

THE DESIGN OF A
LEAKAGE CURRENT MONITOR
FOR
LIVE LINE BARE HAND MAINTENANCE

A thesis submitted in fulfilment of the requirements for the Degree of
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ABSTRACT

This thesis describes the design of an instrument for the protection of personnel carrying out live line bare hand maintenance of power transmission circuits. This instrument monitors the leakage current along equipment to ground and sounds an alarm when preset thresholds are exceeded. The leakage current monitor is microprocessor controlled, resulting in both flexible and user friendly operation. The prototype constructed, has been tested and found to perform very well.

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INTRODUCTION

In order to obtain maximum efficiency from a power transmission system and to ensure uninterrupted supply of electric power to consumers, it becomes necessary for maintenance of transmission circuits to be carried out while the system is energised. The safety of workers during such live line maintenance operations is the primary consideration. The sole technical protection for personnel carrying out this maintenance is an instrument to monitor the leakage current along equipment to ground.

This instrument sounds an alarm when the maximum safe level of leakage current is exceeded. The maximum safe current is generally lower than that which can be felt by a person and much lower than the point at which flashover occurs. The alarm therefore provides the maintenance crew with an advance warning, long before the leakage current reaches dangerous levels. The object of this project is to design such an instrument.

Commercial leakage current monitors, purchased by Power Mark NZ Ltd to be used with their live line maintenance activities, proved to be deficient in a number of ways. The unit under consideration is the *CHANCE SENTINEL*, manufactured by *A. B. CHANCE COMPANY*. Tests undertaken by P. S. Bodger at the Electrical and Electronic Engineering Department of the University of Canterbury revealed that the audible alarm sounds intermittently or not at all, depending on the rate of rise and the magnitude of the current. A second problem was that the paint on the enclosure caused the mounting brackets, used for the connection to earth, to be insulated. This makes it impossible for the instrument to measure leakage current. Both a problem and an inconvenience is the need for two different instruments, one for use with AC and one for use with DC transmission lines. The problem arises when, by accident, the wrong unit is used, in which case the instrument indicates zero current. As a result of these problems, linemen have no confidence in the instrument that is to protect their lives.

The motivation behind this project is to improve on commercially available equipment. The initial design was guided by a set of generalised specifications and

requirements. These specifications formed a starting point only and were subject to refinement as the design progressed. The initial design specifications are as follows:

1. Easily understood, digital readout of leakage current, readable from several metres and obtuse angles,
2. Input range from 0 to 2000 μA with an accuracy of $\pm 1\%$,
3. Measure leakage current generated by AC (50 Hz and 60 Hz), positive DC and negative DC voltages without operator interference,
4. Audible alarm with variable threshold setting over full current range,
5. Audible early warning alarm at 90 % of threshold setting,
6. Audible rate of rise alarm if rate of change exceeds 10 $\mu\text{A}/\text{minute}$,
7. Visual display to show trend of leakage current,
8. 4 channel input for monitoring several pieces of apparatus at once,
9. One side of the instrument to be attached to earth (pylon),
10. Rugged enclosure to deal with outdoor environment, up to 80% air humidity, wind, dust, water and salt spray, varying temperature, vibration, above ambient electric and magnetic fields and able to withstand hauling by ropes and travelling in the back of a truck.

The thesis is divided into chapters. Each chapter deals with an important aspect of the overall project. Chapter 2 describes common live line practices and discusses the application of this instrument. The hardware and software descriptions of the design are in chapters 3 and 4 respectively. Chapter 5 describes the enclosure designed for the instrument. The user instructions are in chapter 6. The calibration procedure, to be included in a service manual, appears in chapter 7. The prototype test procedure and results are listed in chapter 8. Chapter 9 discusses the unfinished work and makes some suggestions for enhancements. The thesis report finishes with the concluding remarks in chapter 10. For easy reference, appendix A lists the components used for the final version of the prototype. Photographs of the completed prototype can be found in appendix B.

LIVE LINE TECHNIQUES

Live line maintenance is defined as any maintenance activity performed on energised electrical conductors or equipment with a phase to phase voltage rating exceeding 33 kV. The maintenance techniques can be divided into two categories: hot stick and bare hand.

The hot stick technique is a method of performing live line work using tools which insulate workers from the live equipment being worked on. The hot stick is an insulated pole. A variety of tools can be fitted to the end of the pole, such as a prong for instance, to remove a cotter pin. The hot stick can sometimes be awkward to use. Changing a pin with a pole of 4 or more meters in length in the top of a tower can be frustrating. However, an experienced hot stick crew are very agile.

Live line maintenance using this technique has been performed in New Zealand since the 1930's, but the practice was discontinued in the 1950's as a result of increased transmission voltages, larger insulation distances and the lack of good quality insulators.

In those days, the poles were made of wood with a varnish coating. The varnish coating was kept immaculate to avoid the wood absorbing moisture. In addition, the poles were kept in heated storage to ensure they were completely dry. Nowadays, the poles are manufactured from fibreglass. Fibreglass is lighter and stronger than wood and does not absorb moisture.

The bare hand technique is a method of performing work where the workers are energised to the same potential as the equipment being worked on. The term bare hand is actually a misnomer. During bare hand maintenance, the worker's entire body, including the hands, is covered with a conductive suit. Only the face remains uncovered. The suit equalizes the potential across the workers body, avoiding an uncomfortable tingling sensation as a result of induced current flow.

Bare hand work puts to practical use a phenomenon that protects any bird that perches on a power line. When the person in contact with the live conductor is isolated from ground or any other conductor at a different voltage, no fatal current will flow. Workers reach the live conductors by a variety of means. Wearing a

lifting harness, the worker can be hoisted with an insulated rope attached to a pulley mechanism controlled by an electric winch. The pulley mechanism is fixed to the tower or suspended from a boom. The worker can either approach the conductor from below (the ground) or from above (the crossarm). The worker can climb or slide along an insulated ladder secured between the tower and the live conductor. Another method is to lift the worker using an aerial bucket platform. Perhaps the most spectacular method is where the worker sits on a platform clamped to a helicopter's struts. Irrespective of the method used to approach the line the worker will bond to the line. Bonding is the process of making contact with a live line to eliminate the potential difference between worker and line. A strong electrostatic field, extending for several tens of meters, surrounds the conductor. The worker's presence in the field will cause the body to be energised to a level several kilovolts less than the conductor potential. An arc will leap between the worker and the line as the conductor is approached. The worker is holding a wand, extended toward the line, to avoid the arc reaching the suit. After the worker is bonded, contact is maintained through a short tie, called a bonding lead, from suit to conductor. The suit, acting like a Faraday cage, equalises the charge across the surface. The suit not only protects against current but against the corona effect as well. The corona effect is caused by the ionization of the air around a person's body and results in a prickly sensation on such protruding body parts as the ears, as well as a distinct buzzing sound.

Most maintenance is carried out near the tower, usually involving the insulators. To allow inspection of the conductors between towers, a cart, hanging from the line is used. The cart, with seating for the worker, is pulled along the line from the ground or is motorised.

Live line maintenance cannot be carried out in all towers. Some towers do not allow enough clearance between the worker and the conductors for safe working conditions.

Live line maintenance was reintroduced into New Zealand by Power Mark NZ Ltd in 1988 for the purpose of upgrading the HVDC transmission line between Benmore and Haywards. Both techniques are used depending on which is most appropriate. Live line maintenance is now carried out on a wider scale.

The safety of personnel is of the utmost concern. Codes of practice exist to provide minimum requirements and workers are highly skilled, having received special training. Maintenance is only carried out during favourable weather

conditions. All equipment, in particularly the insulators, are kept in impeccable order and free from contaminants.

While the equipment is in use, the insulating qualities may be reduced, mostly caused by condensation, high air humidity, grease and filings from pulleys or salt water spray. The decrease in insulation resistance results in an increase in leakage current. The leakage current therefore, is a measure of the amount contamination. The leakage current has to be kept within limits to ensure safe operating conditions.

The leakage current monitor, which is, in essence, an ammeter, bridges the last section (25 to 50 mm) of the insulator to ground. The insulator may be any of the devices mentioned above: ladders, ropes, hot sticks, aerial bucket booms, etc. The insulating devices are fitted with connectors for the test leads to the leakage current monitor. The leakage current monitor sounds an alarm when the safe threshold has been exceeded. The alarm prompts workers that something is amiss. On hearing the alarm, workers quickly evacuate the energised conductor. Work is suspended until the fault is found and rectified.

The leakage current monitor gives confidence that the other equipment is functioning correctly. The monitor will warn maintenance personnel of equipment that has developed a fault during use or of a fault that has escaped a previous inspection.

The benefits from of bare hand work, saving in cost from doing the work faster and without taking the line out of service, is a very attractive alternative to de-energised line maintenance.

CIRCUIT DESCRIPTION

3.1. INTRODUCTION

The general design of the leakage current monitor is shown in Figure 3.1. The microcontroller is at the heart of the circuit, controlling the analogue to digital converter (ADC), doing the necessary computations and comparisons and performing the task of user interface. The ADC, with integral multiplexer, samples the four leakage current inputs, charging current from the battery charger and the signal from the earth return detection circuitry. The precision rectifier can be included in the

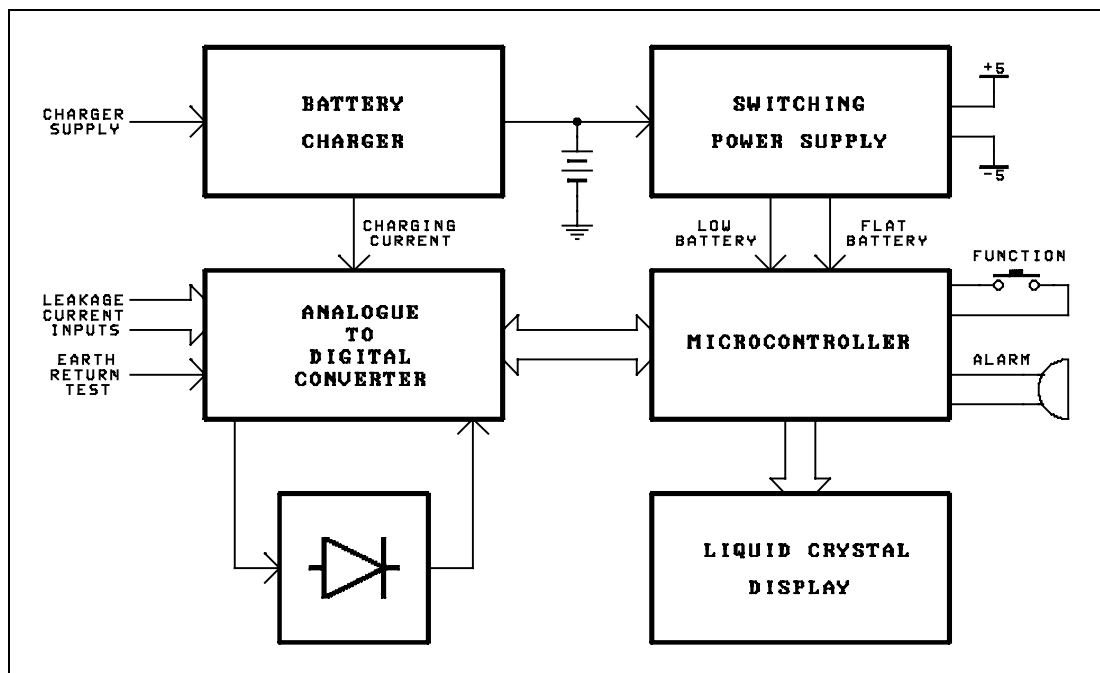


Figure 3.1. Block schematic diagram of the leakage current monitor

signal path to enable the measurement of AC leakage currents. The entire circuit is powered from a 4 V rechargeable battery, the symmetrical 5 V regulated power supply being provided by two DC to DC converters. The final section, the user interface, comprises a single push button for user input, an audible alarm and a 40 segment liquid crystal display to indicate leakage current, alarm thresholds, battery charging progress or operating mode.

Most of the components used for the prototype have commercial grade specifications with a typical operating temperature range from 0 °C to +70 °C. This was convenient since these parts were readily available. In practical use however, it is likely that ambient temperatures of less than 0 °C are encountered. For this reason, extended grade versions are available for all the parts selected. The use of extended grade parts would result in an increased operating temperature range, the upper and lower limits being defined by the LCD and the battery respectively. With the appropriate components installed, the operating temperature range is -25 °C to +50 °C.

The schematic diagram for the leakage current monitor is divided into three sheets. The detailed circuit description is conveniently divided into three sections also, each referring to one sheet of the schematic. The power supply and battery charger are shown in Figure 3.2. Figure 3.3. shows the leakage current inputs and the analogue to digital converter, while the microcontroller and display appear in Figure 3.4.

The final section of this chapter describes the development board that was built to assist with the writing of the software. This board does not form part of the leakage current monitor, but was found to be very helpful, particularly since an In Circuit Emulator was not available.

3.2. POWER SUPPLY

Since the leakage current monitor is a portable instrument, it is required to be battery powered. The digital logic requires a regulated +5 V supply. The analogue circuits need a symmetrical supply. To avoid duplication of a positive supply, a -5 V supply is added to provide these components with ± 5 V.

The power source is a 4 V, 1 Ah, sealed, lead-acid rechargeable battery. A rechargeable battery is used for convenience (no need to stock spares) and the significantly lower overall cost. The alternative to a lead-acid battery, nickel-cadmium, was rejected because they have a lower energy density, are more expensive and exhibit a memory effect when recharged after partial discharge. The main advantage of nickel-cadmium is the longer expected lifespan.

The battery chosen, is manufactured by Sonnenshein. It is charged with a constant voltage, the battery itself regulating the charging current. A fully discharged

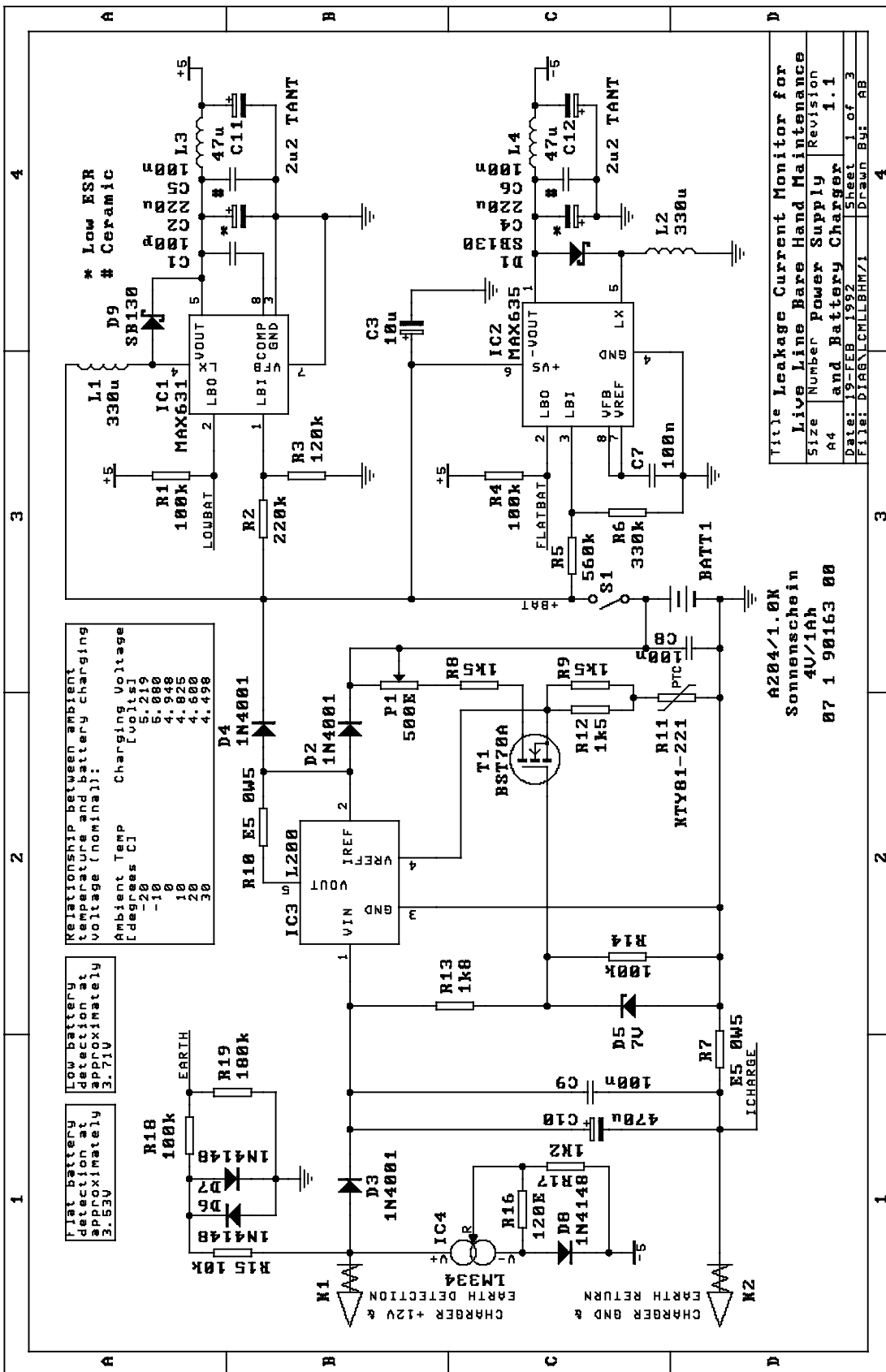


Figure 3.2. Circuit diagram for the power supply and battery charger.

Title Leakage Current Monitor for
 Live Line Bare Hand Maintenance
 Size Number Power Supply
 and Battery Charger 1.1
 Date: 19-FEB-1992 Sheet 1 of 3
 File: DIA6VLCMLLBM71 Drawn By: AB

A204/1.0K
 Sonnenschein
 4U/1Ah
 07 1 90163 00

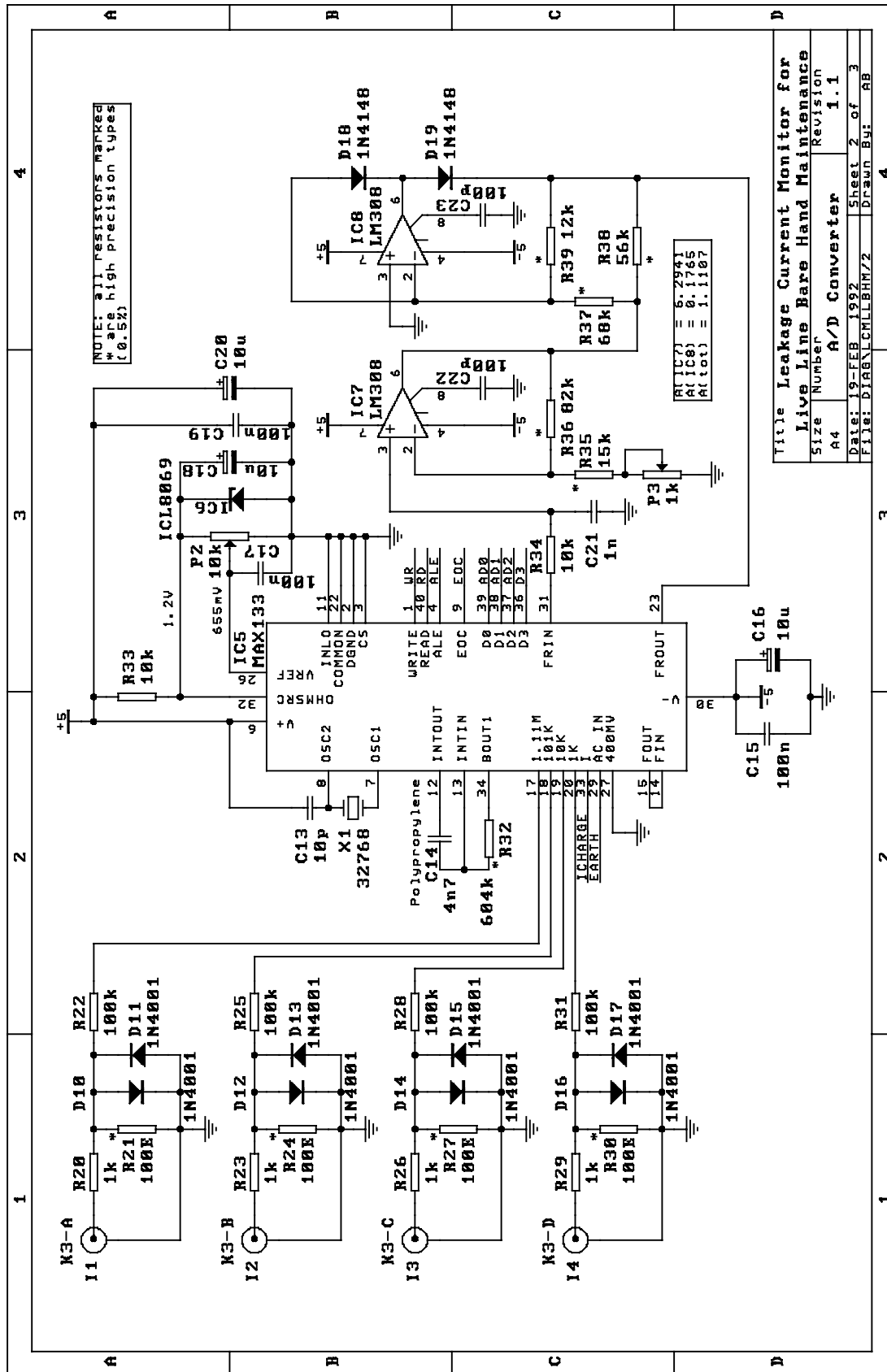


Figure 3.3. Circuit diagram for the analogue input section.

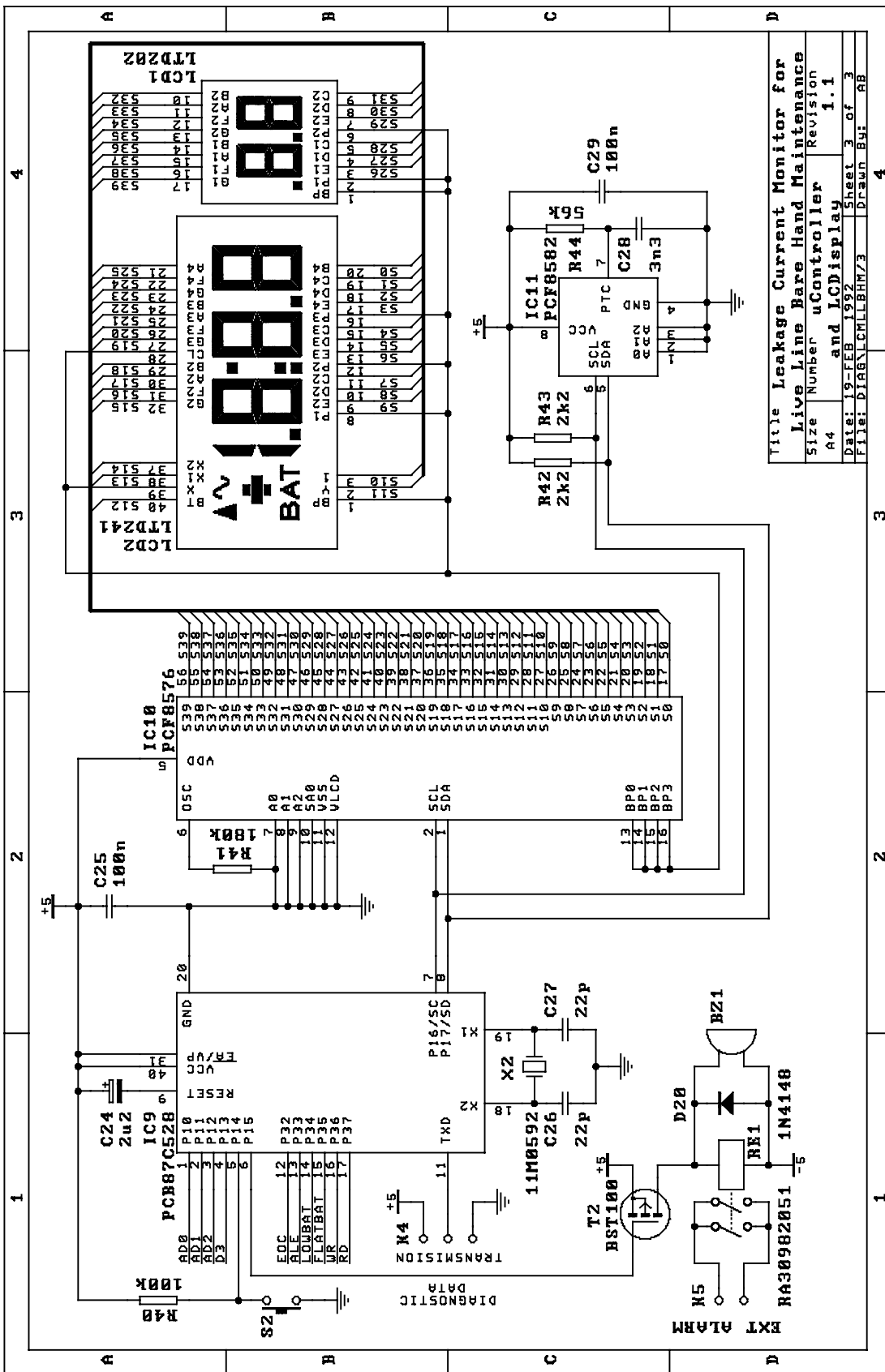


Figure 3.4. Circuit diagram for the digital processing section.

battery can be recharged to approximately 50 % of its capacity in only 1 hour and to 90 % in 3.5 hours.

It is possible to use disposable batteries, in the form of three AA size alkaline cells. This would reduce the size of the instrument since they occupy about half the space needed for the lead-acid battery (for twice the capacity) and do not require a charger. The main disadvantages are the need for a user accessible battery compartment in a splash proof enclosure and the quite frequent replacement operation (approximately every 90 hours of use). The present design has the flexibility of using alkaline batteries merely by omitting the charger and providing a suitable enclosure.

Switching regulators are used for both the output voltages, a step-up converter for the positive supply and an inverting converter for the negative supply. The increased complexity and larger PCB area required for this type of regulator are compensated by a number of advantages.

A linear power supply requires an input voltage greater than the output voltage. This means two 6 V batteries, one for each supply rail, followed by low dropout and low quiescent current regulators. The space advantage of a simpler design with fewer components is eliminated by the larger, higher voltage, batteries. Linear converters are less efficient, but have the advantage of less output noise and better transient performance than their switching counterparts. Since the battery output voltage drops during discharge not all of the battery capacity can be withdrawn before the voltage drops below the minimum dropout voltage of the regulator, unless this is compensated for by increasing the initial battery voltage.

The two batteries cause another problem. The batteries for the positive and negative supply do not discharge at equal rates since the current drawn from the +5 V supply does not equal the current in the -5 V supply. This problem can be eliminated if the entire negative supply is replaced by an inverting switching regulator powered from the positive supply. This topology is a compromise between a fully linear and switching power supply.

The diagram of Figure 3.2. shows the completed power supply. The charger is build around a L200 linear regulator. The leakage monitor is connected to an external power source through two spring loaded contacts, K1 and K2, when it is placed on the charger base. The external power source can be either a 12 V car battery or a 9 to 12 VDC, 1 A, unregulated mains plug pack. The car battery charging lead incorporates a filter to remove electrical noise caused by the engine

ignition system and alternator. K1 and K2 perform a second function as earth return and earth detection, to be described later. Diode D3 protects the input against accidental reverse voltages. D4 turns on the instrument when the charging source is present. This enables the microcontroller to monitor and display the charging progress. Diode D2 protects the regulator from the battery. As previously mentioned, this is a constant voltage charger, however, the optimum charging voltage varies with battery temperature.

To ensure optimum performance, the battery temperature is measured and used to adjust the output voltage. This is achieved by placing a temperature sensor, R11, in the voltage regulation loop comprising P1, R8, R9, R11, R12 and T1. R11 is in thermal contact with the battery. The charging voltage characteristic is shown in Figure 3.5. The broken curves represent the tolerance of the ideal charging voltage and the solid curve the actual charger output. Transistor T1 together with the gate

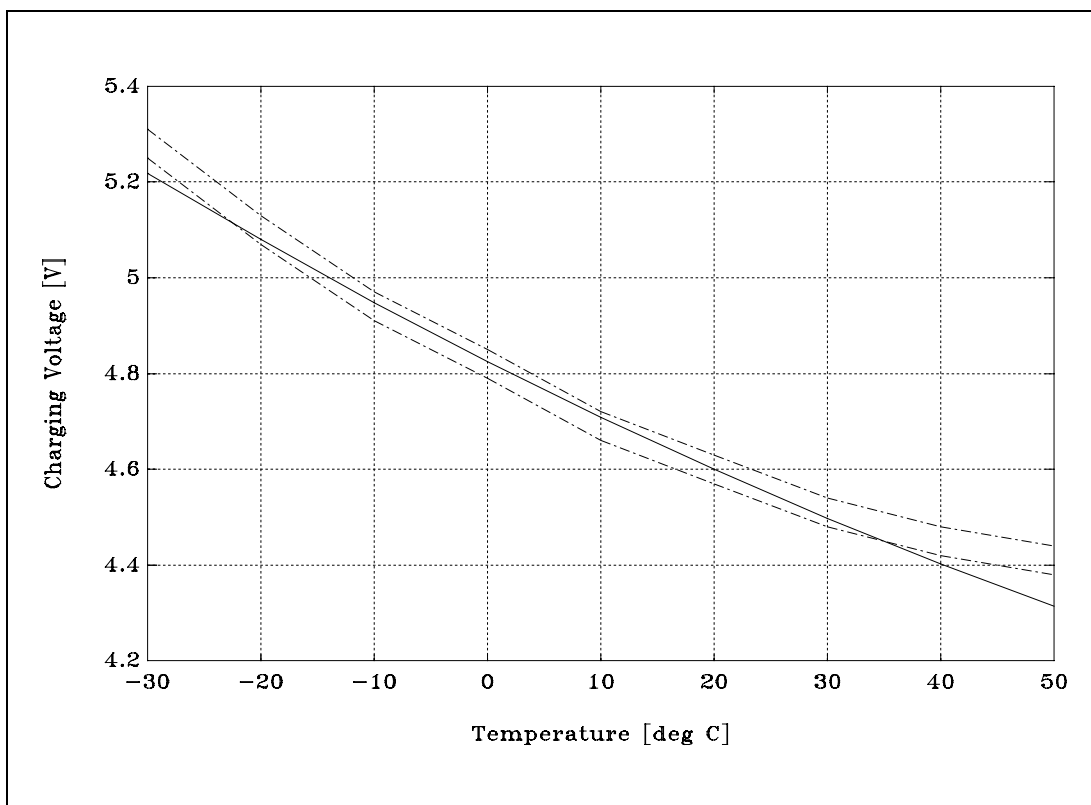


Figure 3.5. Charging voltage versus ambient temperature characteristic.

drive circuitry R13, D5 and R14 ensure that the voltage regulation loop is disconnected from the battery when it is not being charged. It would otherwise discharge the battery even when the instrument is switched off. Resistor R10 limits the maximum output current to about 900 mA, the maximum charging current,

regulated by the battery itself, is typically 500 mA. The final component associated with the charger, R7, allows the microprocessor to measure the charging current and from this compute the charged-in current in mAh.

The +5 V regulated power supply is provided by a MAX631 (IC1) step-up switching regulator. The output is low pass filtered by L3 and C11. The -5 V regulated power supply is provided by a MAX635 (IC2) inverting switching regulator, with the output filtered by L4 and C12. Both converters operate on the pulse-skipping method. The internal switches are driven by a constant frequency oscillator that regulates V_{OUT} by skipping pulses when the output is sufficiently high. The comparator circuit in IC1 with components R1, R2 and R3 are used to signal the microprocessor to switch on the low battery indicator (**BAT**). The comparator in IC2 with resistors R4, R5 and R6 detect when the battery is flat (approximately 3.5 V). The microprocessor uses this signal to shut itself down, thereby preventing unpredictable operation and limiting further discharge.

The only components not associated with the power supply are IC4, R15, R16, R17, R18, R19, D6, D7 and D8. These components form a constant current source (set to approximately -1 mA) and ADC input protection. The leakage current monitor is attached to the pylon with the aid of magnets. Contacts K1 and K2 must touch the steel structure, since K2 is also used as the return for the leakage current. It is important to know if this point is actually connected to the pylon and for this reason a constant current source is connected to K1. When K1 is not connected to K2 through a low impedance, the steel tower, a potential of about -4 V exists at this point. This signal, limited by R15 and D6 to -0.7 V and attenuated by R18 and R19, is applied to the ADC which will return a maximum negative value to the microcontroller and so indicate an improper earth connection. A correct earth connection will return a value slightly less than zero, the magnitude of which is directly proportional to the resistance between K1 and K2. The ADC will return a maximum positive voltage when the charging source is present, indicating to the microcontroller to enter the charge monitoring mode.

This current source has a second function as a simple input lead test. A serviceable lead, plugged into the unit, will cause the display to indicate the source current and sound the alarm (if it is set to less than 1 mA) when the free end is touched to K1.

3.3. ANALOGUE INPUT CIRCUITRY

Sheet 2 of the schematic (Figure 3.3.) shows the leakage current inputs and all the components associated with the analogue signal path including the analogue to digital converter.

Each of the leakage current inputs is protected against small overloads by a 1 k Ω resistor and a pair of antiparallel diodes. The instrument is not protected against flashover since it is very difficult to dissipate the energy involved in a controlled manner. This situation however, should never arise if the insulators used, are of good quality and properly maintained. The 100 k Ω resistors act as ADC input protection for transients too fast to be clamped by the diodes.

The 100 Ω resistors form the burden. At the full scale input current of 2 mA, the signal applied to the ADC is 200 mV. The ADC is of the integrating type. This type of converter is eminently suitable for instrumentation applications. They combine high resolution, accuracy and normal mode rejection with low cost and conversion speed.

The ADC used (MAX133) is actually a digital multimeter circuit with the input attenuator inputs functioning as a multiplexer. The ADC chip requires only a minimum of additional components to operate and is intended to work as an analogue front end of a microprocessor. The additional parts required are: a capacitor and resistor, C14 and R32, for the integrator, a crystal and capacitor, X1 and C13 for the clock generator and an adjustable voltage reference. The voltage reference comprises an ICL8069 1.2 V precision reference diode (IC6) in series with a current limiting resistor (R33), a preset (P2) to calibrate the full scale range and several decoupling capacitors. The voltage reference output is, ideally, set to a different value depending on whether 50 Hz or 60 Hz mode is selected. In order to avoid selecting different reference voltages, it is fixed at 655 mV (adjusted for 50 Hz mode) and the conversion result is corrected digitally when the converter is used in 60 Hz mode.

The signals applied to the multiplexer are: the four leakage current inputs, the charging current, the earth test signal and ground. The chip contains switches to route the signal through an external precision rectifier, required for the measurement of AC signals. The rectifier is build around two LM308 operational amplifiers, IC7 and IC8. The ADC is average responding and in order for the instrument to indicate RMS current, a gain, equal to the form factor of a rectified sinewave (1.1107), is included with the rectifier stage. Preset P3 is used to set the overall gain. The

rectifier is not connected to the ADC in the position intended by the manufacturer for two reasons. The first reason is that when the rectifier is not part of the signal path, the input floats near +5 V, causing an unacceptably long settling delay when it is subsequently included. In the present position the rectifier input is always connected and does not exceed ± 400 mV during normal operation. The second reason is that it frees up an additional input.

No smoothing is provided at the rectifier output. This is not required since the ADC inherently performs the integration and is undesirable because it would reduce the response time. This is made possible by a very important characteristic of an integrating ADC: high normal mode rejection. The integrator will attenuate high frequency noise from the switching PSU, the digital logic and from external sources, producing smoothing and combined with the fixed averaging period, will null out those frequencies that have integral numbers of cycles during the averaging period. The fixed averaging period is chosen to be exactly 20 msec in 50 Hz mode or 16.67 msec in 60 Hz mode. A deviation of the line frequency from nominal causes the ADC output to vary up or down in an apparently random manner. The worst case normal mode error is shown in Figure 3.6. for small variations of input

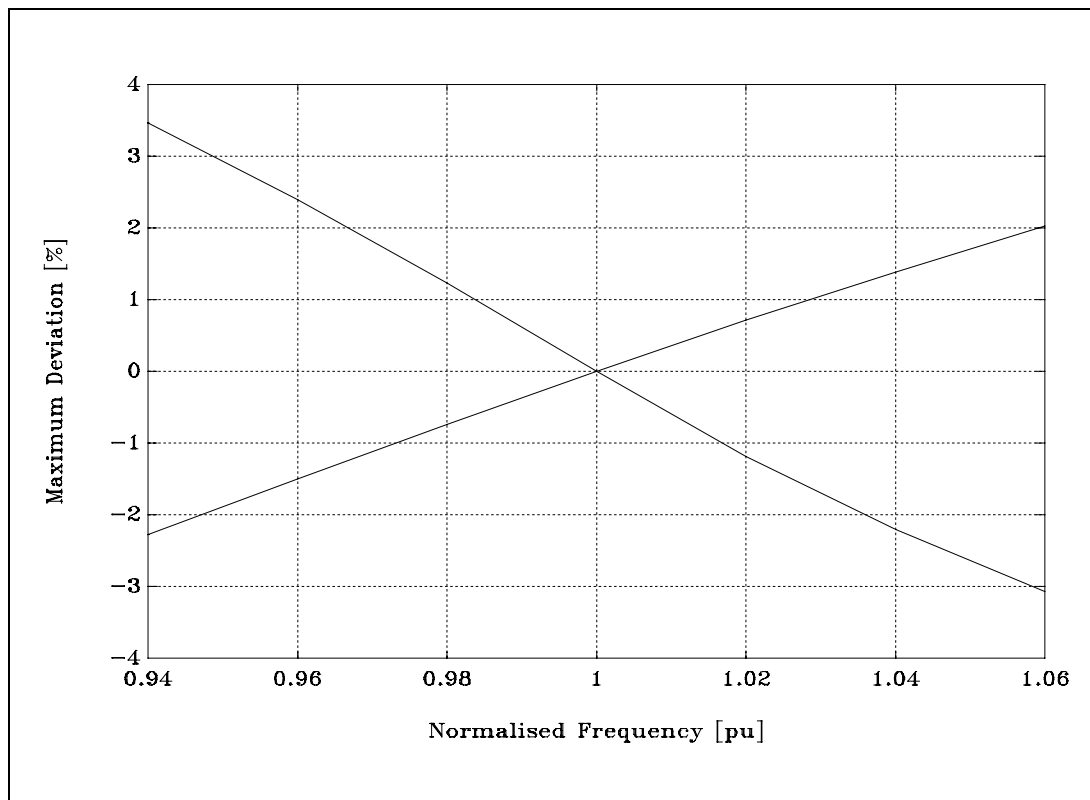


Figure 3.6. Worst case normal mode error versus input frequency.

frequency. In practice this error will be very small since the line frequency seldom deviates from nominal by any significant amount.

One of the inputs of the ADC (pin 27) is connected to ground. This enables the microcontroller to direct the ADC to perform a conversion with a zero input. When this conversion includes the rectifier in the signal path the result obtained will be equal to the sum of the offset errors introduced by the rectifier and the ADC. The microcontroller will use this value to correct subsequent leakage current conversions. This arrangement does away with the need for expensive, low drift op-amps and offset null calibration.

The ADC receives its instructions and returns status and results through the microprocessor interface with multiplexed 4 bit data and address bus and associated control lines. The converter has 5 input (control) registers and 6 output (result and status) registers.

3.4. DIGITAL PROCESSING CIRCUITRY

All the functions of the leakage current monitor are controlled by a single chip microcontroller. The microcontroller is a PCB87C528, manufactured by Philips and is a derivative of the popular Intel 8051 family. It has a number of additional features compared with the standard 8051. The extra features made use of are the watchdog timer, the additional ROM and RAM and the I²C bus.

The microcontroller directs the ADC and processes the results, tests the user input, displays results to the user and sounds the alarm when required. All these functions are performed by the control program contained within the processor.

Only a single push button (S2) is required for user input. Its function depends on the current operating mode. On power up it is used to enter the set up mode, in set up mode it changes the value of the digit being adjusted, in charging mode it toggles the display between charging current and charged-in current and in monitoring mode it selects the channel displayed. Full operating instructions are described in the Operating Instructions section.

Two slave devices are connected to the I²C bus (pins 7 and 8 of IC9), an EEPROM and a LCD driver. The EEPROM is used to store the alarm levels and operating parameters. This permits the instrument to be turned off while retaining the preset operating parameters. The operating mode is retrieved from the EEPROM

at power up, so setting up of the instrument needs to be done only once or until the operating mode needs to be changed.

The second I²C slave device, a LCD driver, connected to two liquid crystal displays provides visual output. The larger of the two displays, LCD2, is a 3½ digit, 7 segment display with additional indicators. The second display, LCD1, is a 2 digit 7 segment display. LCD2 is used to indicate measured leakage current, charging current or to display the alarm thresholds. The additional annunciators show increasing current (▲), AC signal (~) and low battery (**BAT**). LCD1 provides additional information identifying the source of the information on LCD2, such as leakage current channel number or alarm threshold. This display configuration has a number of advantages and one disadvantage when compared with a dot matrix alphanumeric display. The disadvantage is the limited alphabetic character abilities, but this is minor compared with the advantages. Firstly the display is large, digit height for the large display is 17.8 mm, making it readable from up to 5 meters. Secondly it has high contrast and a wide viewing angle and last but not least, its significantly lower cost.

Audible output is provided by a piezo buzzer (BZ1) switched by MOSFET T2. Relay RE1, connected in parallel with BZ1, provides a pair of normally open contacts with a maximum rating of 0.5 A, 50 V and 10 WDC for driving an external alarm.

The serial port transmit line is connected to a terminal on the PCB. This line can be connected to an ASCII terminal to display diagnostic information. This not only proved to be useful during the development of the software but will be worthwhile during future faultfinding as well. The information displayed includes: self test progress and result, the conversion results from all sources including zero offset, the computed rate of change of current and the status of the IC1 and IC2 comparators.

3.5. THE DEVELOPMENT SYSTEM

In order to keep the physical dimensions and parts count of the leakage current monitor to a minimum the microcontroller is used in internal ROM mode. This causes a problem during software development because an In Circuit Emulator (ICE) was not readily available. To facilitate software development an add on circuit

board was used. On this board the microcontroller is wired for external ROM mode. This means that ports P0 and P2 are not available because their alternate function as address and data bus is used. These pins are left disconnected on the PCB for the leakage current monitor. The circuit diagram of the development system is shown in Figure 3.7. The circuit shows the standard layout with a ROMless microcontroller (IC1), an address latch (IC2) and an EPROM (IC3). In place of the EPROM an EPROM emulator is used. This offers a significant time saving in the writing and debugging of the software. When the software is completed, the board is removed from the monitor and replaced with a programmed microcontroller. Figure 3.6. shows a block diagrammatical representation of the interconnections between the various components comprising the development system.

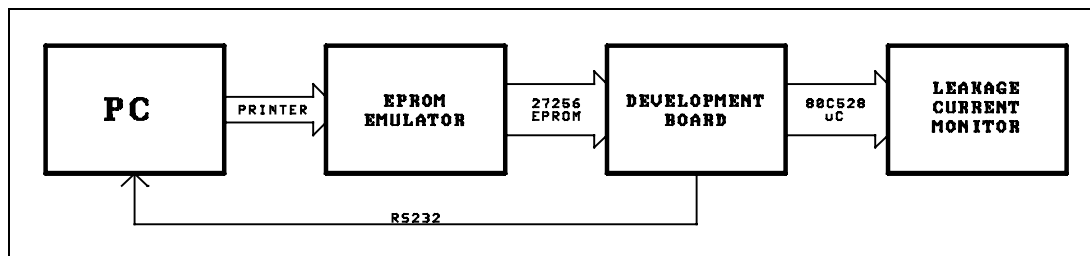


Figure 3.8. Block diagram for the development system.

As previously discussed the serial port transmit line is used for debugging purposes. To ensure voltage level compatibility a RS232 driver chip (IC4) is added. This chip is not provided on the PCB for the leakage current monitor since it is not required for normal operation.

FIRMWARE DESCRIPTION

4.1. INTRODUCTION

This chapter describes the software developed for the leakage current monitor. The software is stored in the microcontroller and is not user accessible, hence the title FIRMWARE. The word software will be used throughout since the firmware is accessible from the designer point of view. The software is entirely written in 8051 assembly language and occupies approximately 7500 bytes of ROM space. It is the software that, to a large extent, determines the features of the leakage current monitor. It controls all the functions with the exception of battery charging, which it monitors.

4.2. POWER ON PROCEDURE

Before entering the monitoring mode the instrument performs a series of functions as depicted in Figure 4.1.

Immediately after power on the instrument executes a selftest. This selftest comprises the following functions after sounding the buzzer for 0.5 seconds and activating all the LCD segments:

1. Comparison of computed ROM checksum with stored checksum,
2. Walking bit test of free internal RAM,
3. Walking bit test of auxiliary RAM,
4. Acknowledge test for LCD driver,
5. Zero offset value, holding and not holding time and always 1 bit of ADC,
6. Acknowledge, signature and checksum of EEPROM.

If any of these tests fail, with exception of the EEPROM signature or checksum, the instrument will display the error code and discontinue further operation. The error

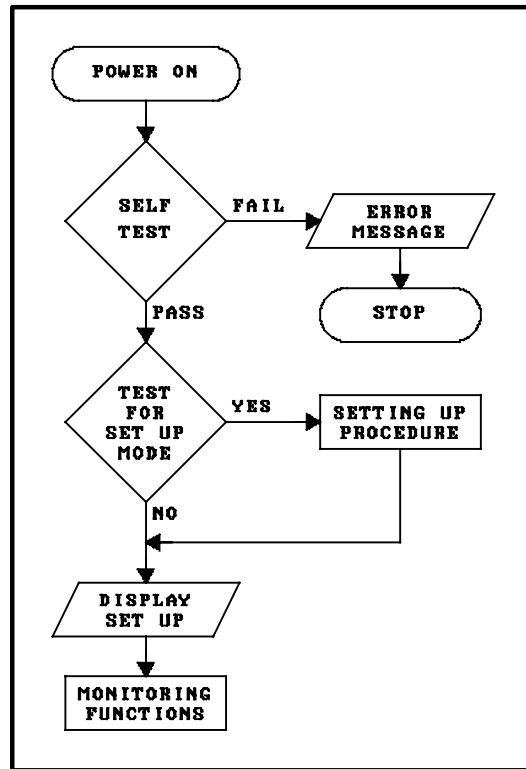


Figure 4.1. Simplified flow chart of power up procedure.

```

LEAKAGE CURRENT MONITOR FOR LIVE LINE BARE HAND MAINTENANCE
VERSION 1.1
(C) COPYRIGHT 1991, 1992 BY A. DE BEUN

TESTING INTERNAL CODE MEMORY... CHECKSUM=C0ABH, PASS
TESTING FREE INTERNAL DATA MEMORY... PASS
TESTING AUXILIARY DATA MEMORY... PASS
TESTING LCD CONTROLLER... PASS
TESTING ANALOGUE TO DIGITAL CONVERTER... PASS
TESTING EEPROM... PASS
  
```

Figure 4.2. Diagnostic data display on ASCII terminal.

code is displayed on the LCD (provided it works) after the selftest is completed. Testing progress and results can also be displayed on a serial ASCII terminal connected to the diagnostic data out connector (K4). Figure 4.2. shows the ASCII terminal display from power on until completion of the selftest. The error code displayed on the LCD is a decimal representation of the binary error code. One bit in the error code is set when the corresponding test fails. Multiple faults will be displayed as the sum of the individual bit values. Table 4.1. lists the possible errors with their corresponding codes.

If the EEPROM signature or checksum is incorrect then the software will attempt, once, to re-initialize the EEPROM contents, restoring the operating parameters to their default values. Again, if this is unsuccessful then the error code

will be displayed. The automatic initialisation serves a second purpose of initialising the instrument after it is manufactured. This will put the monitor into a known state without spending any time manually setting it up. The default values, which are also the factory preset values are shown in Table 4.2.

Type of Error	Bit Position	Bit Value
ROM Checksum	0	1
Free Internal RAM	1	2
Auxiliary RAM	2	4
Liquid Crystal Display Driver	3	8
Analogue to Digital Converter	4	16
EEPROM	5	32

Table 4.1. Description of selftest error code.

User Set Up Condition	Default or Initial Value
Alarm Threshold	100 μ A
Power Line Frequency	50 Hz
Early Warning Alarm Threshold	90 %
Rate of Rise Alarm Threshold	10 μ A/minute

Table 4.2. Default or initial set up parameters.

The selftest is restricted to what the microcontroller can examine. It relies on the user to check if the buzzer sounds and if the LCD segments function and to periodically connect the instrument to a test source of known current to verify its calibration. An additional problem is that it is hard to predict exactly how the instrument will fail or whether the selftest will discover the failure or not. Despite these limitations, successful completion of the selftest will give confidence in the correct operation of the instrument.

The user has to press the **FUNCTION** switch at power on and for the duration of the selftest (approximately 10 seconds) to enter the set up mode. This relatively long time has been chosen, so that entering the set up mode must be a conscious effort on part of the user, to protect the contents of the EEPROM from inadvertent change. During set up mode each of the user adjustable digits will flash in turn. The flashing digit can be incremented by briefly pressing the **FUNCTION** switch. All that is required to proceed to the next digit is to release the **FUNCTION** switch for three seconds once the current flashing digit is set to the desired value.

The set up procedure is completed by storing the new operating parameters in the EEPROM.

The last operation before entering the monitoring mode is to display the operating parameters. This allows the user to verify the previously set or newly updated alarm thresholds and line frequency.

4.3. MONITORING MODE

The monitoring mode is an endless loop, performing 16 ADC conversions per second. The 16 conversions (frames) are made up of 12 leakage current, one AC zero, one DC zero, one charging current and one earth test conversion. Timer 2 on the microcontroller is programmed to cause an interrupt every 62.5 msec. The interrupt service routine processes the result from the previous ADC conversion, initiates a new one and performs some additional tasks. The actual additional task performed depends on the frame currently being processed.

The functions of the interrupt service routine are illustrated in Figure 4.3. Each time the service routine is executed the user input is tested. This allows the user to select the display mode. The display mode cycles through the following options: display channel with highest current, lock display into one channel (1, 2, 3 or 4) or display each channel in turn for 1 second. The next task for the service routine is to test the battery level using the outputs from the comparators in IC1 and IC2. When the battery has been fully discharged (i. e. flat) the message **BAT E** will be displayed and the buzzer activated for 10 seconds. The controller then goes into POWER DOWN mode.

Provided the battery is not exhausted, the routine proceeds to test the type of alarm to determine if the buzzer should be on. The last operation, before executing the actual task allocated to that frame, is to increment the counter that keeps track of progress through the cycle. The charging mode frames are a subset of the normal frames. When charging, all the conversions not required, are omitted.

Each of the 16 frames performs a different task, generally related to the ADC conversion just completed. Table 4.3. gives a summary of these tasks. In frame number 7 the controller makes a decision between AC and DC leakage currents. The decision is based on the greater of the sum of the DC or the AC leakage currents. When the AC currents are greater the ~ annunciator on the display is turned on to

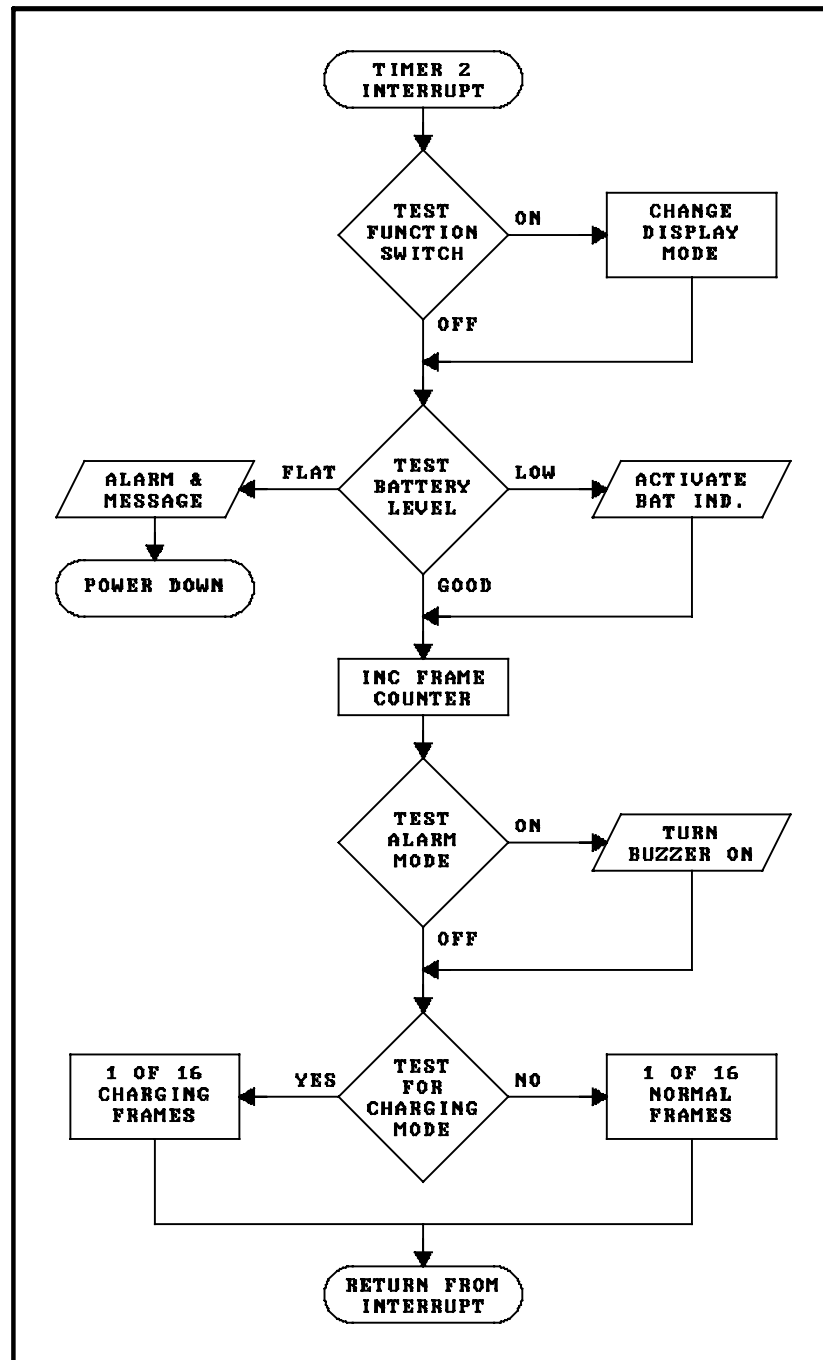


Figure 4.3. Simplified flow chart of the timer 2 interrupt service routine.

reflect this. The outcome from this decision determines the type of conversion initiated in frames 7 to 10 inclusive.

The AC and DC zero conversions allow the microcontroller to measure the offset of the ADC and precision rectifier. All ADC results are corrected by the appropriate offset, before being stored or displayed.

The rate of rise computation is performed in frame 14. This algorithm attempts to fit a straight line of the form $y=ax+b$ through a set of 32 data points.

Frame No.	Task
0	Store DC channel 1 ADC result, start sum of DC leakage currents, increment cyclic channel display counter, start DC channel 2 conversion.
1	Store DC channel 2 ADC result, add to DC sum, start DC channel 3 conversion.
2	Store DC channel 3 ADC result, add to DC sum, start DC channel 4 conversion.
3	Store DC channel 4 ADC result, add to DC sum, start AC channel 1 conversion.
4	Store AC channel 1 ADC result, start sum of AC leakage currents, start AC channel 2 conversion.
5	Store AC channel 2 ADC result, add to AC sum, start AC channel 3 conversion.
6	Store AC channel 3 ADC result, add to AC sum, start AC channel 4 conversion.
7	Store AC channel 4 ADC result, add to AC sum, find greater of DC sum or AC sum, start AC or DC channel 1 conversion, find highest current channel, test alarm thresholds, update LCD.
8	Store AC or DC channel 1 ADC result, start AC or DC channel 2 conversion.
9	Store AC or DC channel 2 ADC result, start AC or DC channel 3 conversion.
10	Store AC or DC channel 3 ADC result, start AC or DC channel 4 conversion.
11	Store AC or DC channel 4 ADC result, start DC offset conversion, find highest current channel.
12	Store ADC DC offset result, start AC offset conversion.
13	Store ADC AC offset result, start charging current conversion.
14	Store charging current ADC result, start earth test conversion, compute rate of rise of leakage current.
15	Store earth test ADC result, start DC channel 1 conversion, test earth, test alarm thresholds, update LCD

Table 4.3. Summary of the tasks performed during each normal frame.

Each data point is the average of two conversions so that 32 data points represent a history of 32 seconds. Each leakage current channel has a first in first out (FIFO) buffer, 64 bytes long, to store this data. The oldest data point, number 1, is lost

when the data in the buffer is shifted to make room for the most recent data point, number 32.

The algorithm to compute the gradient is based on the step function or group method. The grouping method is arithmetically much simpler than the least squares formulae commonly used for line fitting. The significant saving of computation time results in a small loss of accuracy. The 5 group method implemented, is given by the equation

$$slope = \frac{2\sum_{n=1}^6 i_n + \sum_{n=7}^{13} i_n - \sum_{n=20}^{26} i_n - 2\sum_{n=27}^{32} i_n}{2\sum_{n=1}^6 t_n + \sum_{n=7}^{13} t_n - \sum_{n=20}^{26} t_n - 2\sum_{n=27}^{32} t_n} \mu A \text{ sec}^{-1} \quad (4.1)$$

As all the t 's are fixed ($t_1=0$, $t_2=1$, etc.) the denominator of (4.1) can be simplified. Since the slope is required in $\mu A/\text{min}$ it is necessary to multiply (4.1) by 60. This results in equation

$$slope = \frac{N}{D} = \frac{2\sum_{n=1}^6 i_n + \sum_{n=7}^{13} i_n - \sum_{n=20}^{26} i_n - 2\sum_{n=27}^{32} i_n}{-6.7166} \mu A \text{ min}^{-1} \quad (4.2)$$

To reduce the computational effort even further only the changes in the numerator (N) of (4.2) need to be computed. If the most recent data point is i_{33} then the calculation required, before shifting the data, is given by

$$N = N - 2i_1 + i_7 + i_{14} + i_{20} + i_{27} - 2i_{33} \quad (4.3)$$

Therefore, after all the variables have been initialised, the only computation required is the calculation of (4.3) multiplied by -0.1488 (the reciprocal of the denominator of (4.2)). The 62.5 msec available in one frame is ample time to perform the computation four times, once for each channel.

The measurement of charging current gives the microprocessor the ability to compute charged-in current. The charging current display gives the user an indication of how far the charging has progressed or if the unit is charging correctly. Charging current reduces to near zero when charging is completed. The charged-in

current display allows the user to make an assessment of the amount of battery life available after a partial charge. Since the battery is a 1 Ah type, a charged-in current display of approximately 1000 indicates a fully charged battery. The software does not take into account the charge remaining after a partial discharge or the efficiency of the battery. This or an 'hours use' indicator could easily be added if deemed useful. There is however, the possibility that too many features may confuse the user.

The final ADC result for each cycle is the earth test. When the resistance between K1 and K2 is greater than approximately 50 Ω , the user is alerted that the instrument is not properly attached by sounding the alarm and displaying **noE** (no Earth). The earth test conversion serves a dual purpose to enable the processor to sense the presence of the battery charging source.

In addition to the tasks listed in Table 4.3. each conversion result is also available on the diagnostic data connector (K4) for display on an ASCII terminal.

The format of the data out is shown in Figure 4.4. The first line shows the result from the first 4 DC leakage current conversions in 10^{-7} A (one more digit than

```
DC,      DC ZERO=99130: I1=00010, I2=00005, I3=00005, I4=00005
AC=50, AC ZERO=99173: I1=00009, I2=00006, I3=00006, I4=00004 >1
DC,      DC ZERO=99130: I1=00003, I2=00007, I3=00006, I4=00010 >4
SLOPE: I1=+00039, I2=+00031, I3=+00032, I4=+00029
Icharge=00000, EARTH=-36384, LOW BAT=1, FLAT BAT=1
```

Figure 4.4. Sample of diagnostic data out transmission.

shown on the LCD) and the actual result from the DC zero conversion in 9's complement BCD. The second line shows the same information for the first 4 AC conversions. The 'AC=50' indicates that the 50 Hz mode is selected. The '>1' indicates that channel 1 has measured the largest current, this would be the channel displayed in highest current mode. The third line shows the result from the second set of 4 leakage current conversions. The line starts with 'DC', this indicates that the controller decided that the input currents are DC. The fourth line shows the results from the slope calculation in 10^{-7} A/min. The last line shows that the battery charging current is zero, that the earth test terminals are open and that the battery is in good condition. The 1's shown, refer to the actual logic level, the comparator output goes low once the battery voltage has dropped sufficiently.

After exiting the service routine the microcontroller resets the watchdog timer, enters IDLE mode to conserve battery power and waits for the next interrupt.

The on-chip watchdog timer acts as a safeguard to ensure that the controller cannot crash. The purpose of the watchdog timer is to reset the microcontroller if it enters erroneous processor states, possibly caused by electrical noise or RFI, after a short period of time. The watchdog timer is set to time out after a minimum of 100 msec. In the event that the watchdog timer causes a reset, the microcontroller will sense that this is a warm start and bypass the selftest. The buzzer will sound briefly to warn that something has happened before resuming monitoring functions.

ENCLOSURE DESIGN

The prototype for the leakage current monitor was housed inside a box, folded from aluminium sheet, 1.6 mm thick. This was adequate for testing the prototype circuitry but is not appropriate for practical use.

The ideal enclosure would be sealed against water, dust and contaminants, shielded from EMI, is impact, oil and solvent resistant and easy to handle. Figure 5.1. shows the enclosure designed for the leakage current monitor. The enclosure has not been manufactured. No dimensions are shown because the actual measurements will mainly depend on the size of the completed circuit boards. The final dimensions are expected to be approximately 200 mm high, 100 mm wide and 50 mm deep.

The case is made from a suitable high impact, brightly coloured, synthetic material with windows for the displays. The fragile LCDs are protected by a sheet of transparent material. The inside is covered with a conductive layer or contains a box from folded galvanised steel sheet to act as an EMI shield. The two case halves and all holes for connectors, switches and screws are sealed against water and dust. The sides of the enclosure are indented to allow the instrument to be grasped firmly for removal.

The display, controls and connectors are located on the front panel. The switches, connectors and buzzer are individual parts mounted on the enclosure. These parts are all splash waterproof types. An alternative is that it may be possible to incorporate switches and connectors as part of the case moulding. Sealing caps protect the exposed contacts of unused connectors. The power switch is a rotary type to avoid the need for an indicator. The indicator function is accomplished by the rotary switch lever which turns through 90°. A rotary switch is less likely to be inadvertently operated than a toggle switch.

On the back of the case are two magnets. The magnets are used for fixing the instrument to a steel member of a pylon. This enables quick installation and removal of the instrument without the need for any tools. The connection to earth is made through two spring loaded contacts. One contact is the actual earth return.

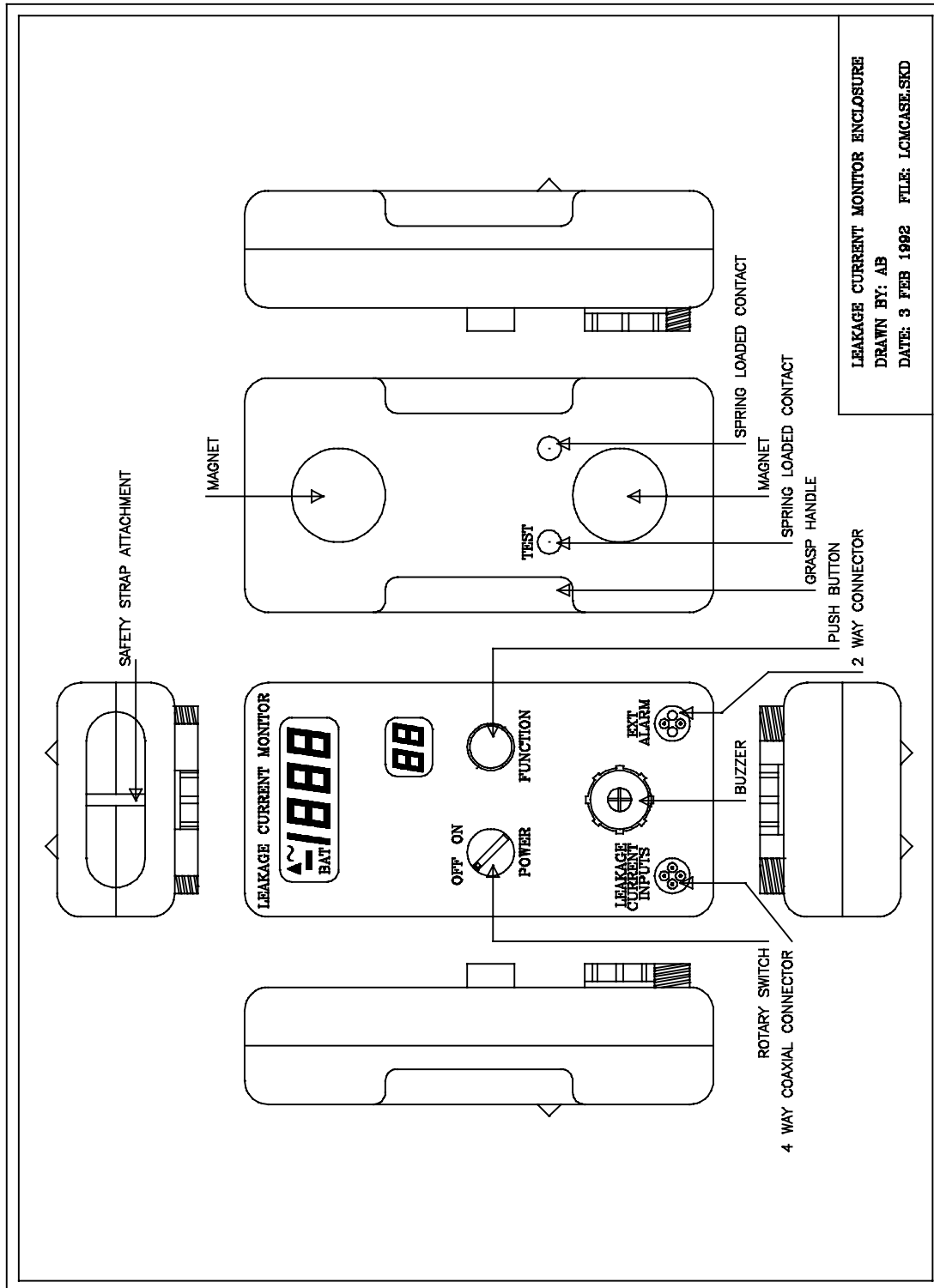


Figure 5.1. Design for the leakage current monitor enclosure.

The second contact is required to permit testing for a proper earth connection. The maximum spacing between the contacts is determined by the minimum width of the angle iron used for construction of the tower. The minimum width is typically 50 mm, therefore, the contact spacing has to be no greater than 40 mm to avoid troublesome alignment. The contacts have a sharp point to penetrate an oxide or paint layer. The points are small enough not to damage the galvanised coating.

The two contacts also serve as battery charger inputs. The instrument would be placed in a battery charging base when not in use. When placed into the base the contacts make the connection to the charging source. Soft iron plates, fixed to the base, directly opposite the magnets hold the monitor in place and act as keepers for the magnets. The base has an input to allow the lead to a car battery or a mains adaptor to be connected.

On top of the case is an indentation with a bar inserted across. A safety strap fixed to this bar and secured to the pylon protects the instrument from falling in the event it is accidentally dislodged. The safety strap serves a second purpose as a means of fastening a rope for hoisting or for attaching to a tool belt.

OPERATING MANUAL

6.1. INTRODUCTION

This chapter contains the operating instructions that would accompany each instrument in booklet form. They are intended for the end user. The QUICK REFERENCE GUIDE may be printed on plastic covered cardboard for durability and stored with the instrument for handy reference. Alternatively, all or part may be printed or engraved on the actual enclosure.

6.2. OPERATING MANUAL

6.2.1. INTRODUCTION

This manual provides operating instructions for the Leakage Current Monitor. This specialised instrument is designed for use by personnel carrying out live line maintenance on power transmission lines. This instrument monitors the leakage current along insulators and sounds an alarm when safe levels are exceeded. It can be used with a variety of live line techniques employing hot sticks, ropes, ladders or aerial buckets.

6.2.2. DESCRIPTION

The leakage current monitor is a microprocessor controlled instrument to monitor leakage currents along insulators. The monitor works like an ammeter. When the current exceeds preset levels, an alarm will sound, warning maintenance personnel of dangerously high leakage currents. The location of controls is shown in Figure 6.1.

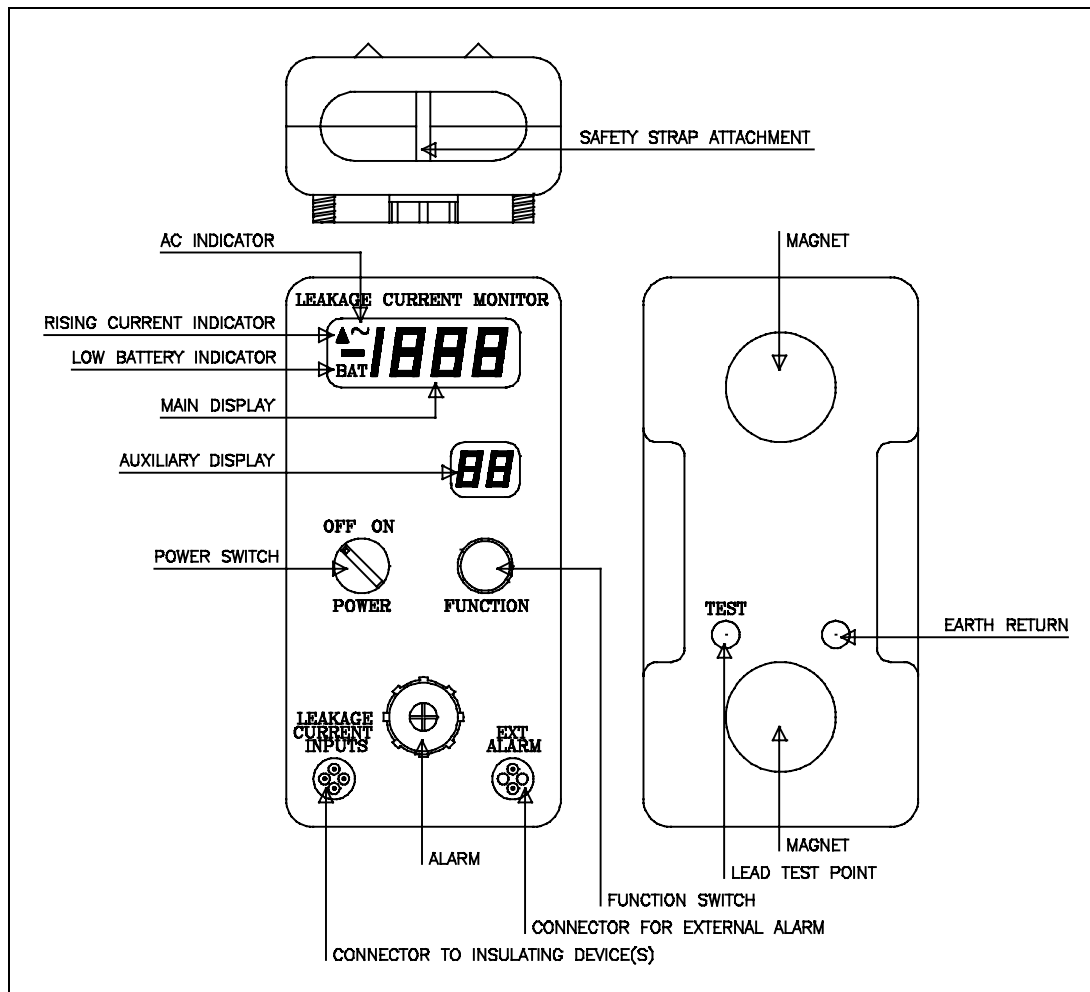


Figure 6.1. Location of controls.

6.2.3. MONITORING MODE OPERATION STEPS

1. Visually inspect the instrument for damage, dust or water that might cause malfunction.
2. Turn the power switch to the on position:
 - The alarm will sound briefly and all the display segments are activated,
 - The monitor will perform a selftest,
 - If a fault is detected the message **Er**, accompanied by the fault code, will be displayed.
3. The display will show the preset operating parameters:
 - **XXXX AL** - Alarm threshold in microamps,
 - **X0 EA** - Early warning alarm as % of alarm threshold,
 - **X0 Fr** - Line frequency in Hz,

- **XXXX rr** - Rate of rise alarm threshold in microamps per minute.
4. Connect the external alarm, if used, to the terminal marked **EXT ALARM**. Connect the input lead(s) to the input terminal labelled **LEAKAGE CURRENT INPUTS**. Touch the free end of the lead(s) to the terminal marked **TEST** on the back of the instrument. If the display does not indicate a current of about 1000 microamps then the lead is faulty. The alarm should sound if it is set to less than 1000 microamps.
 5. Attach the leakage current monitor to a grounded, steel structure with the aid of the magnets. Ensure that both the lead test point and the earth return contact are touching the support structure. Fasten the safety strap. The monitor is now ready to display leakage current in microamps on the main display and sound the alarm when the preset thresholds are exceeded. Connect the insulating devices to be monitored to the input leads. The alarm sounds different depending on which threshold is exceeded:
 - Double beeps - Rate of rise threshold exceeded,
 - Single beeps - Early warning, beep frequency increases with rising current or,
 - when accompanied by the **noE** message: improper earth connection,
 - Continuous - Alarm threshold exceeded.
 6. Three different display modes can be selected with the **FUNCTION** switch indicated on the auxiliary display:
 - **Hn** - Display highest current together with channel number,
 - **Ln** - Lock into any one channel,
 - **Cn** - Cycle through all channels automatically displaying each one for one second.
- NOTE:** The unit always monitors all channels independent of the channel displayed.
7. The ▲ on the main display indicates that the current is rising.

8. The ~ on the main display indicates that the instrument has selected AC mode.
9. The **BAT** indicator warns that the battery is low. Approximately 5 hours of use remain when the indicator first appears. **BAT E** will appear when the battery is completely flat, the alarm will sound for 10 seconds and the monitor will shut down. Turn the monitor off and recharge the battery.
10. Replace the connector sealing caps when the instrument is not in use. This will protect the connectors from water and dust.

6.2.4. SET UP PROCEDURE

1. Switch the monitor on while pressing the **FUNCTION** switch.
2. Keep pressing the **FUNCTION** switch until the alarm threshold appears on the main display, with the first digit flashing.
3. Pressing the **FUNCTION** switch will increment the flashing digit.
4. Once the first digit is set to the desired value do not press the **FUNCTION** switch for 3 seconds after which the next digit will start flashing and may be adjusted.
5. Proceed to adjust the other preset values in a similar manner:
 - **XXXX AL** - Alarm threshold in microamps [range 0 to 1999 in steps of 1],
 - **X0 EA** - Early warning alarm as % of alarm threshold [range 10 to 100 in steps of 10],
 - **X0 Fr** - Line frequency in Hz [50 or 60] ,
 - **XXXX rr** - Rate of rise alarm threshold in microamps per minute [range 0 to 1999 in steps of 1].

6. The monitor will automatically switch to monitoring mode after displaying the new operating parameters.

6.2.5. BATTERY CHARGING

1. Place the monitor onto the battery charging base and plug the base into a source of 12 volts DC using the vehicle battery lead or into a wall socket using the mains adaptor:
 - the monitor will switch itself on.
2. The display will show the charging conditions using the **FUNCTION** switch:
 - **CC** - Charging Current in milliamps,
 - **Ah** - Charged-in Current in milliamp hours.

The charging current will reduce to less than 10 mA when charging is complete.
3. When new, charging from completely flat will take about 12 hours, a 1 hour charge will give approximately 20 hours use. The charged-in current display shows the capacity as a fraction of 1000.
4. A full charge will give at least 40 hours use, when new.
5. The battery will last at least 200 full depth cycles, the battery will last longer if recharged after partial discharge.
6. The monitor must be stored with the battery fully charged.
7. The charging may continue indefinitely, trickle charging will start automatically.

6.2.6. QUICK REFERENCE GUIDE

FUNCTION	Press to cycle through display options
SWITCH	Press at power-up to enter set up mode
	Press to increment flashing digit while in set up mode
AL	Alarm threshold in microamps
Fr	Line frequency in Hz
EA	Early warning alarm as % of alarm threshold
rr	Rate of rise alarm threshold in microamps per minute
H	Highest current, together with corresponding channel number
L	Display locked into channel number shown
C	Cyclically display each input current for 1 second
noE	No Earth, the instrument is not properly attached to ground
▲	Symbol displayed when current is rising
~	AC mode selected
BAT	Low battery, approximately 5 hours of battery life remains when first displayed
BAT E	Battery is completely exhausted
OL	Over Load, 2000 microamp maximum input current exceeded
Er	Error detected during selftest
CC	Battery charging current in milliamps
Ah	Battery charged-in current in milliamp hours

CALIBRATION PROCEDURE

7.1. INTRODUCTION

The number of calibrations to be carried out has been kept to a minimum. The fewer calibrating points the less time is spent during manufacture and the less opportunity exists for long term drift. There are only three calibrations to be carried out. The first is to adjust the full scale range or gain of the ADC. The second is to adjust the form factor of the precision rectifier. And the third is to adjust the output voltage of the battery charger.

Start with all presets set to midrange. Switch the instrument on. Do not proceed with the calibration if the instrument fails the selftest. Investigate the cause of the failure and remedy the problem before continuing.

7.2. ADC GAIN CALIBRATION

The first calibration concerns preset P2. The objective is to adjust the gain of the ADC. The calibration sequence is as follows:

1. Connect a digital voltmeter between pin 26 of IC5 and ground. Adjust P2 for a reading of 655 mV.
2. Connect an accurate ($\pm 1 \mu\text{A}$) source of DC current to leakage current input channel number 1. Set the source to 1000 μA .
3. Press the **FUNCTION** switch until the auxiliary display shows **L1**. Make fine adjustments to P2 until the main digital display reads 1000.
4. Set the current source to 100 μA . Check that the display shows 100. Make fine adjustments to P2 if necessary.
5. Now connect the current source to the other inputs and verify the correct reading for a range of input currents.

Use the **FUNCTION** switch to change the channel being displayed. If the error is greater than 0.5 % and the reading for channel 1 is correct check that R21, R24, R27 and R30 are closely matched.

7.3. RECTIFIER CALIBRATION

The second calibration concerns preset P3. The objective is to adjust the gain of the precision rectifier to 1.1107, being the form factor of a rectified sine wave. Proceed as follows:

1. Check that the instrument is in 50 Hz mode. Change the set up if it is not.
2. Connect an accurate ($\pm 1 \mu\text{A}$) source of AC (50 Hz) current to leakage current input channel number 1. Set the source to 1000 μA .
3. Press the **FUNCTION** switch until the small display shows **L1**. Adjust P3 until the digital display reads 1000. Check that the AC indicator '~' is activated.
4. Set the current source to 100 μA . Check that the display shows 100. Make fine adjustments to P3 if necessary.
5. Now connect the current source to the other inputs and verify the correct reading for a range of input currents. Use the **FUNCTION** switch to change channels.
6. Change the set up to 60 Hz mode. Set the AC current source to 60 Hz. Verify the correct reading on all channels for a range of inputs.

7.4. BATTERY CHARGER CALIBRATION

The last calibration concerns preset P1. The objective is to adjust the battery charging voltage until it follows the solid curve of Figure 3.5. The procedure is as follows:

1. Connect the instrument to the charger source. The leakage current monitor will switch itself on if it was not on already.
2. Measure the temperature at the battery BATT1 next to R11.
3. Connect a voltmeter across the battery terminals.
4. Adjust P1 until the output voltage is equal to the value shown on Figure 3.5. for the measured temperature. To facilitate in making the adjustment, instead of reading the graph, Table 7.1. may be used.
5. Verify that the instrument indicates the correct charging current by connecting an ammeter between the charger source and K1. The meter should indicate a current equal to the current displayed on the monitor plus approximately 35 mA. The 35 mA represents the current drawn by the circuit itself.

T[°C]	V _{BATT} [V]	T[°C]	V _{BATT} [V]	T[°C]	V _{BATT} [V]
-20	5.08	-1	4.84	18	4.62
-19	5.07	0	4.82	19	4.61
-18	5.05	1	4.81	20	4.60
-17	5.04	2	4.80	21	4.59
-16	5.03	3	4.79	22	4.58
-15	5.01	4	4.78	23	4.57
-14	5.00	5	4.77	24	4.56
-13	4.99	6	4.76	25	4.55
-12	4.97	7	4.74	26	4.54
-11	4.96	8	4.73	27	4.53
-10	4.95	9	4.72	28	4.52
-9	4.94	10	4.71	29	4.51
-8	4.92	11	4.70	30	4.50
-7	4.91	12	4.69	31	4.49
-6	4.90	13	4.68	32	4.48
-5	4.89	14	4.67	33	4.47
-4	4.87	15	4.65	34	4.46
-3	4.86	16	4.64	35	4.45
-2	4.85	17	4.63	36	4.44

Table 7.1. Ambient temperature and charging voltage relationship.

TEST RESULTS

8.1. INTRODUCTION

The prototype was subjected to a number of tests. The most important test was to determine the accuracy of the instrument. Other tests included the behaviour of the instrument in the presence of high electric fields, both in the high voltage laboratory and in the field. A final series of tests concerned the battery, to determine the operating time.

8.2. ACCURACY

To test the accuracy of the leakage current monitor the circuit of Figure 8.1. was used. The test was conducted at room temperature.

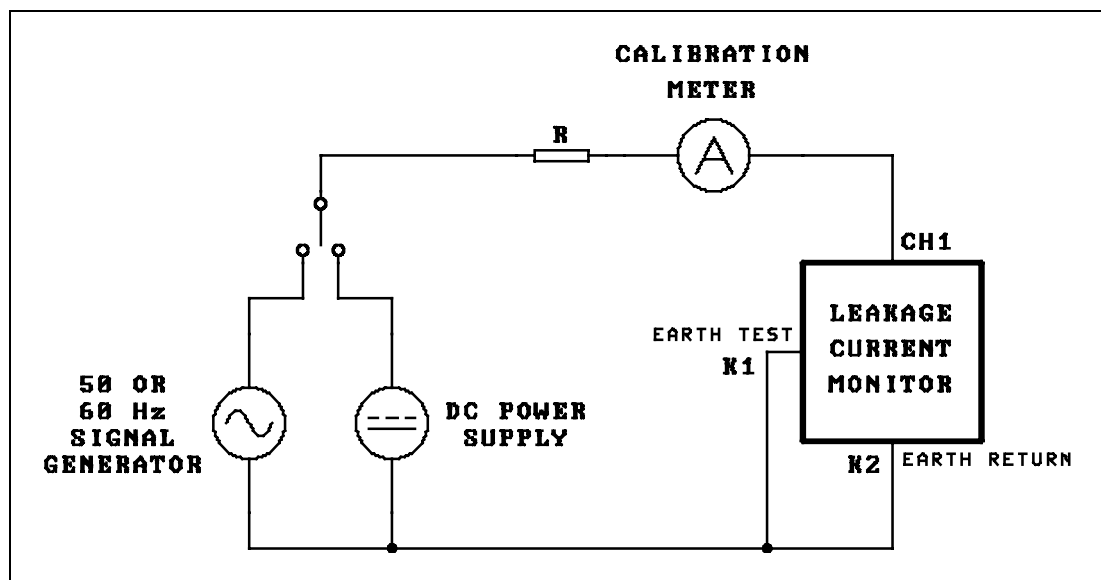


Figure 8.1. Accuracy test circuit.

The equipment used is as follows:

Test Sources:

AC: Hewlett Packard HP3310A Function Generator

DC: Topward TPS DC Power Supply

Calibration Meter (both current and frequency):

Fluke 87 Multimeter (accuracy specification: DC current $\pm(0.2\% + 2 \text{ LSD})$, AC current $\pm(1\% + 2 \text{ LSD})$, frequency $\pm(0.005\% + 1 \text{ LSD})$)

Resistor:

Refer Table 8.1.

I_{TEST} [μA]	Readings AC Mode [μA]		R [Ω]	Readings DC Mode [μA]		R [Ω]
	f=50Hz	f=60Hz		+DC	-DC	
0.00	1	1	100k	0	0	1M
1.00	1	1	100k	0	1	1M
2.00	2	1	100k	1	2	1M
5.00	7	7	100k	6	6	1M
10.00	11	12	100k	9	11	1M
20.00	21	21	100k	19	20	1M
50.00	51	51	100k	50	51	100k
100.00	102	101	100k	99	101	100k
200.0	202	201	10k	200	202	100k
500.0	501	500	10k	502	505	10k
1000.0	1002	1001	10k	1005	1008	10k
1500.0	1504	1503	1k	1510	1511	10k
1900.0	1906	1905	1k	1912	1913	10k

Table 8.1. Accuracy test results for Channel 1.

The test results are shown in Table 8.1. The number of digits shown in the column for the calibration meter is equal to the number of digits displayed. Only the test results for input channel 1 are shown. The test results for the other channels are nearly identical to the results for channel 1. Listing these results would merely result in a duplication of information. The reason that these results are so similar is that the burden resistors, R21, R24, R27 and R30, were hand-picked from a box of resistors using an ohmmeter to ensure close matching.

The tests were repeated after a period of four months to establish long term drift. The result: no significant variation of test results was encountered.

To test the coupling between channels each of the inputs in turn was supplied with a test current of 1900 μA , both AC and DC. The other channels were left

disconnected. The readings for the non connected channels were zero, therefore, there was no measurable coupling between channels.

By examining Table 8.1. the overall accuracy of the instrument can be defined as:

$$\pm(1\% \text{ of reading} + 2 \text{ least significant digits}).$$

8.3. HIGH VOLTAGE TEST

The monitor was tested in the high voltage laboratory to ascertain the performance of the circuit on actual hot sticks. The test circuit is shown in Figure 8.2.

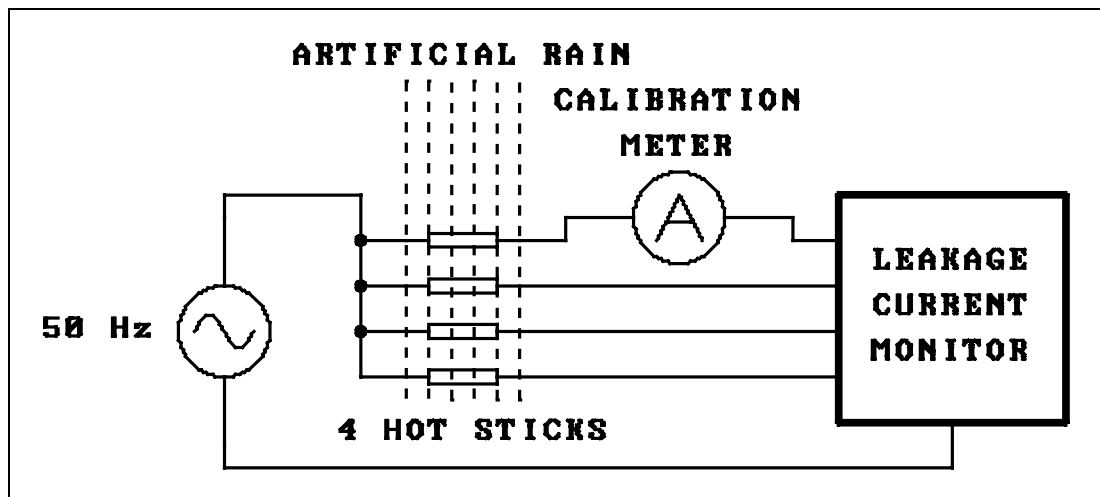


Figure 8.2. High voltage laboratory test circuit.

The hot sticks, manufactured from high quality fibreglass, have a very high impedance. To reduce the impedance, an artificial rain generator was constructed to moisten the hot sticks. The sticks were mounted on an angle of 45°. The top end was connected to the secondary of a high voltage transformer. The primary of this transformer was supplied by a variable autotransformer from the mains. The output from the high voltage transformer was adjustable from 0 to 25 kV. The bottom end of the sticks were connected to the leakage current monitor.

The autotransformer was adjusted until the current in one of the sticks reached approximately 200 μA . It was not possible to make an accurate comparison between the readings from the calibration meter and the monitor. The impedance of the sticks was constantly changing, as water droplets struck, resulting in a widely varying

current. The readings, however, were of a similar magnitude. The test current was not increased beyond 200 μA because of the risk of flashover.

This test shows that the instrument works when used in its intended application. It also shows that the instrument continues to function in the presence of strong electric fields.

8.4. FIELD TEST

The prototype was tested, with the cooperation of a Power Mark (Christchurch) live line maintenance crew, on a 66 kV transmission line. The weather conditions were fine: clear sky, windy and $\approx 20^\circ\text{C}$.

The leakage current monitor was attached to the pylon and the input connected to a hot stick. The other end of the hot stick was clamped to the live conductor. The instrument measured zero current.

Discussions with the maintenance crew revealed that the highest current they had ever measured was 5 μA on a 220 kV line, under much poorer weather conditions. The zero leakage current reading is probably correct, considering the relatively low line voltage and fine weather conditions.

One point was proved: the instrument did not malfunction in the presence of strong electromagnetic fields.

One other point raised during discussions with the maintenance crew was that some expected to set the instrument to the line voltage, not the leakage current. A maximum safe level of 1 μA of leakage current per kV of line voltage was suggested. If this type of set up is preferred then it can easily be included by making changes to the software. In this case the software would contain a look up table containing line voltages and maximum safe levels of leakage current. The table need not be fixed in ROM but can be stored in EEPROM.

8.5. BATTERY OPERATING TIME

The battery has been subjected to a series of tests in order to determine the operating time. The battery was charged and discharged at three different

temperature conditions: $\approx 19\text{ }^{\circ}\text{C}$, $\approx 5\text{ }^{\circ}\text{C}$ and $\approx -15\text{ }^{\circ}\text{C}$. The battery was charged for 24 hours at room temperature prior to the first discharge at each test temperature. Charging time before the second and third discharge was 12 hours at the test temperature. The test results are shown in Table 8.2.

Test number	Discharge Time [hours]		
	$T \approx 19^{\circ}\text{C}$	$T \approx 5^{\circ}\text{C}$	$T \approx -15^{\circ}\text{C}$
1	44.1	43.3	38.9
2	42.7	38.8	36.1
3	41.7	37.6	35.0

Table 8.2. Results for battery life tests.

The **BAT** indicator first appears after approximately 30 hours, initially flashing only briefly. The indicator on time increases as discharge progresses. The operating time was slightly reduced at low temperatures. The difference however, is much smaller than expected. The second and third discharge times are shorter than the first in all cases. This probably means that the 12 hour charging period is too short, although this value was predicted from the manufacturer's data sheet. If the battery is recharged after each use, overnight for instance, than the battery will never reach the fully discharged level. This practice will prolong battery life and ensure the availability of a functional instrument. The results show that a minimum operating time of 40 hours can be expected from a new and fully charged battery under normal temperature conditions. Under extremely cold conditions the operating life is reduced to about 38 hours.

The ability to store energy is reduced as the battery ages. According to the battery's manufacturer a minimum of 200 full discharge cycles are available before the battery's end of life is reached. The battery's end of life is defined as the point where it fails to hold more than 60 % of its initial capacity. The battery is still usable at this point, with an expected operating time of 24 hours.

8.6. MAGNET CONTACT

To test the feasibility of the magnet attachment and spring contact system, a test magnetic contact was made by the Electrical and Electronic Engineering

Department workshop. The drawing for the test magnetic contact is shown in Figure 8.3.

The contact comprises a cylindrical magnet with a pointed steel pin inserted through the centre. The contact is held in the forward position using a spring. The pin is allowed to move backwards, against the spring force, when the magnet is affixed. The spring force was 8 N.

The contact has been tested on a variety of surfaces. On both new and weathered galvanised steel surfaces the contact resistance is less than 0.5Ω . The connection is made reliably. On painted surfaces the connection is less reliable. A thin paint layer is easily penetrated, but a primed and painted surface is not.

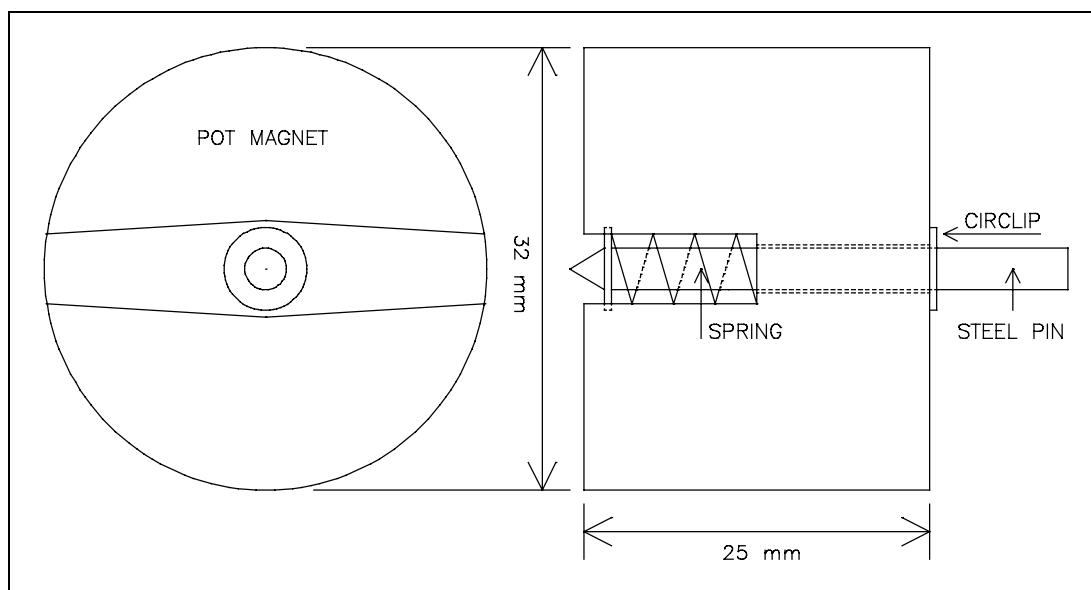


Figure 8.3. Mechanical drawing for the test magnetic contact.

This test shows that this type of contact is feasible for use with galvanised steel. Galvanised steel is the main construction material for pylons, which is the intended application area for this instrument.

WORK REMAINING

The prototype was not completed to the point where it is a commercially sellable item. A number of tasks need to be completed.

The first task is to redesign the printed circuit boards to match the circuit diagrams and to fit the enclosure design. The use of surface mount components will greatly reduce the overall dimensions when compared to standard parts. This is followed by finalising the actual enclosure design and dimensions. The battery charging base needs to be designed and build.

The completed enclosure needs to be tested for water proofing and shock and vibration resistance.

One important test remains: to determine the extend of the damage resulting from flashover. Other tests could be conducted, like testing to comply to appropriate standards and guidelines.

The instrument appearance and user friendliness would be enhanced with a custom designed LCD. The LCD could spell out the operating and display modes instead of using abbreviated messages.

CONCLUSIONS

A prototype leakage current monitor was constructed to test the design and housed in an aluminium enclosure. The design has achieved the primary objective of improving on a commercial design. The prototype meets or exceeds the requirements listed in chapter 1. A practical enclosure has been designed but has not been manufactured.

The electronics has been kept to a minimum, incorporating only those components necessary for the power supply, measurement and user interface functions. The use of a microcontroller reduces the overall parts count and results in a user friendly operator interface. Many of the instrument's features are defined in software and can easily be changed at the manufacturing stage, perhaps to meet individual customer requirements or to keep up with changing practices.

The next step is to construct a second, more complete, prototype to fit the enclosure and turn the design into a finished product.

REFERENCES

- Analog Devices Engineering Staff, Analog-Digital Conversion Handbook, Englewood Cliffs, Prentice-Hall, 1986.
- Bodger, P. S., Code of Practice for Bare-Handed Live-Line Maintenance, Christchurch, Canterbury (University of Canterbury), December 1989.
- Bodger, P. S., Correspondence to Electricorp Marketing, Christchurch, 25 August 1989.
- Dekis, Jim, "Careful Power Supply Design Extends Portable System Battery Life Part I: Battery and Regulator IC Fundamentals", Power Conversion and Intelligent Motion, February 1991, pp. 15 to 22.
- Dekis, Jim, "Careful Power Supply Design Extends Portable System Battery Life Part II: Step-Down Switching Regulator With 9V Battery", Power Conversion and Intelligent Motion, April 1991, pp. 58 to 64.
- Dekis, Jim, "Careful Power Supply Design Extends Portable System Battery Life Part III: Step-Up Switching Regulator By Two AA Cells", Power Conversion and Intelligent Motion, May 1991, pp. 50 to 57.
- Forgie, G. C. et al, "The Introduction of Bare Hand Live Line Techniques For Reinsulating of The New Zealand HVDC Inter Island Link", Proc. 5th Int. Conf. on Transmission and Distribution Construction and Live Line Maintenance, June 19-21, 1990, Toronto, Canada, pp. 145 to 148.
- Intersil Inc., Component Data Catalog 1987, Cupertino, 1987, pp 6-39 to 6-40.
- Jung, Walter G., IC Op-Amp Cookbook, Indianapolis, Howard W. Sams & Company, 1988.
- Lion, Arthur L., Dealing With Data, Oxford, Pergamon Press, 1970.
- National Semiconductor Corporation, Linear Databook 1, Santa Clara, 1988, pp. 2-308 to 2-313.
- National Semiconductor Corporation, Linear Databook 2, Santa Clara, 1988, pp. 7-20 to 7-27.
- Philips, I²C-bus compatible ICs Types PCF8582A to UMA1010T, Data Handbook IC12b, 1989, pp. 707 to 715.
- Philips, 8051-based 8-bit Microcontrollers, Data Handbook IC20, 1991.
- Philips, Liquid Crystal Displays and Driver ICs for LCD, Data Handbook LCD01, 1991.
- Sonnenschein, Sonnenschein Batteries dryfit maintenance-free, Bűdingen.

Stix, Gary, "Working hot: life at 765 kV", IEEE Spectrum, September 1988, pp. 54 to 56.

COMPONENT LIST

RESISTORS:

9	100k	R1, R4, R14, R18, R22, R25, R28, R31, R40
1	220k	R2
1	120k	R3
1	560k	R5
1	330k	R6
2	0.5E, 0.5W	R7, R10
3	1k5	R8, R9, R12
1	KTY81-221	R11
1	1k8	R13
3	10k	R15, R33, R34
1	120E	R16
1	1k2	R17
2	180k	R19, R41
4	1k	R20, R23, R26, R29
4	100E, 0.5%	R21, R24, R27, R30
1	604k	R32
1	15k	R35
1	82k	R36
1	68k	R37
2	56k	R38, R44
1	12k	R39
2	2k2	R42, R43
1	500E, multiturn preset	P1
1	10k, multiturn preset	P2
1	1k, multiturn preset	P3

CAPACITORS:

3	100p	C1, C22, C23
2	220 μ , 16V, low ESR	C2, C4
4	10 μ , 16V	C3, C16, C18, C20
5	100n, ceramic	C5, C6, C7, C8, C9
1	470 μ , 25V	C10
2	2 μ 2, 16V, tantalum	C11, C12
1	10p	C13
1	4n7, polypropylene	C14
5	100n, monolithic	C15, C17, C19, C25, C29
1	1n	C21
1	2 μ 2, 16V	C24
2	22p	C26, C27
1	3n3	C28

INDUCTORS:

2	330 μ	L1, L2
2	47 μ	L3, L4

SEMICONDUCTORS:

2	SB130	D1, D9
11	1N4001	D2, D3, D4, D10, D11, D12, D13, D14, D15, D16, D17
1	7V zener	D5
6	1N4148	D6, D7, D8, D18, D19, D20
1	MAX631	IC1
1	MAX635	IC2
1	L200	IC3
1	LM334	IC4
1	MAX133	IC5
1	ICL8069	IC6
2	LM308	IC7, IC8
1	PCB87C528	IC9
1	PCF8576	IC10
1	PCF8582	IC11
1	BST70A	T1
1	BST100	T2

MISCELLANEOUS:

1	Battery A204/1.0K	BATT1
1	Buzzer RS 626-141	BZ1
1	AMP P/N 206430-1	K3
1	AMP P/N 206061-1	K5
1	LCDisplay LTD202	LCD1
1	LCDisplay LTD241	LCD2
1	DIL relay RA30982051	RE1
1	rot. SW eao 52-271.025	S1
1	PB SW eao 51-131.025	S2
1	32768kHz crystal	X1
1	11.0592 MHz crystal	X2

PROTOTYPE PHOTOGRAPHS

This appendix shows photographs of the prototype. Figure B.1. shows the circuit boards produced for the initial design together with the modifications for the present circuit. The circuits from left to right are the: back of the LCD, precision rectifier (on prototype board), microcontroller and ADC, current source (on prototype board) and power supply with battery charger. Shown at the top is the buzzer, the power switch is on the far right and the user input is at the bottom centre.

The circuit boards are stacked together as shown in Figure B.2.

The prototype enclosure is shown in Figure B.3. The four BNC sockets at the top are the leakage current inputs.

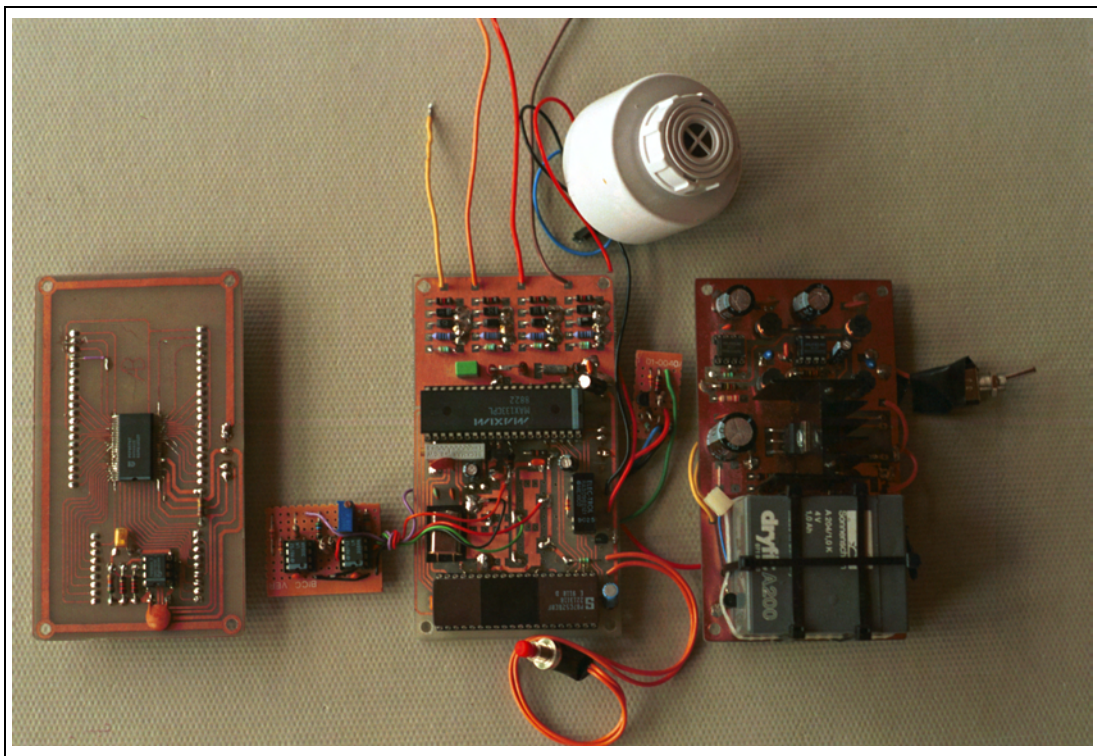


Figure B.1. Individual printed circuit boards.

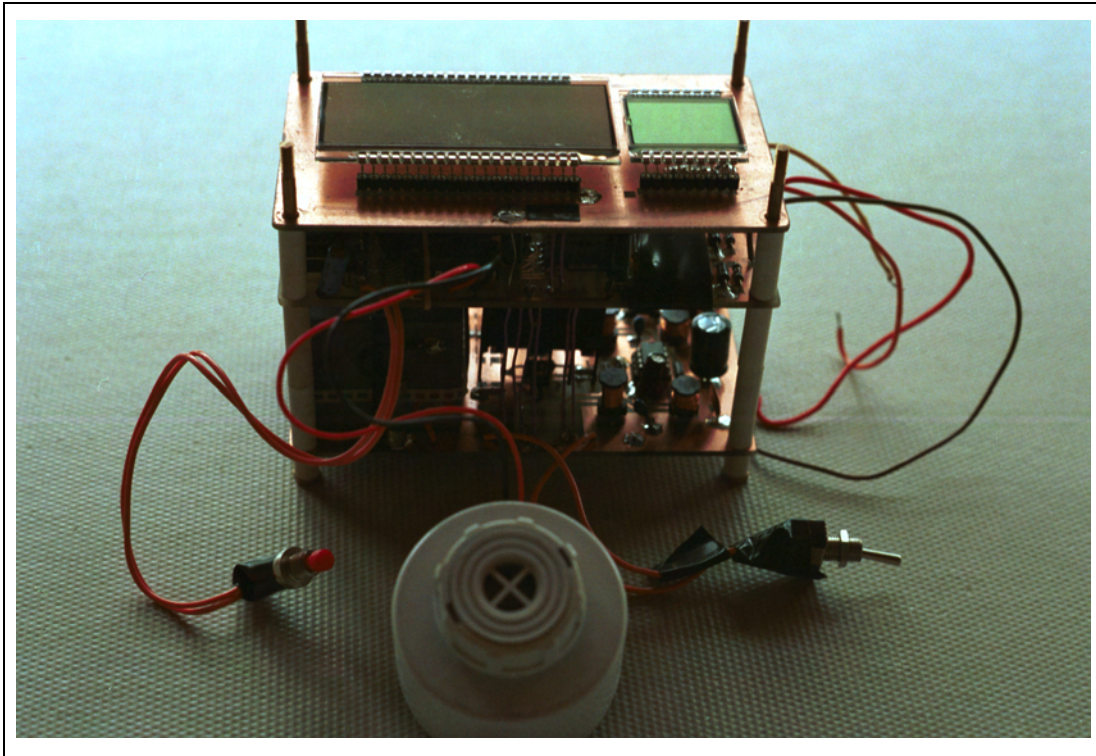


Figure B.2. Assembled circuit boards.

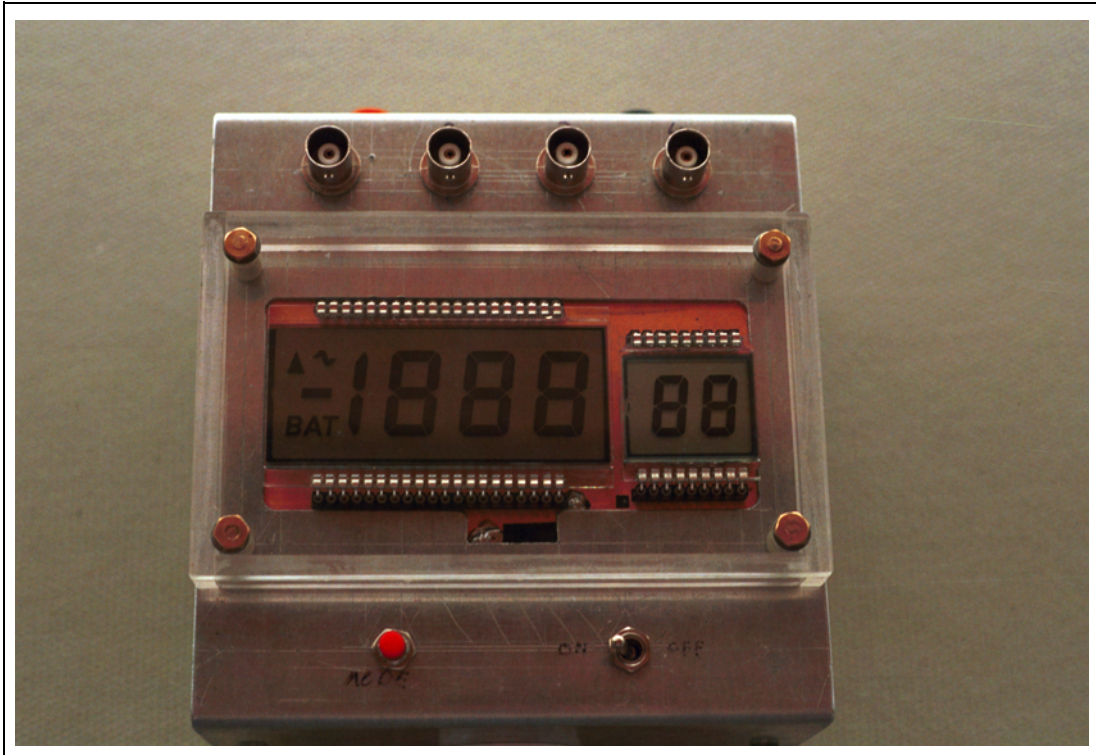


Figure B.3. Completed prototype.