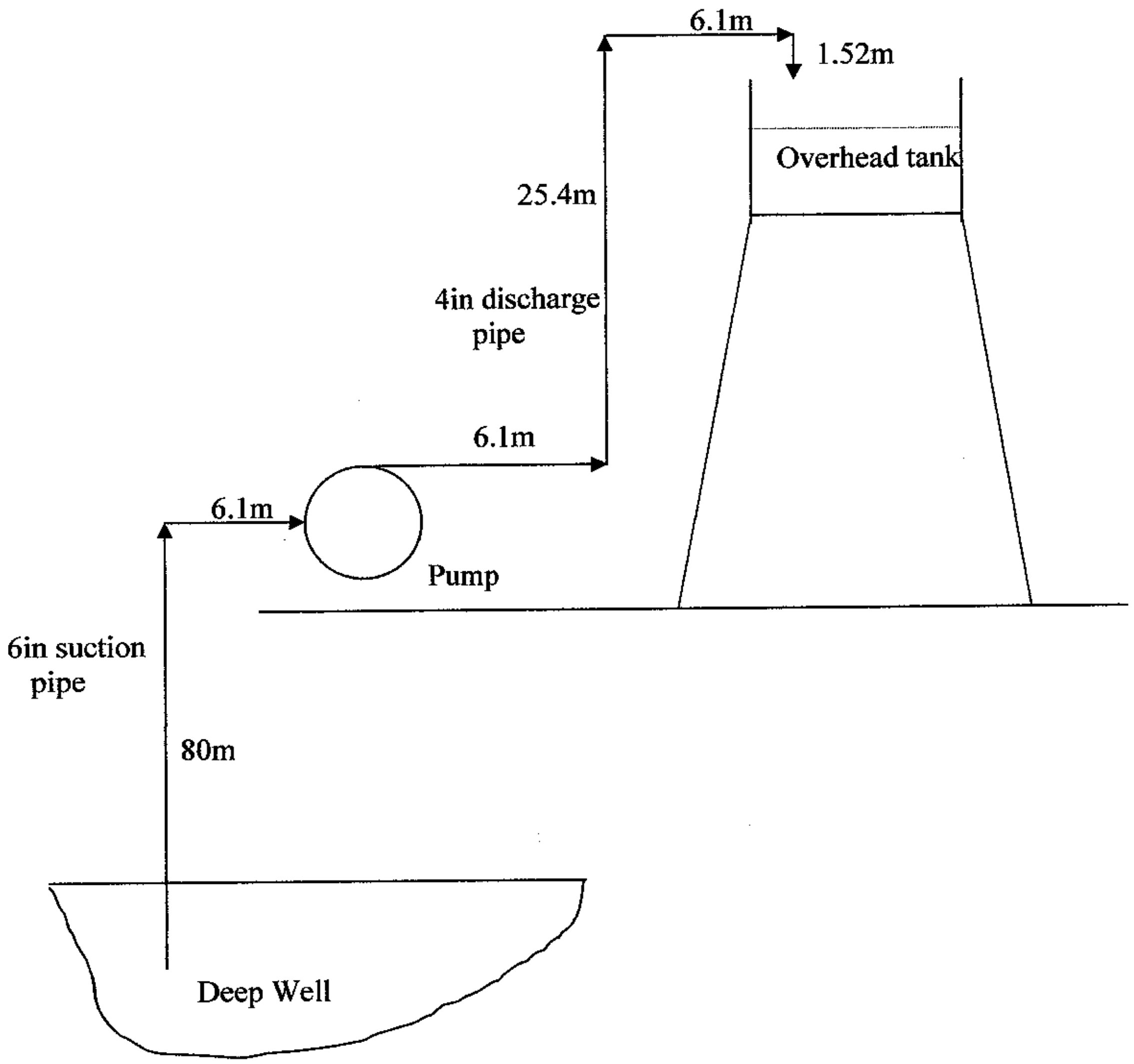


Figure 8: Dimensions of Suction and Discharge Pipes

The suction pipe vertical run (80m) is chosen to be moderately less than the typical maximum well depths in Malaysia (120m), whereas the discharge pipe vertical run (25.4m) is based on measurements from the UTP water tower and tank near the Chancellor's Complex. Horizontal runs (6.1m) are chosen such that they are as short as possible to minimize cost and friction losses (section d below), but not too short such that turbulence at the 90^0 pipe knees becomes significant. A 6.1m (20ft) run is the best compromise. Adding up dimensions in figure 8, the suction pipe is 86.1m long and the discharge pipe is 39.12m.

d) Total pressure head loss (H) of the system

Pressure head is an alternative means of specifying pressure applied by a fluid. It is simply a height of liquid that is equivalent to the pressure at the bottom of that liquid, i.e. an amount of pressure – expressed in distance units – that a liquid column applies at its base. Pressure head loss is the energy, expressed as pressure head, which the pump must supply (i.e. lose) to the liquid as it drives the liquid from the well to the overhead tank. This energy is composed of power to: lift the fluid vertically against gravity (static head, H_s); overcome deep well pressure and atmospheric pressure (differential head, H_d); accelerate the fluid though the pump (velocity head, H_v) and overcome friction inside the pipes and fixtures (friction losses, H_f). These heads are illustrated in Figure 9.

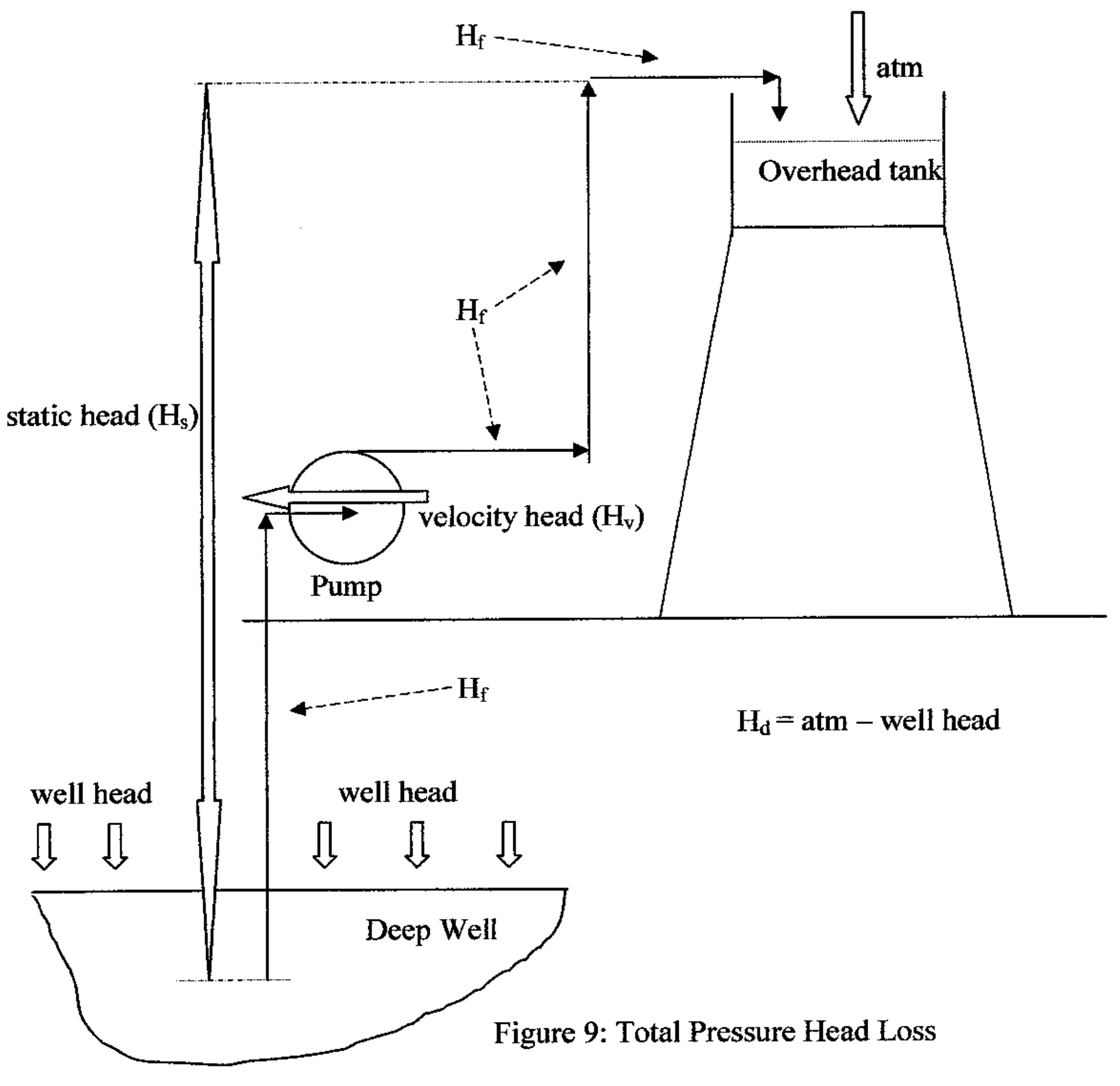


Figure 9: Total Pressure Head Loss

Total pressure head loss (H) of the system is simply the sum of individual heads:

$$H = H_s + H_d + H_v + H_f \quad \text{.....(B5)}$$

Calculations can get quite involved, so each head will be evaluated separately.

Static Head (H_s)

H_s is the vertical distance from the lowest suction point (end of pipe in the deep well) to highest discharge point (top of pipe above the overhead tank). i.e.

H_s = well depth + (tower height + tank height)

= 80m + 25.4m   from figure 10

= 105.4m (346 ft)

Differential Head (H_d)

H_d is the difference between the pressure head in the suction source (deep well) and the pressure head in discharge storage (overhead tank).

H_d = Tank pressure head – Well pressure head

Assuming that the storage tank is open to atmosphere, its pressure is 1atm (33.9 ft, table H).

As for the pressure head inside a deep well, a more elaborate calculation is necessary. The diameter of the suction pipe was calculated to be 6 in (0.152 m), so its cross sectional area is:

$$A = \pi D^2 / 4$$

$$= \pi(0.152)^2 / 4$$

$$= 18.15 \times 10^{-3} \text{ m}^2$$

Natural outflows from deep wells range from 1000L/hr to 10 000 L/hr (2.778×10^{-4} m^3/s to 2.778×10^{-3} m^3/s). Well pressure is simply the velocity head ($v^2/2g$) developed by this flow rate as water enters the suction tube. The higher value is calculated below:

Since $Q = Av$ ....(B6)

Then $v^2 / 2g = (Q / A)^2 / 2g$

$$= (2.778 \times 10^{-3} / 18.15 \times 10^{-3})^2 / 2 \times 9.807$$

$$= 1.194 \times 10^{-3} \text{ m} \quad (3.919 \text{ ft})$$

Note that natural pressure of the well boosts the pump, i.e. it is actually an energy gain (not a loss) in the calculation of total head loss (H). This is accounted for by giving it a negative sign.

$$H_d = \text{Tank pressure head - Well pressure head}$$

$$= 33.9 - (- 3.919)$$

$$= 37.82 \text{ ft}$$

Velocity head (H_v)

Velocity head (H_v) accounts for the energy required to accelerate the flow of the liquid through the pump. It is the difference in the values of velocity head ($v^2/2g$) at the suction and discharge nozzles of the pump. Friction Loss Table (Table H) provides velocity heads for known pipe diameters and flow rates, simplifying the calculation task:

$$H_v = (v^2/2g \text{ on 4in discharge}) - (v^2/2g \text{ on 6in suction})$$

$$= 1.91 - 0.371$$

$$= 1.539 \text{ ft}$$

Friction Loss (H_f)

Friction Loss (H_f) is due to resistance to flow occurring on the inner walls of pipes, valves and fittings. These losses are also evaluated from engineering tables. Friction losses are divided into two: Major losses and minor losses. Major losses occur along lengths of pipes, hence they are also called piping losses. Minor losses are far smaller then piping losses, they occur in valves and fittings.

Since one system can have many pipes and fixtures of various diameters, calculations can easily become tedious and elaborate. Working in tabular form with an aid of a spreadsheet makes all the manipulations manageable. Table E and F, prepared by a spreadsheet program, show calculations of Piping and Minor losses, respectively.

TABLE E: Piping Losses Calculation

Pipe Diameter (in)	*Pipe Length (ft)*	*Hf per 100 ft (ft)*	***Friction Loss (ft)***
6	282.49	1.31	3.701
4	128.35	10.2	13.092
		Net Loss	**16.793**

Notes: Column 3 data (H_f per 100 ft) is extracted from Table I on Appendix D
Friction Loss = (H_f per 100ft) (Pipe length / 100)

TABLE F: Minor Losses Calculation

Item	*K*	$v^2/2g$	H_f *(ft)*	*Quantity*	***Total*** H_f ***(ft)***
6 in Flanged Standard Elbow	0.29	0.371	0.10759	1	0.108
4 in Long Radius Flanged Elbow	0.22	1.91	0.4202	3	1.261
				Net Loss	**1.369**

Notes: K factor is a coefficient of friction (Table I, appendix D)
The velocity head ($v^2/2g$) is extracted from Table H on appendix D
$H_f = K(v^2/2g)$

Adding the net losses from the tables above, the total friction loss is:

$$H_f = \text{Major Loss} + \text{Minor Loss}$$
$$= 16.793 + 1.369$$
$$= 18.162 \text{ ft}$$

This completes the calculations of individual head losses.

The total head loss can now be computed.

$$H = H_s + H_d + H_v + H_f$$

$$= 346 + 37.82 + 1.539 + 18.162$$

$$= 403.52 \text{ ft}$$

$$= \underline{122.99 \text{ m}}$$

e) <u>Power rating (P) of the pump and motor</u>

Power rating can be calculated from the equation:

$$P = \rho_w g Q H \quad \text{.....(B7)}$$

$$= 998.2 \text{x} 9.807 \text{x} 0.0278 \text{x} 122.99$$ ρ_w and g are from table J.

$$= \underline{33.47 \text{ kW}} \ (44.89 \text{ hp})$$

APPENDIX D

ENGINEERING DATA TABLES

TABLE G: Unit Conversion Factors

PARAMETER	CONVETING FROM	TO	MULTIPLY BY -
Length	Meters (m)	Feet (ft)	3.281
	Centimeters (cm)	Inches (in)	0.3937
Volume	m^3	Liters (L)	1000
Flow rate	m^3 per hour	m^3 per second	0.00027778
	m^3 per hour	GPM	4.4033
Pressure or Head	Atmospheres (atm)	Feet (ft)	33.90
Power	Kilowatts (kW)	Horsepower (hp)	1.341

TABLE H: Friction Loss Table for Water in Pipe (steel schedule 40, size 4in and 6in)

DIAMETER (INCHES)	FLOW RATE (GPM)	VELOCITY (FT/SEC)	VELOCITY HEAD (FT)	H_F PER 100FT (FT)
4	400	10.1	1.58	8.47
	420	10.6	1.74	9.30
	440	**11.1**	**1.91**	**10.2**
	460	11.6	2.00	11.1
	480	12.1	2.27	12.0
6	400	4.44	0.307	1.09
	420	4.66	0.338	1.20
	440	**4.89**	**0.371**	**1.31**
	460	5.11	0.405	1.42
	480	5.33	0.442	1.54

TABLE I: Friction Coefficients for Fixtures

FIXTURE	DIAMETER (IN)	K FACTOR
Flanged Standard Elbow	1	0.42
	2	0.37
	4	0.31
	6	**0.29**
	10	0.25
	20	0.22
Long Radius Flanged Elbow	1	0.75
	2	0.42
	4	**0.22**

TABLE J: Physical Constants

CONSTANT	SYMBOL	UNIT	VALUE
Acceleration due to gravity	g	m / s^2	9.807
Density of cold water (20 ^{0}C)	ρ_w	kg / m^3	998.2

APPENDIX E

PROTOCOL FOR PROGRAMMING A PLC

The following six steps should be undertaken to ensure that the PLC is up and running:

1. Establish a detailed sequence of operation. This step requires full understanding of the process to be automated; drawing a schematic of block diagram is recommended.
2. Identify the inputs and outputs relative to the PLC. Once the schematic is drawn, inputs and outputs are read directly from it.
3. Design the program, a ladder diagram. This design requires knowledge of electrical relay/contact control circuitry or equivalently an understanding of ladder programming.
4. Code the ladder diagram into the specific PLC that is to be used. Here it is necessary to study the manufacturer's manual for the chosen PLC.
5. Troubleshot: Test the validity of the design and the accuracy of the operation. Most PLCs come with LEDs for inputs and outputs status, these are very handy for troubleshooting before installing the PLC into the process.
6. Connect the PLC, with its tested program, to the process that IS being controlled. This task requires basic electrical engineering knowledge and skills.

APPENDIX F

OMRON CPM1A PLC INSTRUCTION SET

Sequence Input Instructions

Instruction	Mnemonic	Function
LOAD	LD	Connects an NO condition to the left bus bar
LOAD NOT	LD NOT	Connects an NC condition to the left bus bar
AND	AND	Connects an NO condition in series with a previous condition
AND NOT	AND NOT	Connects an NC condition in series with a previous condition
OR	OR	Connects an NO condition in parallel with a previous condition
OR NOT	OR NOT	Connects an NC condition in parallel with a previous condition

Sequence Output Instructions

Instruction	Mnemonic	Function
OUTPUT	OUT	Outputs the result of logic to a bit
OUT NOT	OUT NOT	Reverses and outputs the result of logic to a bit
SET	SET	Force sets (ON) a bit
RESET	RESET	Force sets (OFF) a bit
KEEP	KEEP	Maintains the status of the designated bit

Sequence Control Instructions

Instruction	Mnemonic	Function
NO OPERATION	NOP	No operation, PLC goes to the next instruction
END	END	Required at the end of the program
INTERLOCK	IL	Turns off all outputs and resets all timers
INTERLOCK CLEAR	ILC	Clears the effect of IL
JUMP	JMP	Ignores all instructions until JME
JUMP END	JME	Resumes instruction execution after JMP

Data Movement Instructions

Instruction	Mnemonic	Function
MOVE	(@)MOV	Copies the content of a word to a word.
MOVE NOT	(@)MVN	Copies the complement of a content of a word to a word.
BLOCK TRANSFER	(@)XFER	Copies the content of a block of up to 1000 consecutive words to a block of consecutive words.
DATA EXCHANGE	(@)XCHG	Exchanges the content of two words.
MOVE BIT	(@)MOVB	Copies the specified bit from one word to the specified bit of a word.
MOVE DIGIT	(@)MOVD	Copies the specified digits (4-bit units) from a word to the specified digits of a word.

Shift Instructions

Instruction	Mnemonic	Function
SHIFT REGISTER	SFT	Copies the specified bit (0 or 1) into the rightmost bit of a shift register and shifts the other bits one bit to the left.
WORD SHIFT	(@)WSFT	Creates a multiple-word shift register that shifts data to the left in one word units.
ASYNCHRONOUS SHIFT REGISTER	(@)ASFT	Creates a shift register that exchanges the contents of adjacent words when one is zero and the other is not.
ARITHMETIC SHIFT LEFT	(@)ASL	Shifts a 0 into bit 00 of the specified word and shifts the other bits one bit to the left
ARITHMETIC SHIFT RIGHT	(@)ASR	Shifts a 0 into bit 15 of the specified word and shifts the other bits one bit to the right
ROTATE LEFT	(@)ROL	Moves the content of CY into bit 00 of the specified word, shifts the other bits one bit to the left, and moves bit 15 to CY.
ROTATE RIGHT	(@)ROR	Moves the content of CY into bit 15 of the specified word, shifts the other bits one bit to the left, and moves bit 00 to CY.

Increment/Decrement Instructions

Instruction	Mnemonic	Function
INCREMENT	(@)INC	Increments the BCD content of the specified word by 1.
DECREMENT	(@)DEC	Decrements the BCD content of the specified word by 1.

BCD/Binary Calculation Instructions

Instruction	Mnemonic	Function
BCD ADD	(@)ADD	Adds the content of a word (or a constant)
BCD SUBTRACT	(@)SUB	Subtracts the contents of a word (or a constant) and CY from the content of a word (or a constant).
BCD MULTIPLY	(@)MUL	Multiplies the contents of two words (or constants)
BCD DIVIDE	(@)DIV	Divides the contents of a word (or constant) by the content of a word (or constant).
BINARY ADD	(@)ADB	Adds the contents of two words (or constants) and CY
BINARY SUBTRACT	(@)SBB	Subtracts the content of a word (or constant) and CY from the content of a word (or constant).
BINARY MULTIPLY	(@)MLB	Multiplies the contents of two words (or constants)
BINARY DIVIDE	(@)DVB	Divides the content of a word (or constant) by the content of a word and obtains the result and remainder.

Data Conversion Instructions

Instruction	Mnemonic	Function
BCD TO BINARY	(@)BIN	Converts 4-digit BCD data to 4-digit binary data.
BINARY TO BCD	(@)BCD	Converts 4-digit binary data to 4-digit BCD data.
4 TO 16 DECODER	(@)MLPX	Takes the hexadecimal value of the specified digit(s) in a word and turns ON the corresponding bit in a word(s)
16 TO 4 DECODER	(@)DPMX	Identifies the highest ON bit in the specified word(s) and moves the hexadecimal value(s) corresponding to its location to the specified digit(s) in a word.

Logic Instructions

Instruction	Mnemonic	Function
COMPLEMENT	(@)COM	Turns OFF all ON bits and turns ON all OFF bits in the specified word.
LOGICAL AND	(@)ANDW	Logically ANDs the corresponding bits two words (or constants)
LOGICAL OR	(@)ORW	Logically ORs the corresponding bits two words (or constants)
EXCLUSIVE OR	(@)XORW	Exclusively ORs the corresponding bits two words (or constants)
EXCLUSIVE NOR	(@)XNRW	Exclusively NORs the corresponding bits two words (or constants)

Special Calculation Instructions

Instruction	Mnemonic	Function
BIT COUNTER	(@)BCNT	Counts the total number of bits that are ON in the specified block of words.

Subroutine Instructions

Instruction	Mnemonic	Function
SUBROUTINE ENTER	(@)SBS	Executes a subroutine in the main program
SUBROUTINE ENTRY	SBN	Marks the beginning of a subroutine program
SUBROUTINE RETURN	RET	Marks the end of a subroutine program
MACRO	MACRO	Calls and executes the specified subroutine, substituting the specified input and output words for the input and output words in the subroutine.

Interrupt Control Instructions

Instruction	Mnemonic	Function
INTERVAL TIMER	(@)STIM	Controls interval timers used to perform scheduled tasks
INTERRUPT CONTROL	(@)INT	Performs interrupt control, such as masking and unmasking the interrupt bits for I/O interrupts

Step Instructions

Instruction	Mnemonic	Function
STEP DEFINE	STEP	Defines the start of a new step and resets the previous step when used with a control bit. Defines the end of step execution when used without a control bit.
STEP START	SNXT	Start the execution of the step when used with a control bit.

Peripheral Device Control Instructions

Instruction	Mnemonic	Function
7-SEGMENT DECODER	(@)DSEG	Converts the designated digit(s) of a word into an 8-bit, 7-segment display code.
I/O REFRESH	(@)IORF	Refreshes the specified I/O word
MESSAGE	(@)MSG	Reads up to 8 words of ASCII code (16 characters) from memory and displays the message on the Programming Console or other Peripheral Device.

Damage Diagnosis Instructions

Instruction	Mnemonic	Function
FAILURE ALARM	(@)FAL	Generates a non-fatal error when executed. The Error/Alarm indicator flashes and the CPU continues operating.
SEVERE FAILURE ALARM	(@)FALS	Generates a fatal error when executed. The Error/Alarm indicator lights and the CPU stops operating.

Special System Instructions

Instruction	Mnemonic	Function
SET CARRY	(@)STC	Sets Carry Flag 25504 to 1
CLEAR CARRY	(@)CLC	Sets Carry Flag 25504 to 0

APPENDIX G

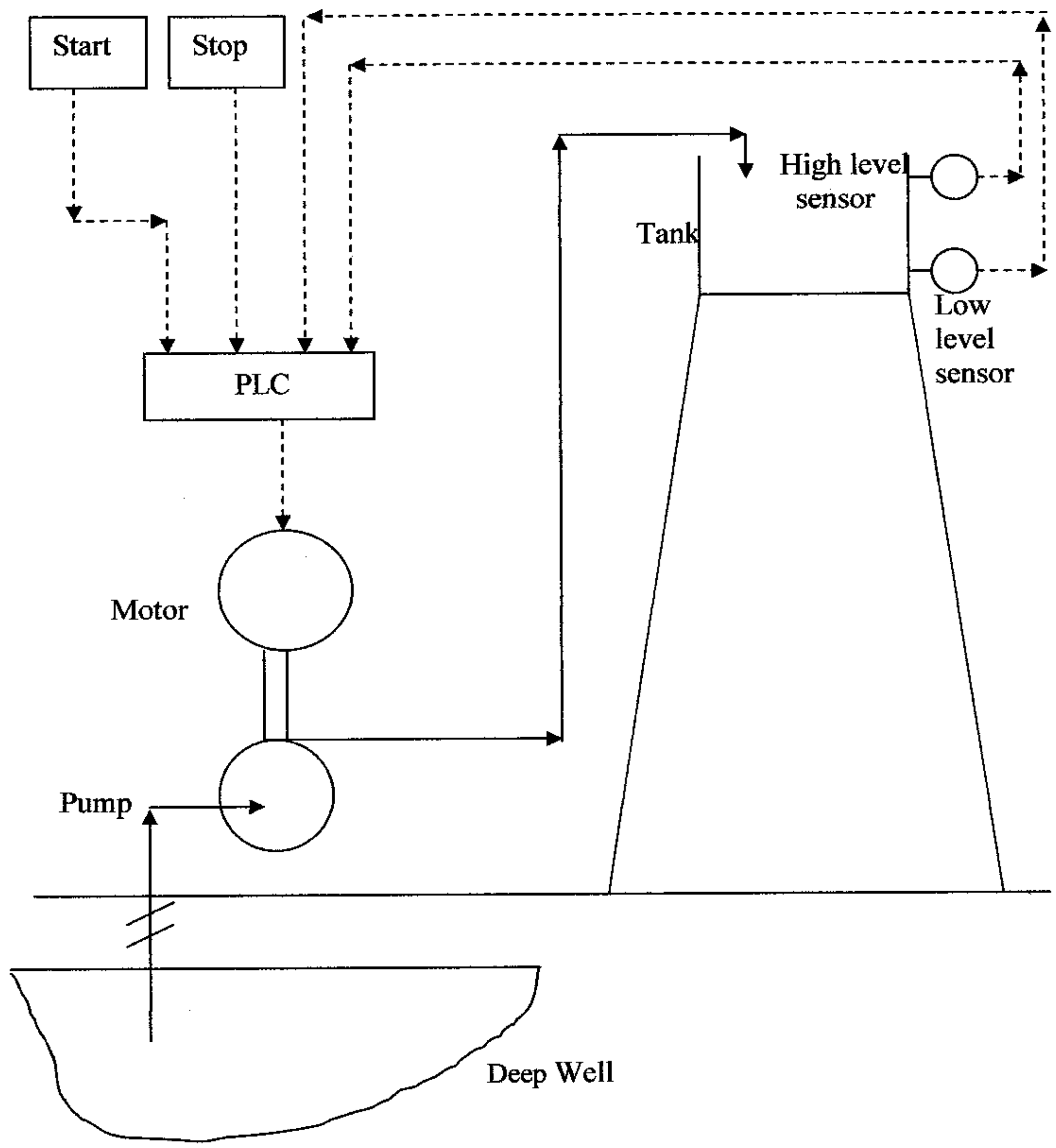
OMRON CPM1A PLC MEMORY STRUCTURE

Data area		Words	Bits	Function
IR area [1]	Input area	IR 000 to IR 009 (10 words)	IR 00000 to IR 00915 (160 bits)	These bits can be allocated to the external I/O terminals.
	Output area	IR 010 to IR 019 (10 words)	IR 01000 to IR 01915 (160 bits)	
	Work area	IR 200 to IR 231 (32 words)	IR 20000 to IR 23115 (512 bits)	Work bits can be freely used within the program.
SR area		SR 232 to SR 255 (24 words)	SR 23200 to SR 25515 (384 bits)	These bits serve specific functions such as flags and control bits.
TR area		---	TR 0 to TR 7 (8 bits)	These bits are used to temporarily store ON/OFF status at program branches.
HR area[2]		HR 00 to HR 19 (20 words)	HR 0000 to HR 1915 (320 bits)	These bits store data and retain their ON/ OFF status when power is turned off.
AR area[2]		AR 00 to AR 15 (16 words)	AR 0000 to AR 1515 (256 bits)	These bits serve specific functions such as flags and control bits.
LR area [1]		LR 00 to LR 15 (16 words)	LR 00000 to LR 1515 (256 bits)	Used for a 1:1 data link with another PC.
Timer/Counter area[2]		TC 000 to TC 127 (timer/counter numbers) [3]		The same numbers are used for both timers and counters.
DM area	Read/write[2]	DM 0000 to DM 0999 DM 1022 to DM 1023 (1,002 words)	---	DM area data can be accessed in word units only. Word values are retained when the power is turned off.
	Error log [4]	DM 1000 to DM 1021 (22 words)	---	Used to store the time of occurrence and error code of errors that occur. These words can be used as ordinary read/write DM when the error log function isn't being used.
	Read-only [4]	DM 6144 to DM 6599 (456 words)	---	Cannot be overwritten from program.
	PC Setup [4]	DM 6600 to DM 6655 (56 words)	---	Used to store various parameters that control PC operation.

Note:

1. IR and LR bits that are not used for their allocated functions can be used as work bits.
2. The contents of the HR area, LR area, Counter area, and read/write DM area are backed up by a capacitor. At 25°C, the capacitor will back up memory for 20 days.
3. When accessing a PV, TC numbers are used as word data; when accessing Completing Flags, they are used as bit data.
4. Data in DM6144 to DM6655 cannot be overwritten from the program, but they can be changed from a Peripheral Device.

APPENDIX H
PROCESS SCHEMATIC



APPENDIX I
MODEL DESIGN AND PICTURES

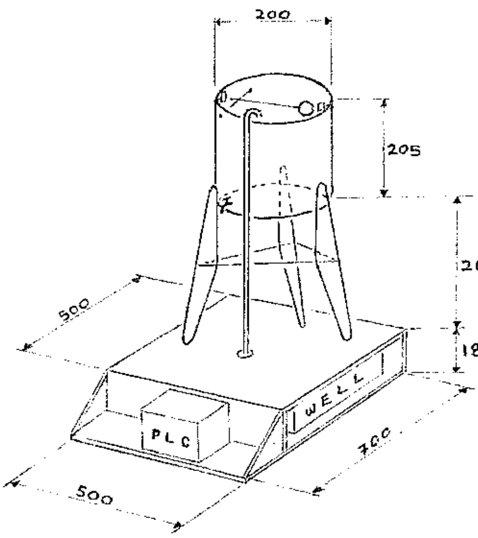


Figure 10: Model Design (units = mm)

Figure 11: Actual Model

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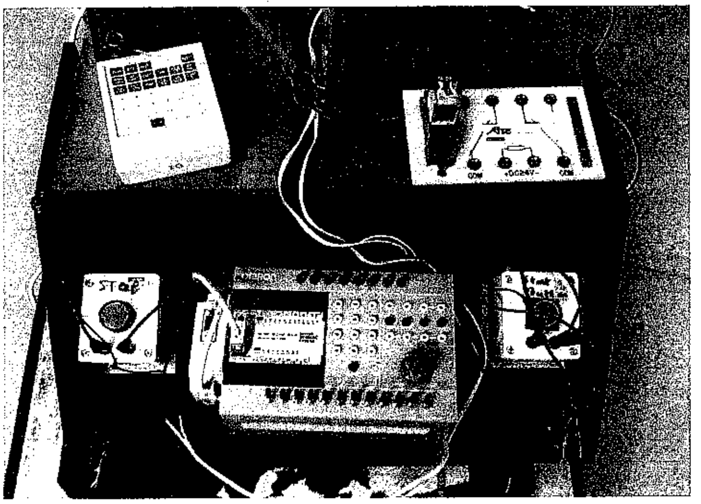

Figure 12: Programming Console, PLC, Pushbuttons and Relay

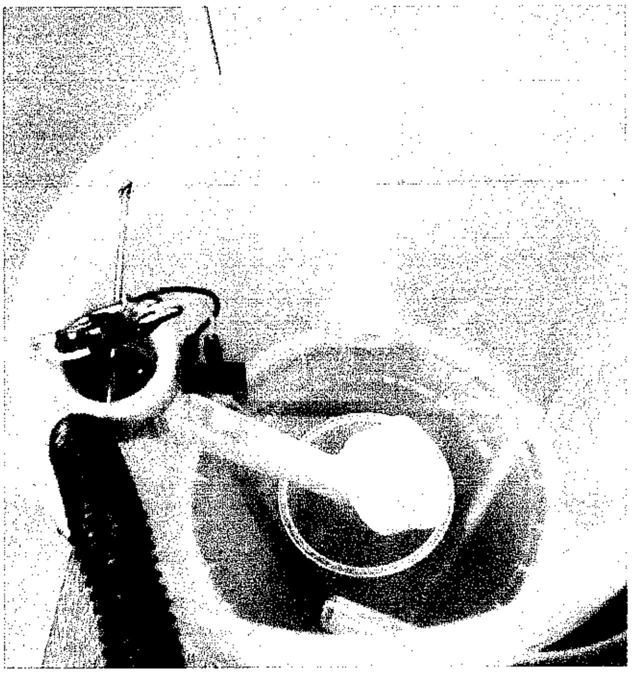

Figure 13: Level Sensing Mechanism

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