TRANSIENT INTERFERENCE TESTING OF A DATA ACQUISITION AND CONTROL SYSTEM

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ABSTRACT

A Supervisory Control System has been designed to be immune to electrical noise levels experienced in High Voltage Switchyards. A prototype version version of this system has been tested in the High Power Labs at IREQ, and in the 735 kV Switchyard at Boucherville near Montreal.

This thesis describes the circuit design techniques and noise testing procedures used and discusses the ways by which noise immunity can be achieved. The circuits subjected to the electrical noise tests constitute a series of remote interface modules which monitor alarm/status and telemetry input signals for a centrally located control computer, and which also execute control output commands from the computer. Such interface modules are used extensively in modern switchyards for Data Acquisition and Control; Sequence of Events Recording; Remote Multiplexing; and Power Dispatching Equipment.

The test programme included subjecting the equipment to magnetic fields up to 40,000 amperes/metre, high voltage pulses from 2 to 5 kV, and electric fields generated by 735 kV arcs less than 40 feet away.

The Conclusions show that when proper surge suppressors are used, Supervisory Control Systems can be operated with excellent reliability in modern High Voltage Switchyards. Reliability calculations confirm this conclusion.

ACKNOWLEDGEMENTS

While the Author was Project Engineer in charge of the test program described in the dissertation he received much assistance from engineers at CAE Electronics Ltd. and at Hydro Quebec's Institute of Research. In particular, thanks are due to Mr. Gilles Provençal (who wrote test specs and carried out most of the tests), Mr. David Thompson (who wrote the computer programs and assisted with the tests). The author is also grateful for guidance and encouragement received from his Department Manager Mr. C. "Case" Vandersluis and from his advisor Professor James Lindsay.

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1.0 INTRODUCTION

Electromagnetic interference in power stations and switchyards has long been a problem for Control System Designers, but has recently become more acute.

One reason is the widespread use of solid state devices in control circuits and particularly integrated circuits, such as logic circuits, operational amplifiers, etc. While these components are highly reliable under normal conditions, and do not seem to suggest any definite wear-out mechanism, they are fairly vulnerable to fast, high-voltage transients. Also, due to the speed and sensitivity of modern integrated circuits, whereas the transients may not always cause component failures, they may cause misoperations that may be extremely difficult to diagnose.

The second factor causing increased interference levels is, of course, the increased voltage and power levels being handled in today's power distribution systems. The newest part of the electrical distribution network in the Province of Quebec is operating at 735 kV, and studies are under way for distribution systems operating in the 1000 to 1500 kV range. It is therefore, hardly surprising that a lot of effort is presently being devoted in order to determine just how these interference problems can be overcome.

1.1 Definition of Problem

Electrical interference noise can enter into electronic equipment via two paths. The most difficult path involves noise being coupled into cables, either input cables, output cables, or power cables. The other path involves direct electromagnetic or electrostatic radiation and coupling into the equipment itself.

Switchyard Control Equipment can be protected against the effects of this noise by the combined efforts of two groups of people. On the one hand, the electrical engineers who design switchyard and power station wiring and cabling systems, can do a lot to reduce the interference levels which the electronic equipment will be subjected to, by the use of proper grounding techniques, shielded cabling, buried cable conduits and shielded control rooms. On the other hand, the manufacturers of the electronic equipment, can devise circuit design techniques which increase the inherent ability of a system to handle noise levels.

1.2 Electrical Interference Levels in Switchyards

In the literature, several papers describing transient noise levels in switchyards are available[1,2,3]. These papers concentrate specifically on transient noise picked up by control cables. Such noise bursts may have peak amplitudes up to 15 kV. Data on magnetic fields and electric fields is very rare, but it has been estimated that magnetic fields of several hundred amperes per metre may be encountered.

Since the cabinets of most types of electronic control equipment will provide a considerable amount of shielding, it seems reasonable to assume that noise on the control wiring will represent the most serious problem. The paper by R. L. Hicks and D. E. Jones[2] discusses how different shielding techniques may be employed to reduce the noise picked up by control cables. Since sophisticated types of shielded cables are expensive, it becomes desirable to reduce noise levels no more than necessary to ensure reliable equipment operation. The following quote from the above paper is particularly relevant:

> The question remains, however, how far is it necessary to lower transient amplitudes? Obviously, transient voltages must be kept less than the level where insulation failures occur, which is considered to be about 3 kV. Since solid state equipment can be built to withstand such transients, it would seem that the design of station wiring need be modified only to the extent necessary to keep transients below 3 kV.
>
> These levels can be achieved by careful grounding practices in the switchyard, such as keeping neutral grounds separate from ground leads of apparatus connected to the high voltage bus and assuring that duct work is continuous. Measures such as these together with adequate surge protection on solid state equipment should eliminate equipment failures due to transients.

The Supervisory Control System described here meets the call for control equipment which can withstand 3 kV noise transients.

1.3 Noise Test Specifications

Some organizations have published specifications for noise testing of electronic equipment, notably the American National Standards Institute (ANSI) in cooperation with the Institute of Electrical and Electronics Engineers (IEEE)[4], and also the Hydro-Electric Power Commission of Ontario (Ontario Hydro)[5].

The IEEE/ANSI document specifies that an oscillatory wave with 2.5 kV to 3 kV peak amplitude, 1.0 to 1.5 MHz oscillation frequency, and a 6 microsecond time to decay to 50% amplitude should be used as a test wave. The surge wave generator should have a source impedance of 150 ohms. The specification also gives a description of a suitable voltage generator, definitions of the test procedures, explanations of why the specific test parameter values were chosen, and contains an extensive bibliography with 42 entries.

The Ontario Hydro test specification establishes four test levels of decreasing severity. Test level A corresponds to a high voltage switchyard environment, and specifies a decaying oscillatory waveform, amplitude 5000 to 6000 volts, frequency 200 kHz to 2 MHz, source impedance 100 to 150 ohms, and a 5 cycle decaying time to half amplitude. This test is therefore more demanding than the IEEE/ANSI test, and requires a more complex surge voltage generator.

With regard to the rather high surge voltage amplitude of 5 to 6 kV chosen by Ontario Hydro; Hicks and Jones as quoted above mention insulation breakdown at 3 kV levels. The IEEE/ANSI specification mentions secondary circuit insulation ratings of 2.5 kV, and argues that "it does not make sense then to specify a relay surge test voltage above insulation ratings".

1.4 "Noise Immune" Equipment Development and Testing Program

1.4.1 The Supervisory Control System

A typical Supervisory Control System consists of a Master Terminal Unit (MTU) and several Remote Terminal Units (RTUs). The MTU includes a control computer and is located in the Station Control Room. The RTUs are connected to the MTU via communication lines, and serve as remote input/output data multiplexers.

Noise immunity was a design goal for this new type of Supervisory Control System from the beginning of its development. As part of this design philosophy it was decided to use COS/MOS integrated circuits throughout, which, in addition to their inherently good noise immunity, have very low power consumption. This makes it possible to use non-ventilated cabinets for the equipment, which may provide better shielding against radiated noise.

1.4.2 The Test Program

Also as part of the initial design concepts was the decision to build a prototype system which would be subjected to the most thorough testing possible. The two main purposes of this test program were to find the "weak links" in the system and redesign the necessary circuits, and to prove that the new system would be capable of operating in a modern 735 kV switchyard.

The testing of the equipment was carried out in five phases as indicated below:

- Preliminary tests of digital input circuits.
- Magnetic field sensitivity tests.
- Tests on effects of differential ground potentials.
- System test in a 735 kV switchyard.
- Redesign and retest

The first phase took place in the CAE laboratories. The other four were carried out at the Hydro-Quebec Institute of Research at Varennes, and at the Boucherville Substation. The test results are given in the description of each test.

2.0 DESCRIPTION OF EQUIPMENT

The prototype supervisory control system used when the tests were carried out included:

- One Master Terminal Unit (MTU) with control computer and teletypewriter built into a desk console.
- One Remote Terminal Unit (RTU) with communications interface, and interface circuit boards for "field devices" such as analog inputs, digital inputs and digital outputs.
- One Field Simulator Console with switches to simulate digital inputs, indicator lights for digital outputs, and adjustment potentiometers with voltmeter and milliammeter to activate the 0 to 5 volt and 4 to 20 milliamperes analog input circuits.

2.1 The Master Terminal Unit

The central control computer was a general purpose "mini" computer with a 16 bit parallel input/output controller for communication with the RTU. The control computer normally carries out the functions of Data Display (CRT monitors, Annunciator panels, line printers), Mass Data Storage (Disc, Mag Tape, Paper Tape), and Field Communications (Computer Interface Unit and Communications Line Transmitter/Receiver). A normal supervisory control system uses a disc memory to maintain a data base with information of the status of the field devices (circuit breakers, disconnect switches, voltages levels, etc). The system operator may request "pages" of specific information to be displayed on the CRT monitors, while standard performance reports will be printed on a line printer at regular intervals.

In the prototype system there was no need to maintain any large data base, and a much simpler test program was used to continuously scan the digital inputs for any change in status, which would be reported on the teletypewriter. The digital output relays were turned on one at a time and then turned off again in a continuous "scanning sequence". An observer near the Field Simulator Console could therefore detect interference with the digital outputs by observing if any indicator lights were turned on or off out of sequence. Noise interference on the analog inputs could be detected by commanding the computer to repeatedly sample one specific analog input channel during the test and store all the readings in their chronological sequence. When the test was completed, these readings were typed on the teletype and visually examined for inaccuracies.

The control computer communicated with the RTU via a serial data transmission line controlled at either end by a D.C. Keyer, which contained a receiver and a transmitter for a 20 mA current loop. The message consisted of two 16 bit computer words (Address word and Data word), 8 bits of polynominal check code for error detection, and start and stop bits for synchronization.

A Manual Mode Control Panel was provided as back-up in case of computer problems, and to assist in trouble-shooting.

2.2 The Remote Terminal Unit

The D.C. Keyer module in the RTU decoded the incoming current loop signals from the MTU, and translated them into logic signals. Two control modules (Timing Control and Function Control) were used to receive the computer message and provide address signals for the input/output modules, and to examine the check bits to verify a "Valid Message".

The input/output modules used during the prototype tests included the following:

- Digital Input Modules	2 types
- Digital Output Modules	3 types
- Pulse Accumulator Module	1 type
- Analog-to-Digital Converter	1 type
- Analog Input Multiplexers	2 types

The digital output modules were used to drive heavy duty "interposer" relays mounted on special relay circuit boards. A power supply assembly provided isolated D.C. power supplies for the various input/output sub-systems, while an RFI filter assembly protected the communications interface and the power supplies against noise on the input cables. There was room provided to install surge suppressors for all digital/analog input/output cables, but none were installed, since the purpose of the tests was not to test the effectiveness of surge suppressors, but the noise immunity of the input/output circuits themselves.

2.3 The Field Simulator Console

The Field Simulator Console contained the following sets of indicator lights and switches:

- 10 indicator lights for digital outputs, static (blue)
- 10 indicator lights for digital outputs, reed relays (red)
- 20 indicator lights for digital outputs, pulsed (10 blue, 10 amber)
- 16 on/off switches for digital inputs, status
- 16 momentary-on switches for digital inputs, latching
- 4 momentary-on switches for pulse accumulator inputs
- 2 control potentiometers plus 2 ten-channel selector switches for the analog inputs (0 - 5 volts and 4 - 20 milliamperes)
- 1 milliammeter (0 - 20 mA)
- 1 voltmeter (0 - 5 V)

A set of 100 foot multiconductor cables connected the Field Simulator Console to the RTU, so that the Simulator Console could be observed and manipulated while at a safe distance from the RTU which would be located in potentially hazardous areas.

A pictorial representation of the prototype supervisory control system is shown in Figure 2.1.

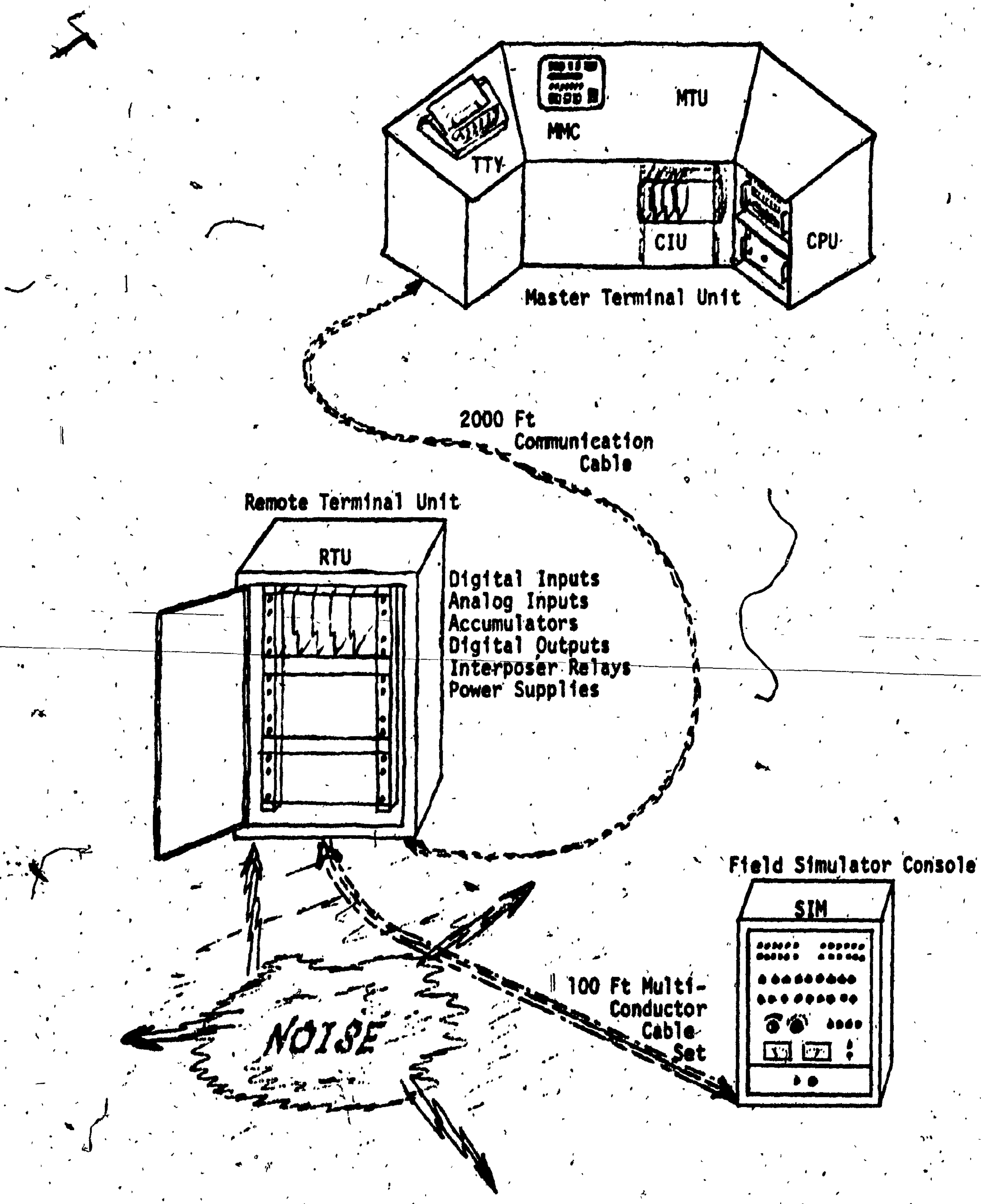

Figure 2.1 - Supervisory Control System Prototype

3.0 CIRCUIT DESIGN TECHNIQUES

3.1 Message Security

Each message between MTU and RTU consisted of two 16 bit words of information plus 8 check bits. The check bits were generated by a cyclic polynomial check bit encoder, and the code was similar to a Bose-Chaudhuri code except for the message length. If the RTU detected an error in the message from the MTU, it would not respond, and the MTU would repeat the request. If the MTU detected an error in the reply from the RTU, the MTU would repeat the original request. During the whole test program several "Error Messages" were detected, but no instances of an undetected error have been observed.

3.2 COS/MOS Integrated Circuits

COS/MOS (COmplementary Symmetry/Metal-Oxide Semiconductors) integrated circuits were becoming commercially available in the early 1970s, and were immediately recognized for their suitability for industrial control circuits where high-speed logic was not required. COS/MOS I.C.s are made from complementary field-effect transistors, and thus do not require collector-circuit load-resistors the way bipolar transistors do. That way power consumption is reduced to the extent that current only flows to charge circuit capacitances during each switching transition.

Current consumption is therefore low, and due to larger circuit capacitances, switching transients are greatly reduced. Since

COS/MOS I.C.s operate from 12 volt power supplies instead of the normal 5 volts for TTL (Transistor-Transistor-Logic) it follows that noise immunity is also higher.

As a side-effect of the low power consumption, COS/MOS systems can often be placed in fully enclosed cabinets, which, when they are grounded, offer further noise protection.

3.3 Digital Input Circuits

A typical digital input module is shown in the diagram below. The 16 field contacts, whose status is monitored, are wired to the input filters, which remove noise due to interference and contact bounce. Optical isolators further reduce noise by separating the contact input power supply from the logic power supply. Also, by virtue of the optical isolator's differential input connection, any common mode noise is rejected. The outputs from the buffer amplifiers are connected to a parallel input, serial output shift register.

When the digital input module is addressed by a "Read" message from the MTU, the current input data from the 16 buffer amplifiers is transferred into the shift register under parallel control, and then clocked out one by one under serial control. At the MTU, the computer compares the new status with the previous status, and types out an alarm report if there are any differences.

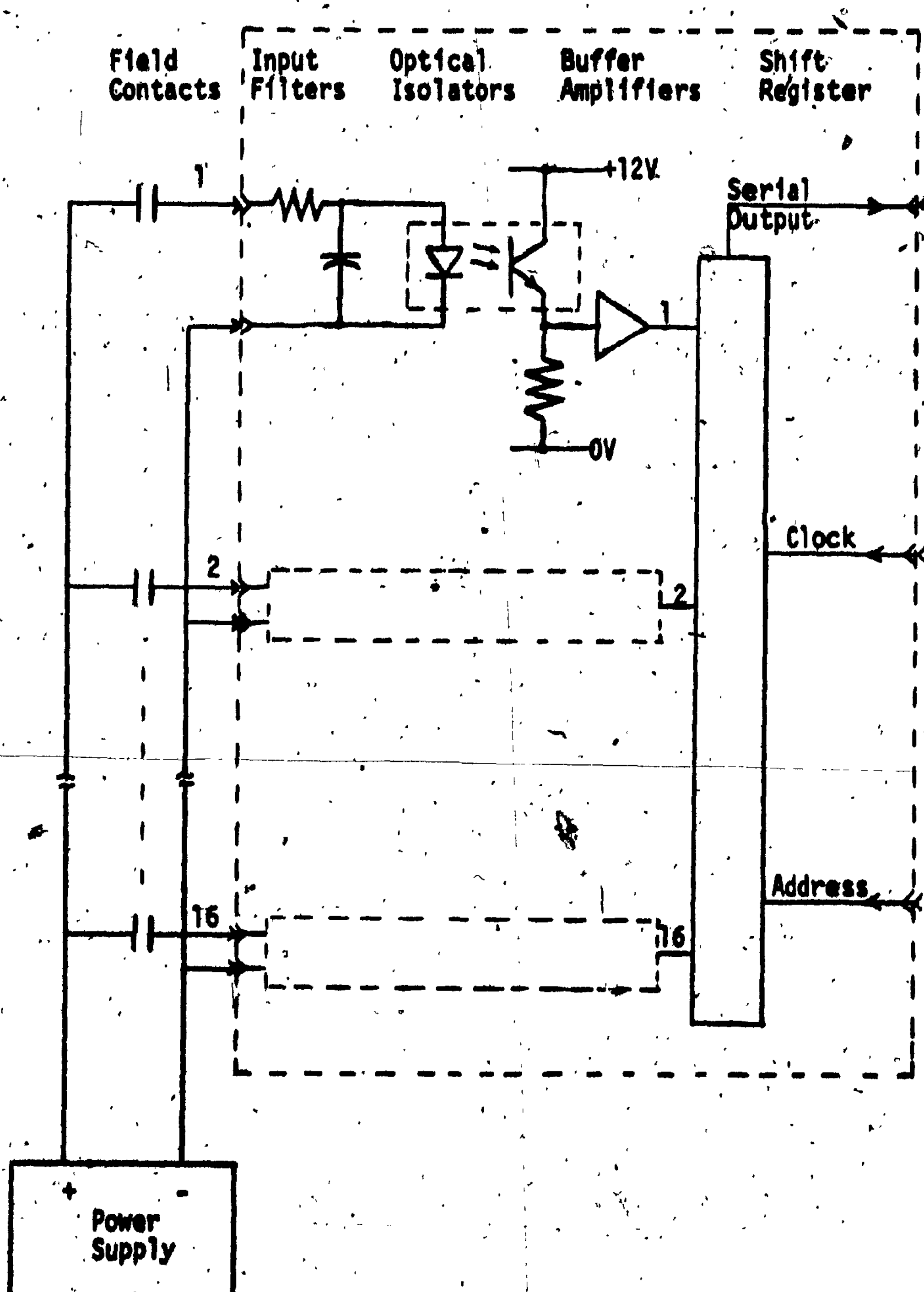

Figure 3.1 - Digital Input Module

Two types of digital input modules were available, viz:

- Static (for normal status monitoring)
- Latching (for "fleeting alarms")

3.4 Pulse Accumulator Circuits

Each pulse accumulator module contains two accumulator channels as shown in Figure 3.2. The field contact will open and close repeatedly as determined by the transducer which is driving it, which may be a kilowatt-hour meter, time pulse generator or similar device.

The input circuit is similar to the digital input circuit described above, and includes an optical isolator for maximum noise immunity. The amplified signal from the optical isolator is used to clock a four-digit pulse counter (0 to 9999), whose output may be transferred to a shift register when that accumulator channel is addressed by a "Read" message from the MTU.

When the new pulse count is received by the MTU, the counter register maintained by the computer for each accumulator channel is updated accordingly. A special software routine monitors if the accumulator has counted beyond "9999", and adds a "carry" to the computers counter register when necessary.

3.5 Digital Output Circuits

Digital output modules are used to drive "interposer" relays as shown in Figure 3.3. The contacts from these relays are then used to control such field devices as circuit-breakers;

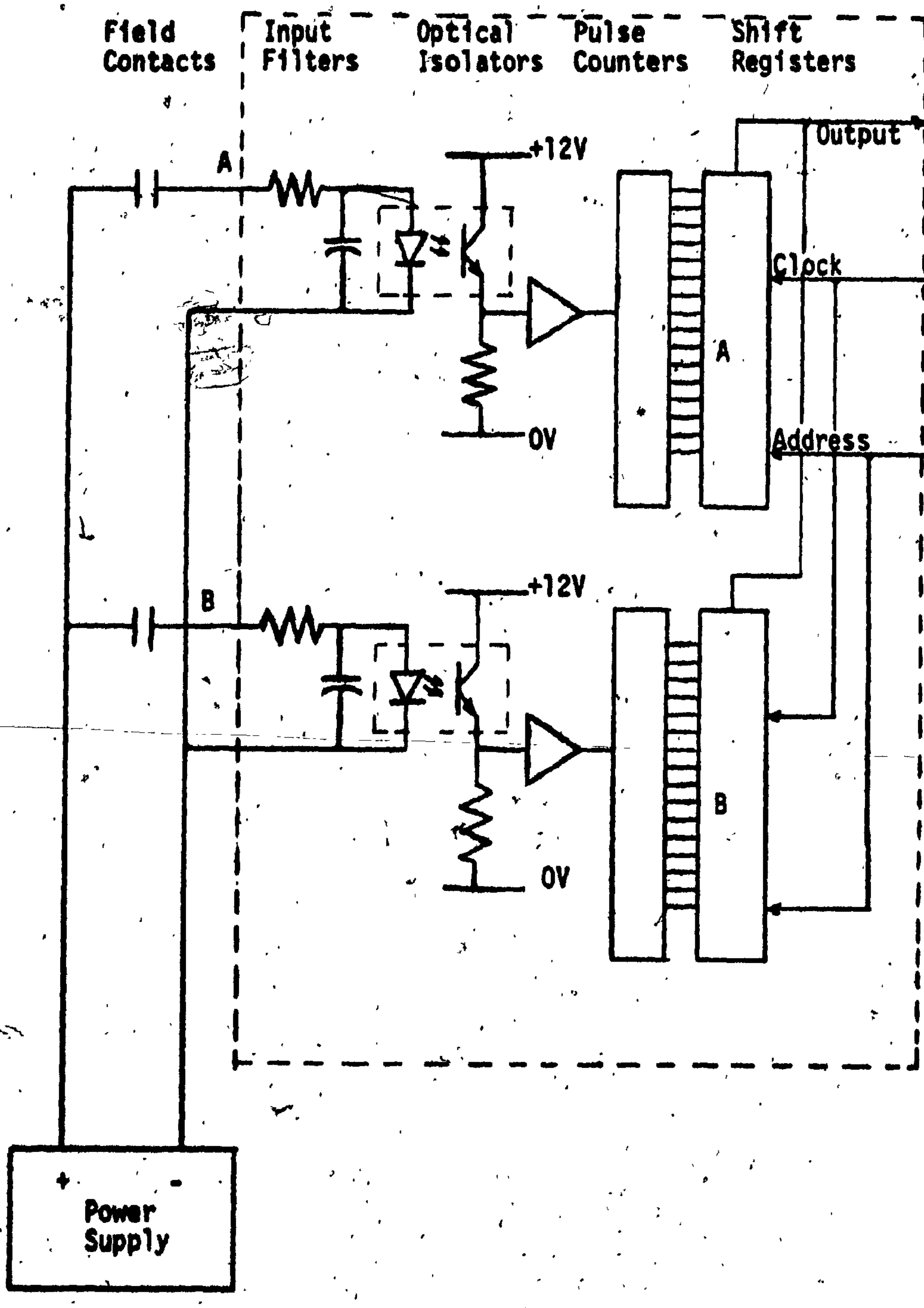

Figure 3.2 - Pulse Accumulator Module

disconnect switches, motors, valves, etc.

When the MTU sends an "Output" command, the "data word" is clocked into the serial input, parallel output shift register on each digital output module. Only that module whose address is specified by the "address word" will transfer the input data to a memory register, whose outputs determine which interposer relays are "On" and "Off".

Noise immunity for this module is provided by the interposer relays, whose contacts are isolated from the coils, and by the low output impedance of the transistor driver.

Three digital output modules were available, viz:

- Digital Output, Static, 10 Channels
  (Used for static loads, such as motors, valves, etc)

- Digital Output, Pulsed, 20 Channels
  (Used for latching devices such as circuit-breakers, contactors, etc. 10 Channels for "Close", 10 Channels for "Trip".)

- Digital Output, Reed Relays, 10 Channels.
  (Used for light loads such as communication lines, indicator lights, small solenoid valves, etc.)

3.6 Analog Input Circuits

The analog input system consisted of several analog input multiplexer modules and one analog-to-digital converter module, as shown in Figure 3.4.

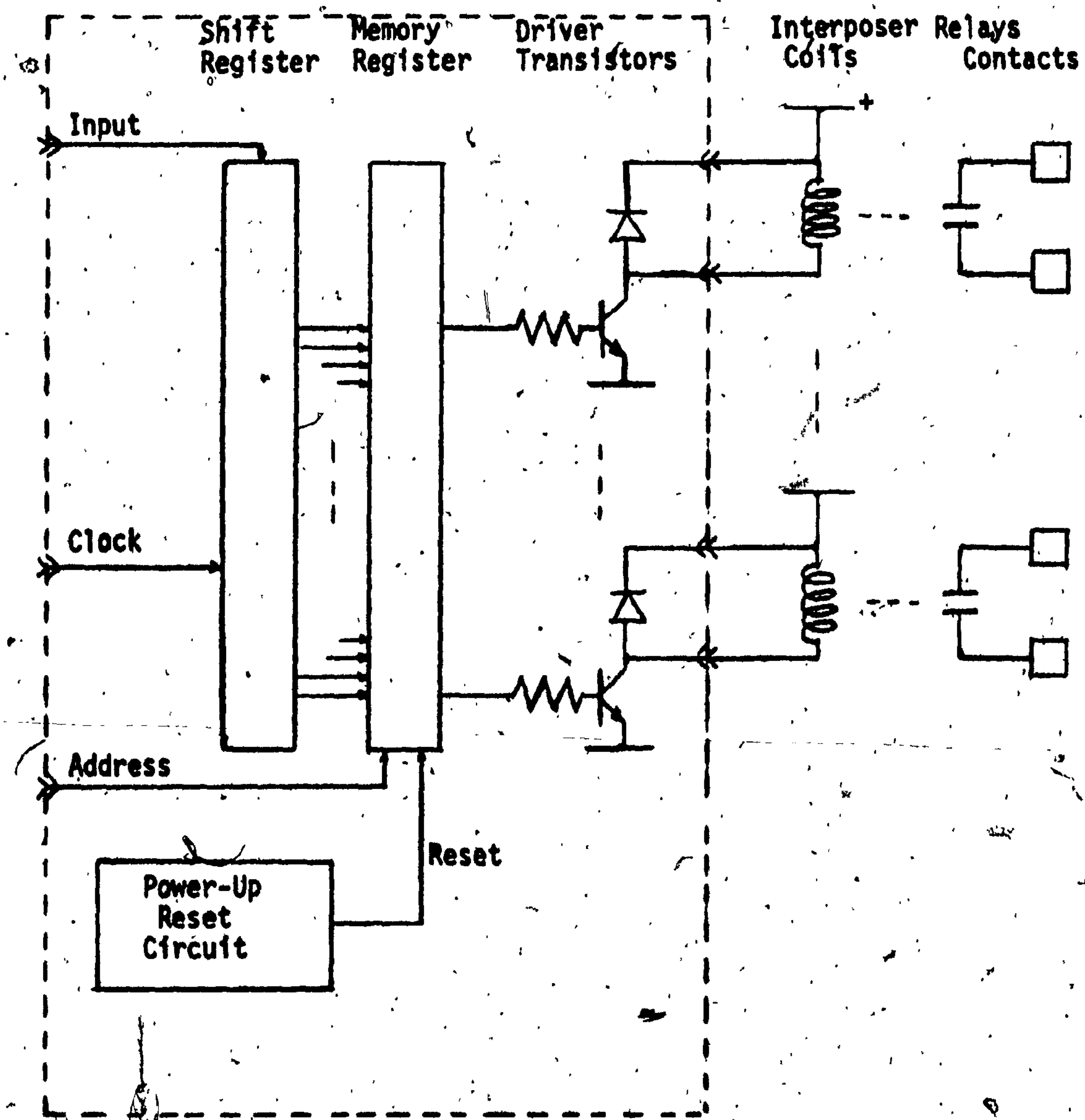

Figure 3.3 - Digital Output Module

The inputs are normally in the 0 to 5 volt range and are supplied from transducers measuring voltage, current, power, temperature, etc. Transducers with a current output (e.g. 4-20 mA) can be accommodated by adding current reference resistors which will convert the input current to a corresponding voltage reading. Noise on the input lines is averaged out by long time constant filters, while current limiting resistors and clamping diodes provide over-voltage protection.

When the MTU sends a command to read a specific analog input channel, the appropriate multiplexer switch (as selected by the "address word") connects the input voltage to the "analog data bus". On the analog-to-digital converter module this signal is amplified and converted to a 3 digit BCD value in the range 0 to 999. All analog input voltages are thus converted to a percentage of "full scale", and the computer will convert to the appropriate engineering units in each case.

Two analog input multiplexer modules were used, one for 0 - 5 volt inputs, the other for 4 - 20 mA inputs.

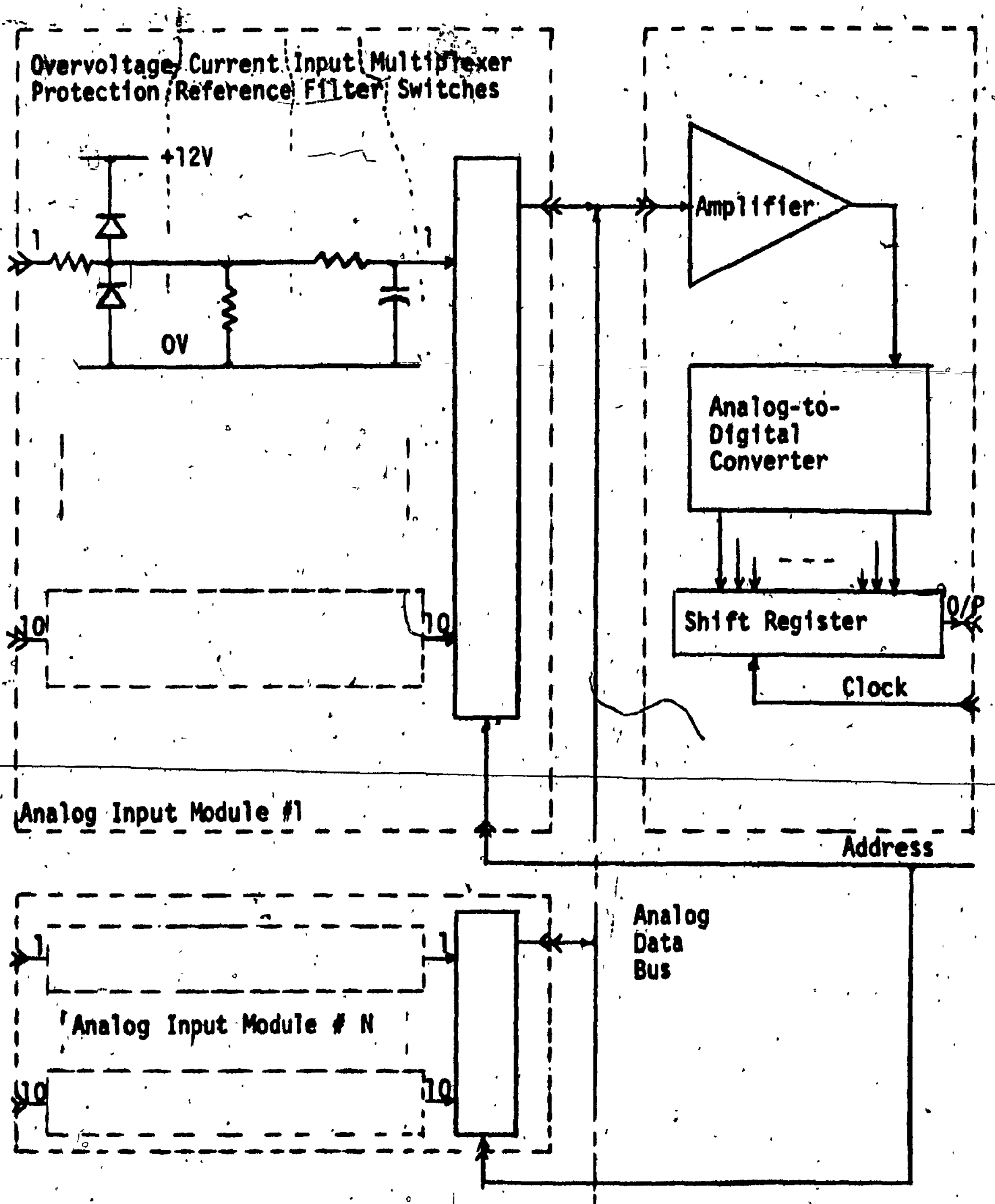

Figure 3.4 - Analog Input System

4.0 PRELIMINARY TESTS OF DIGITAL INPUT CIRCUITS

4.1 Purpose of the Tests

The digital input circuit was singled out for special testing, since it will be used in large numbers in most supervisory systems, and due to the requirement for a latching input for "fleeting alarms", it will be vulnerable to triggering from noise-pulses or spikes. Also, optical isolation techniques needed detailed studies.

4.2 Test Procedure

For the initial test phases, a small high-voltage tester was constructed and used for the following tests:

- Preliminary tests of single input optically isolated digital input circuit.
- Follow-up testing of 16 channel Digital Input Breadboard to allow testing of cross-talk effects.

To allow further testing with the Digital Input Breadboard plugged into the prototype system, a larger noise voltage generator was made and used as follows:

- The prototype system was tested while noise pulses were applied to the Digital Input Breadboard to verify that noise would not be coupled via the Digital Input Board to the rest of the system.

4.3 Test Results

A series of tests was carried out on the original digital input circuit shown in Figure 4.1. The main feature of this circuit is the use of an optical isolator to give complete electrical isolation between the wiring from the input contact located in the field, and the logic circuit on the board. It was discovered that the circuit had two main drawbacks:

1. There was no common mode noise filtering.

2. The differential mode filter (R1-C1) was located on the low impedance side of the isolator.

A common mode filter is required because of the parasitic capacitance of the optical isolator package. This capacitance is only a few picofarads, but is quite sufficient to couple hundreds of volts into the logic circuits when 2000 volt pulses with 100 nanosecond rise time are present at the input.

Differential mode filtering is required to eliminate contact bounce noise and to minimize the effects of unbalanced common mode noise. The test indicated that the differential mode filter should be moved to the output side, or high impedance side, of the isolator. This way, better noise protection for the input of U1 is provided, while requiring smaller and less expensive filter components.

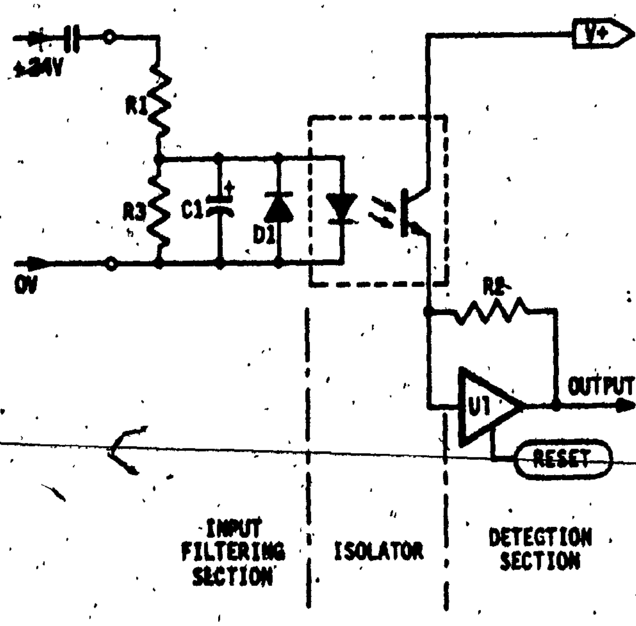

Figure 4.1 - Basic Digital Input Circuit

The revised digital input circuit is shown in Figure 4.2. The value of C1 was reduced to provide high frequency differential noise filtering only, while the main digital input filter is comprised of resistor R4 and capacitor C3. Capacitor C3' is shown as the electrical equivalent C3 while U1 is off, which is when filtering is required.

The parasitic capacitances of the optical isolator package are shown as Cp, and ceramic capacitors C2 and C4 provide common mode filtering for the photo-transistor collector and emitter circuits, respectively.

To further decouple the input circuits from the rest of the logic circuits, a power supply filter consisting of resistor R5 and electrolytic capacitor C5 was included.

The modified digital input circuit was tested extensively using a high-voltage tester (up to 5000 volt pulses), and it was found that the circuit performed much better. However, there was still a problem with noise in the reset line. With reference to Figure 4.2, it can be seen that filter capacitor C3 is connected in a positive feedback configuration. While this circuit gives excellent filtering against noise which would attempt to turn on the latching buffer U1, it did not offer any protection against noise on the reset line.

A new circuit was therefore devised and is shown in Figure 4.3. The circuit changes are deceptively simple. Filter capacitor

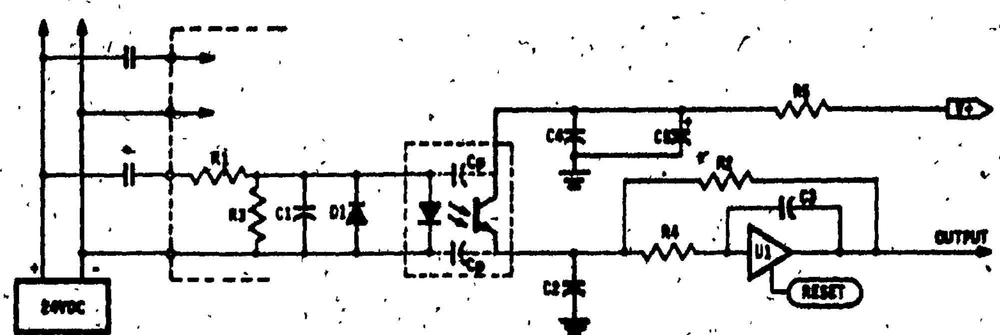

Figure 4.2 - Revised Digital Input Circuit

C3 is now connected to ground, which provides a definite memory of an on-condition as well as an off-condition. Since the reset time constant needs to be much shorter than the latch-up time constant, the diode D2 was added, by-passing resistor R4 during the discharge of capacitor C3.

The new circuit was tested and found satisfactory.

A new prototype board was built, complete with 16 channels of digital input circuits of the final Figure 4.3 configuration. Also, a larger high-voltage noise tester was built, capable of providing higher power output pulses, and this tester was used to test the new digital input board in an actual supervisory control system under on-line computer control.

The tests showed that with regard to noise rejection capability, the new digital input board has the following properties:

- High frequency and low frequency common mode filtering up to 3,000 volt* pulses with 100 nanosecond rise time.

- DC isolation up to 4,000 volts*

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* These figures apply to the actual circuit elements. When mounted on a PCB, the PCB edge connector spacing permits operation up to 1500 to 2000 volts only.

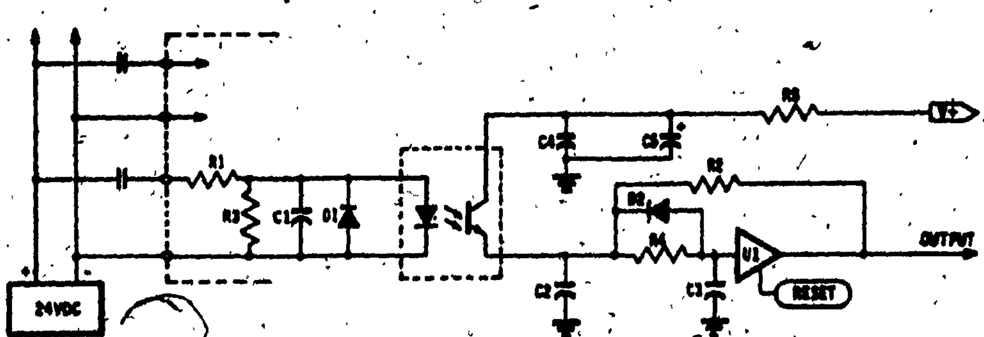


Figure 4.3 - Final Digital Input Circuit

- High frequency and low frequency differential mode filtering up to 1,000 volt pulses with 100 nanosecond rise time.

- Continuous over-voltage protection up to 140 volts AC or DC.

During the tests at IREQ an "old" and a "new" digital input board were used in order to obtain a qualitative evaluation of the two circuits with respect to actual field conditions.

A reliability calculation has been made for the "new" digital input board, and this calculation indicates an MTBF of approximately 300,000 hours, or about 30 years. For further details see Appendix 1.

5.0 MAGNETIC FIELD SENSITIVITY TESTS

5.1 Purpose of Tests

The purpose of the magnetic field test was to prove that the equipment can operate in the presence of magnetic fields of up to 1000 amperes per meter. In addition it was decided to go beyond this level in order to establish at what field strength equipment failure would occur, and to record this field strength as well as themode of failure. It was realized that this might be a destructive test since the failure mode was unknown. Therefore the tests were conducted very cautiously.

5.2 Test Set-Up

Figure 5.1 shows the test set-up for the magnetic field test, while Figure 5.2 shows the field strength curve relative to the three test positions. The magnetic field was generated by a 4 ft. x 4 ft. square loop, constructed from copper bars, connected to the 80 volt secondary winding of 32 KV step-down transformer.

The Remote Terminal Unit under test was first placed outside the loop and then inside. A total of 31 experiments was conducted with this set-up; the results of which are tabulated in Figure 5.3.

5.3 Test Results

The tests were started at low magnetic field strength, which was then gradually increased. The equipment under test showed no deterioration until a field strength of 30,000 to 40,000 amperes per metre was reached, at which point erratic operation

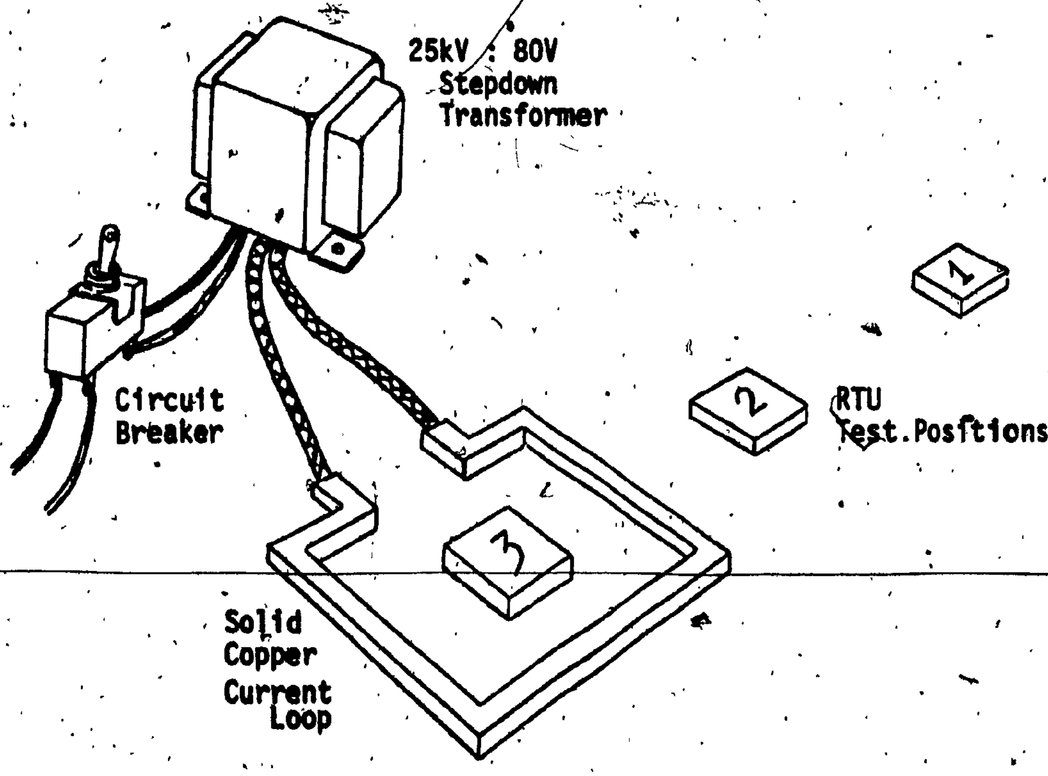


Figure 5.1 - Magnetic Field Test Set-Up

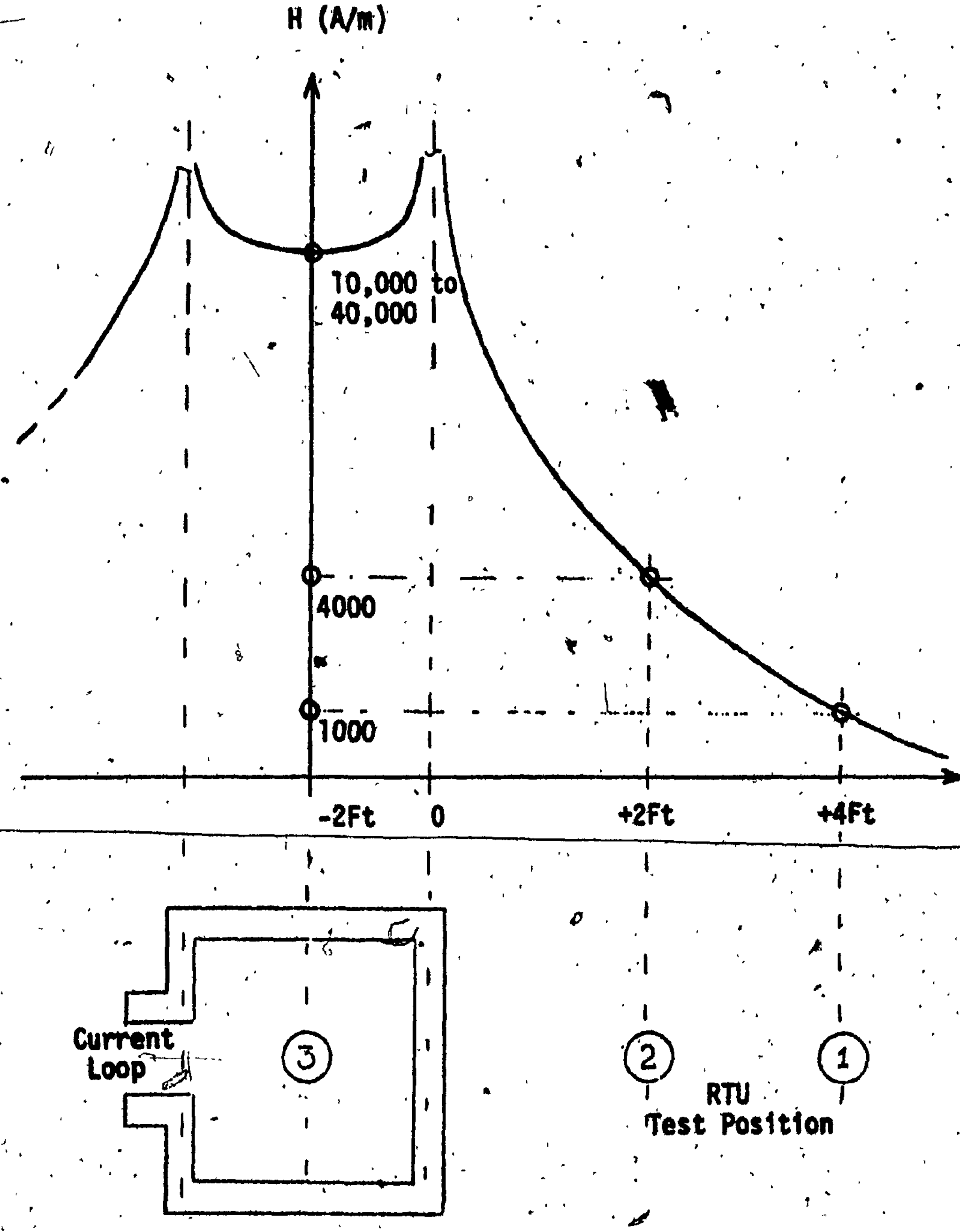


Figure 5.2 - Magnetic Field Strength Curve

TEST NUMBER	TEST POSITION	MAGNETIC FIELD	TEST RESULTS
1 - 5	1	1000 A/m	No interference
6 - 9	2	4000 A/m	No interference
10 - 11	3	10,000 A/m	No interference
12	3	20,000 A/m	No interference
13, 14	3	28,000 A/m	Reed relays energized
15	3	41,000 A/m	- Accumulators reset - Reed relays energized - Heavy duty relays reset - Front door locking bars were welded to cabinet
16	3	20,000 A/m	No interference
17	3	25,000 A/m	Reed relays energized
18 - 21	3	25,000 A/m	Direct magnetic interaction was confirmed
22	3	25,000 A/m	Steel shielding plates added. No more interference
23	3	25,000 A/m	Copper straps added, no interference
24	3	31,000 A/m	Heavy duty relay interference
25, 26, 27	3	31,000 A/m	Reed relays still o.k. with shielding plates
28	3	31,000 A/m	Steel plates were in, 8 straps on each side of door, o.k. for one second
29 - 31	3	31,000 A/m	Field calibration measurements only

Figure 5.3 - Table of Test Results from Magnetic Field Tests

of the relay output circuits was observed. (Tests 13, 14, 15). In addition, the secondary currents induced in the cabinet walls and door were so large that the paint around the hinges was smoking, and the locking bars on the door were welded to the cabinet.

At this stage, it was decided to repeat tests Nos. 13 and 14 to further investigate the erratic behaviour of the reed relays. Tests Nos. 16 to 21 proved conclusively that the high field strength (25,000 A/m) caused direct magnetic interaction with the reed relays.

A simple shielding test was then tried. Two galvanized steel plates were cut to size, and inserted into the slots adjacent to the reed relay board in the card case. Tests 22 and 24 showed that this shield was adequate to protect the reed relays from magnetic interference.

In the meantime, there were repeated problems with the door locking bars welding on to the cabinet during the tests. To overcome these problems copper straps were connected between the cabinet and the door at both the hinge side and the latch side, to better carry the circulating currents.

In the last tests, the field strength was increased to 31,000 A/m to test the heavy duty relays, and to test the shielding plates for the reed relays. When no copper straps were used, but the shielding plates were in place, (tests 25, 26, 27) erratic operation of the heavy duty relays was observed, but the reed relays were normal. In test No. 28, 8 copper straps were used on each side of the door. During this test, all was normal for one second, but then the screws holding the copper straps melted and fell off and the heavy duty relays showed signs of magnetic interference.

It was estimated that at this point, over 1000 amperes of circulating current was flowing through the door.

When the equipment was taken back to CAE for refurbishing, a length of tinned copper braid was soldered all around the inside edge of the cabinet door of the RTU, so as to give good electrical contact with the cabinet and eliminate the locking bar welding problems mentioned above. It is believed that this copper braid has also improved the overall shielding characteristics of the RTU cabinet.

6.0 TESTS ON EFFECTS OF DIFFERENTIAL GROUND POTENTIALS

6.1 Introduction

Differential ground potentials are usually caused by large fault currents in the ground mat, resulting from lightning strokes or short-circuit faults. The amplitudes can reach several kilovolts, but the duration normally is fairly short, typically several milliseconds.

The effects of differential ground potential surges on electronic equipment are equivalent to raising or lowering the input/output signal levels by several kilovolts and may cause component breakdown or insulation flash-over.

6.2 Purpose of Test

This test was designed to verify if the different RTU external links were properly isolated and protected against voltage bursts. The ultimate goal was to prove that the RTU and its associated system will not be affected by lightning or by high voltage induction onto the external connections. The test was divided in two parts:

a) "VELONEX" tests

b) Isolation test

6.3 Test Equipment

6.3.1 "VELONEX" Test

The term VELONEX is the name of a test equipment that can produce variable pulses up to an amplitude of 20 kV. The output pulse simulates a normalized curve that represents the effect in voltage and shape of lightning. This output pulse can be varied in four different ways:

1) Variable amplitude
2) Variable pulse width
3) Variable pulse shape
4) Variable pulse repetition rate

6.3.2 "ISOLATION" Test

This test was simply done using the output of the secondary winding of a transformer. The output could be varied from 0 to 1.5 kV RMS and was applied for one minute. This signal was applied to all the different inputs mentioned in the test procedure below.

6.4 Test Procedure

The output of the "VELONEX" or the transformer was applied to different types of circuit boards, namely:

1) Digital Input
2) Digital Output
3) Analog Input

The potential was applied:

a) between ground and input/output
b) between two inputs/outputs

6.5 Test Results

The test results for the different types of printed circuit board (PCB) are given below:

6.5.1 Pulse Test "Old" Digital Input PCB

Pulses of varying amplitudes were applied between the input terminals and the power supply ground (i.e. across the optical isolators).

- With up to 600 volt pulses, no effects.
- From 600 to 1500 volt pulses, several latches latched up, and some were reset.

6.5.2 "New" Digital Input PCB

- With up to 1500 volt pulses, no latches were set or reset.
- This test proved that the new digital input circuits were a substantial improvement over the old ones.

6.5.3 Digital Output PCB (Relay Driver)

Variable amplitude pulses were applied between the contacts and the power supply ground (i.e. across the relays).

- With up to 2000 volt pulses, there was up to 5 volts of noise on the collectors of the relay driver transistors, but there were no observable effects on the rest of the circuitry.
- When 2000 volt amplitude was reached, the PCB fingers arced over, and one power supply failed. It was subsequently discovered that the flashover transients had destroyed the power supply regulator. No damage was sustained by the digital output board itself.

6.5.4 Analog Inputs

Both positive and negative spikes were capacitively coupled and added to a normal input signal. A series of twenty readings from the channel under test was taken and correlated for errors.

- With up to 1 kV pulse amplitudes, there were no errors and no component breakdowns.

6.5.5 A.C. Isolation Tests

Up to 1500 volts RMS, 60 Hz was applied between the inputs and power supply ground of the new digital input PCB.

- Below 1500 volts, there was up to 4 millivolts of noise after the isolators.
- At 1500 volts, the PCB fingers flashed over, all the inputs latched up, and one isolator was damaged.

It has thus been proven that input voltages in the 1500 to 2000 volt range will cause PCB flashover, and this represents at present the upper limit for satisfactory performance of the equipment.

6.5.6 A.C. Overvoltage Tests of Digital Inputs

A 60 Hz voltage was applied in lieu of a relay contact input, and the input current was monitored. This test caused A.C. current to flow through the input circuits, including the optical isolator, and was carried out to test the circuit's ability to withstand accidental connection to the 120 V AC line.

The input voltage was increased up to 140 volts RMS, which would nominally cause a power dissipation of 8 watts in the 2400 ohm, 1 watt input resistor. However, as a result of the properties of Carbon Composition resistors, the resistance value increased to about 6400 ohms, thus reducing internal power dissipation to 3 watts, which the resistor was capable of sustaining for several days. When the overvoltage was removed, the resistor recovered to its normal resistor value without any apparent damage.

From this experiment it was concluded that the input protection capabilities with respect to AC or DC overvoltage was adequate to protect against accidental application of 120 V AC or 129 V DC. (129 volts DC is a typical standby battery voltage available in electrical switchyards.)

7.0 SYSTEM TESTS IN A 735 kV SWITCHYARD (BOUCHERVILLE)

7.1 Purpose of Test

The testing of the prototype supervisory control system in the Boucherville 735 kV switchyard was the main test for the whole system. The preceeding tests had subjected the system to controlled amounts of known types of electrical interference, while this test included both electric and magnetic interference, radiated and conducted and in unknown and uncontrollable quantities. The purpose of the test was to prove the operation of the prototype system under the most adverse noise conditions available.

7.2 Test Procedures

The basic plan was to install the RTU below the 735 kV line disconnectors, and to verify that, as the preliminary tests indicated, the weak spots in the system design had been eliminated.

Bearing in mind the potentially destructive effects of high voltage noise spikes, the RTU was first located some distance away from the line disconnectors (which were feeding into 100 feet of line) while subsequent tests were carried out directly below disconnectors feeding into 2000 feet of line (See Figure 7.1)

All the tests were performed at Hydro Quebec's Boucherville Sub-station in bitterly cold weather during the period November 1973 to January 1974.

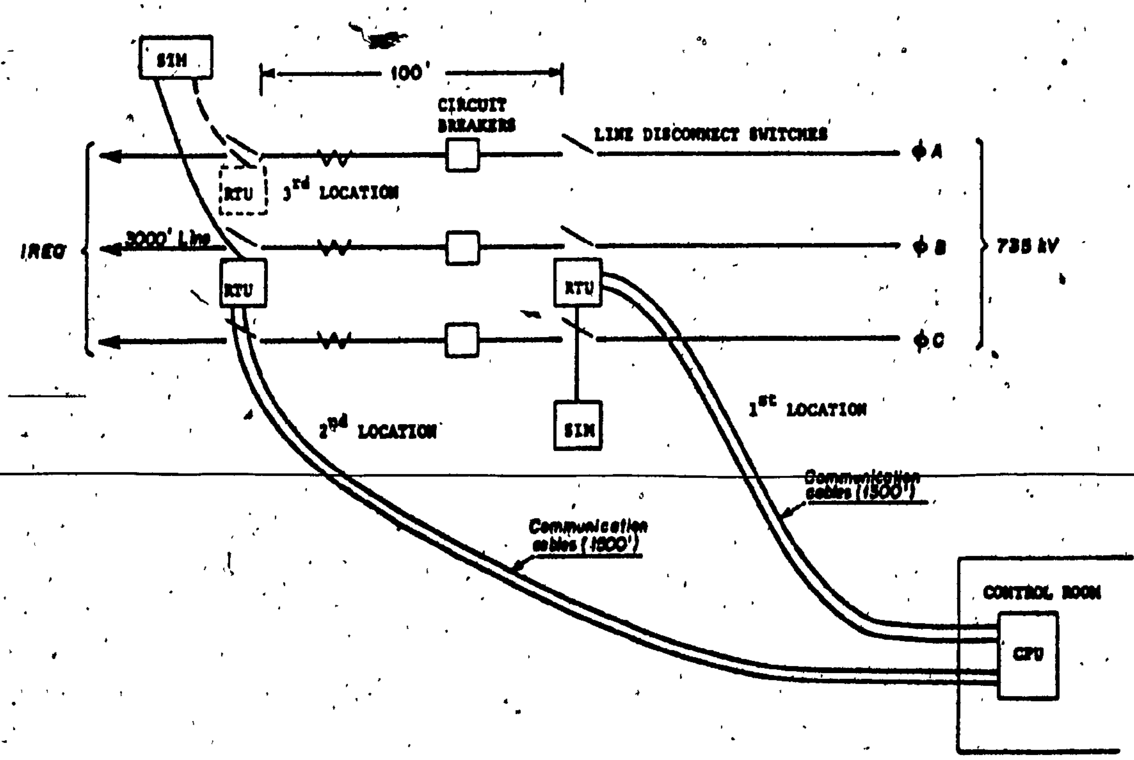


Figure 7.1 - Boucherville Station Test Set-Up

7.3 Test Results

7.3.1 TEST NO. 1

The RTU was located adjacent to 735 kV 3-phase line disconnect switches, operating into 100 feet of line. When the disconnectors were opened, large arcs were created but no problems were experienced.

For the next tests, the RTU was moved directly below the disconnectors, which were operating into 2000 feet of line. This test created much more severe arcing and interference, and caused a number of failures:

- "No response from RTU" was printed out by the computer. (This indicates a communication problem.)
- A power supply failed.
- Flash-over was observed between the communication cables and metal structures in the control building.

To overcome these problems, spark gaps were installed at the communication line interfaces and at the power supplies. The power supply which failed was repaired. (The integrated circuit regulator was open-circuited.)

7.3.2 TEST NO. 2

After the installation of spark gaps for the communication lines and the power supplies, the Supervisory Control System prototype was again tested below disconnectors operating into 2,000 feet of line.

No more problems were experienced with the communication lines or the power supplies, but it was observed that the communication line spark gaps were flashing a lot during the arc tests.

Before each test, a number of pulses was loaded into the accumulator registers, and a computer printout was produced to verify the exact pulse count. Also, several of the relay outputs were turned on via computer commands. After each test a new computer printout of the accumulator pulse counts was produced. These printouts showed a pulse count of zero indicating that the accumulator registers had been reset by the noise interference of the arcs (See Figure 7.2).

By visually examining the relay output indicator lamps, it was observed that the relay outputs were also reset by the noise. The loss of information from the accumulator registers and the control output registers represented a potential failure of the prototype equipment. It remained to be established if it was a limit failure in the sense that it represented an upper limit of operation in high-noise environments, or a total failure, in which case a 'fix' had to be found.

7.3.3 <u>TEST NO. 3</u>

In order to learn more about the failure mechanism involved with the loss of accumulator and relay output information, the RTU was moved back about 75 feet from the disconnect

		No. of Pulses Counted	Time
BEFORE TESTS			
*B PTN: 1,			
ACCUM. #01 :	00*100 ;	45*1	14:22
*B PTN: 2,			
ACCUM. #02 :	00*100 ;	49*1	14:23
AFTER TESTS			
*B PTN: 1,			
ACCUM. #01 :	00*100 ;	00*1	14:28
*B PTN: 2,			
ACCUM. #02 :	00*100 ;	00*1	14:28

Figure 7.2 - Pulse Accumulator Printouts

switches, and after the accumulator and relay output registers had been set, the cables between the RTU and the field simulator were disconnected.

When this configuration was tested, it was found that the accumulator information was still lost, but the digital output relays did not reset. These results indicated that the accumulator circuits were more sensitive to interference than the digital output circuits.

The field simulator cables were then re-connected to the RTU, and the test repeated, and this time both accumulator and relay output informations were lost. The noise therefore seemed to be coupled (at least partly) via the input/output cables.

For the next test, ground isolation resistors were inserted between the logic ground and the relay ground of the digital output boards. When the modified boards were tested, most of the relays were still reset, but not all. In other words, some noise was coupled via the ground lines, but not all.

Although these tests did not completely pin-point the failure mechanisms involved, the main suspicion was that the noise on input/output cables was coupled to the respective reset lines and caused the reported malfunctions.

8.0 REDESIGN AND RETEST

The Boucherville tests had pointed out two weak areas in the prototype system design, namely the accumulator reset circuits and the digital output board memory register reset circuit. However, the actual failure mechanisms involved were not well understood. The logical next step was to carry out additional tests in a better controlled environment to obtain further information.

A series of tests was therefore carried out in the 25 kV arc test cell at IREQ's high power lab.

8.1 High Power Lab Arc Test

The test equipment included a pair of "horns", between which a voltage was applied, so that an arc, about 8 feet long, was created. These arcs represented a less severe environment than that encountered at Boucherville and did not shed any further light on the problems with the accumulators and the digital outputs.

The enclosed polaroid photographs and sketches in Figures 8.1 to 8.3 show the test equipment and one of the arcs.

8.2 Redesign Approach

8.2.1 Pulse Accumulator Module

The pulse accumulator module had been designed for flexibility. It could be configured as a two-channel, four-digit module (count to 9999) or as a four-channel 2 digit module (count to 99) with pre-scaling of the input pulse frequency for each

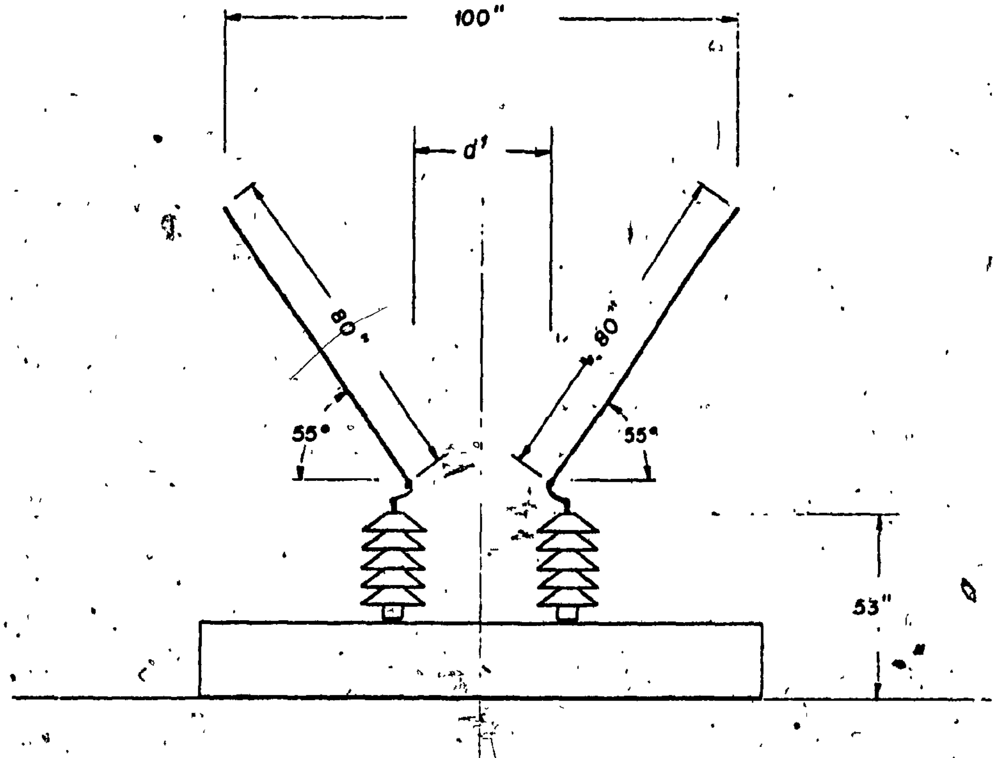
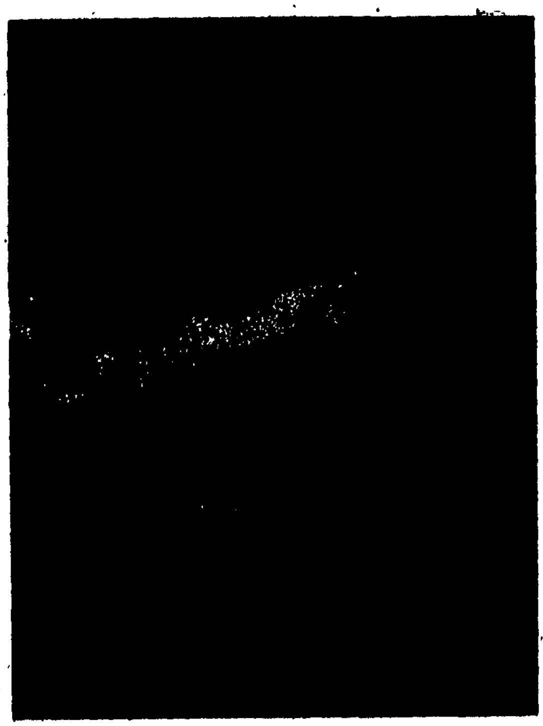


Figure 8.1 - "Horns" Physical Layout

[redacted]

[redacted]



[redacted]

channel by a factor of 10, 100, 1000, or 10,000. Furthermore, the accumulator counters could be reset when power was first turned on, and/or each time the count status was transmitted to the master station, and/or by a programmed reset command either manually initiated or initiated from the computer via a digital output relay. All these different options were programmed with wire links on the front connector, so that the printed circuit boards themselves were identical and interchangeable for replacement purposes.

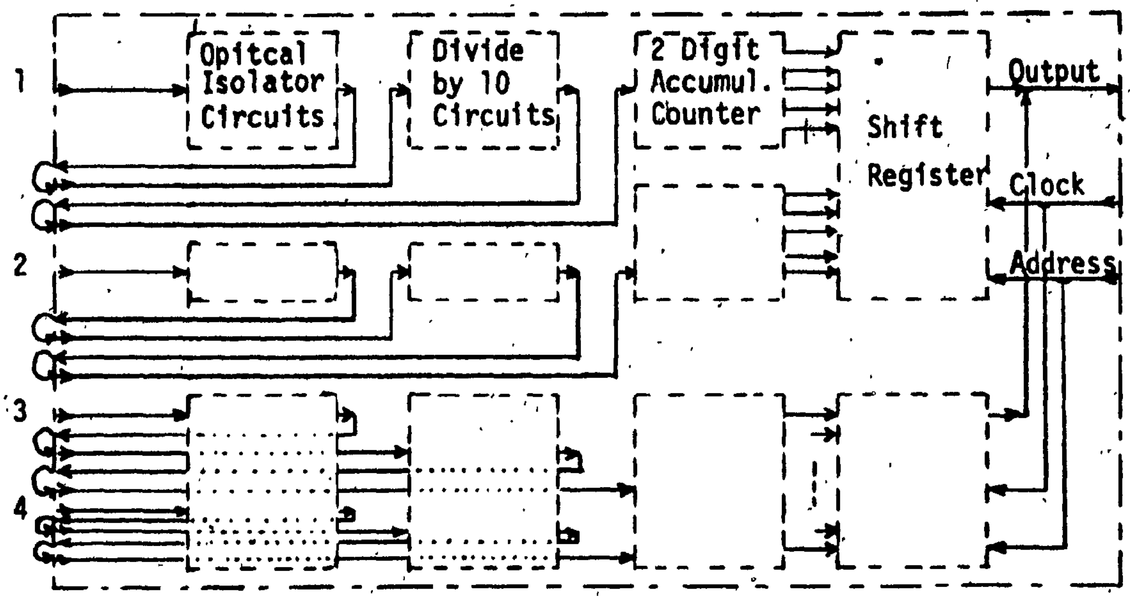
But, the front connector was also used for the pulse input wires, and thus there was a distinct possibility that noise on the input wires coupled into the reset lines, causing a loss of information.

One accumulator channel was therefore completely re-designed so that programming was no longer done on the front connector, and in addition, the programmed reset input was completely filtered and decoupled on the PCB. The other channel on the accumulator board was partially modified to allow a comparison between two possible modifications.

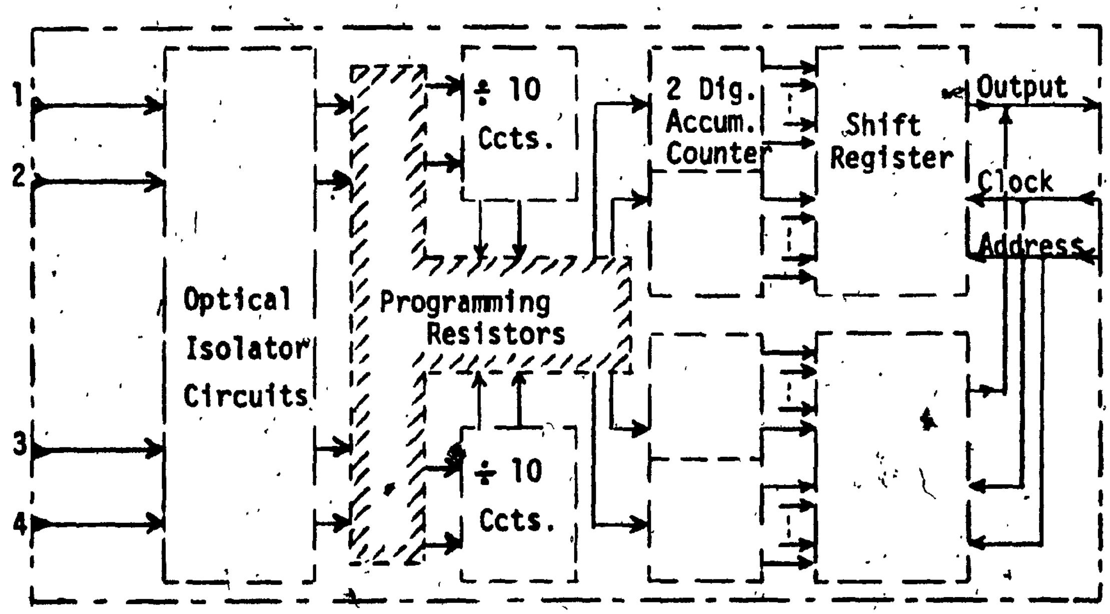
The sketches in Figure 8.4 show how the modifications were done.

8.2.2 Digital Output Module

The digital output boards had only one reset signal, namely the "Power-On" reset signal (sometimes called "Master Reset").



(a) Before Modifications



(b) After Modifications

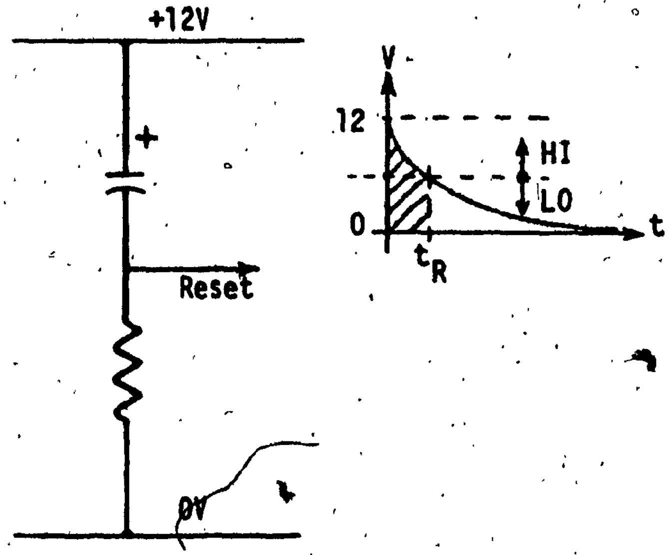
Figure 8.4 - Pulse Accumulator Layout Sketches

This signal was generated at the junction of a capacitor connected to +12 volts, and a resistor connected go ground, so that when power was first switched "on" this junction would be at "Logic High" until the capacitor charged up enough to reach a "Logic Low" level. To increase the noise immunity of this reset line, it was desirable to decouple the line to ground with a capacitor. This could not be done with the existing circuit, and therefore the reset circuit was reversed, and an inverting gate added to return to the original signal polarity. The output of this inverter was decoupled with a high-value ceramic capacitor, ensuring high-frequency decoupling, as shown in Figure 8.5.

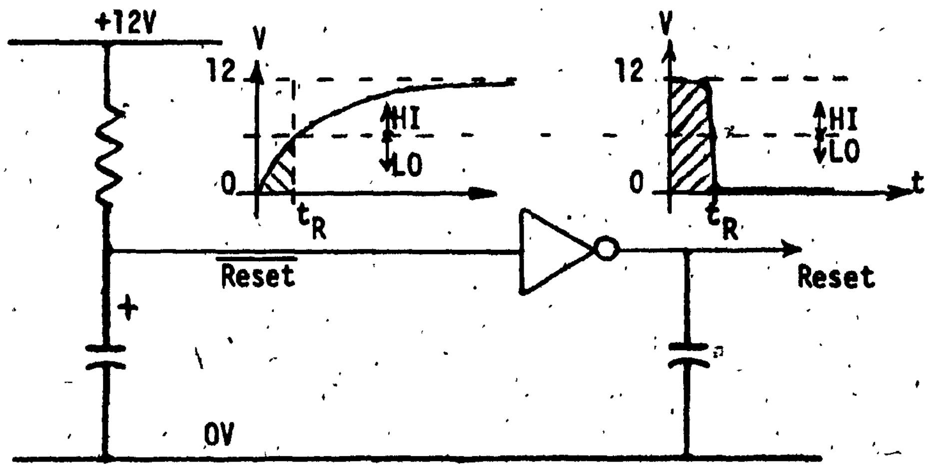
8.3 Retests at Boucherville

After these modifications had been made, the supervisory control system prototype was returned to Boucherville for further tests. As the picture in Figure 8.6 indicates, the RTU was again placed directly below the line disconnectors operating into 2000 feet of line, and this time no failures occurred in redesigned circuits.

The accumulator channel which had only been partly modified did no longer reset, but counted erratically during the arcs, indicating that the reset problem had been masking a pulse input sensitivity problem. The channel which had been completely modified, did neither reset nor mis-count. It was thus shown that well thought-out circuit design and layout modifications had successfully cured the initial problems.



(a) Original Reset Circuit



(b) Modified Reset Circuit

Figure 8.5 - Digital Output Module Reset Circuits

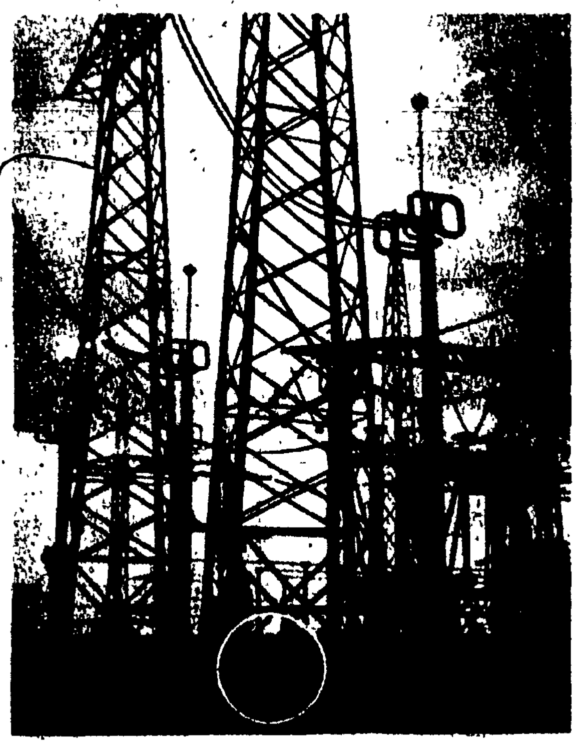


Figure 8.6 - Boucherville Arc Tests

9.0 CONCLUSIONS

9.1 Supervisory Control System for High Voltage Switchyards

The main aim of the development and testing program for the prototype supervisory control system was to prove that such a system could be developed to function reliably in the most severe electrical environments of today's High-Voltage switchyards.

With regard to the specific noise transients encountered under the 735 kV line disconnect switches in the Boucherville switchyard, it was found that such reliable operation could indeed be provided, and there was general agreement that the prototype system had passed the tests.

As described in this paper, several modifications had been made to the equipment in order to achieve satisfactory operation, and these modifications will be discussed below:

9.1.1 A series of tests in CAE's laboratories allowed the digital input optical isolation circuits to be refined until no failures could be generated with the available equipment.

9.1.2 A braided grounding strap was soldered onto the door of the RTU cabinet, to handle the very large circulating currents induced into the cabinet walls during the magnetic field tests in IREQ's High Power Laboratories. This gave a very good electrical connection between the door and the rest of the cabinet, and may have provided extra shielding for the equipment in subsequent tests.

9.1.3 Surge suppressors (spark gaps) were installed on the communication line and the power supply lines at the beginning of the Boucherville tests. Although these spark gaps were active during the tests (blue arcs flashing continuously), no surge suppressors were installed at the input/output terminals of the RTU, where provisions had been made for installing them if it had been necessary.

9.1.4 The Accumulator Board layout was redesigned to avoid noise on the input lines coupling onto the reset lines or counter input lines.

9.1.5 The Digital Output Board "Power-Up Reset" circuit was redesigned to permit the installation of a noise decoupling capacitor from the reset line to the power supply return line.

9.2 Testing of Prototype Supervisory Control System

The second expressed aim of the test program was to find the "weak links" in the prototype system, and correct the situation if possible.

Two such weak links were the Accumulator and Digital Output Boards; and the lessons learned with regard to separating input/output signals from logic signals, and careful design of sensitive circuits such as "reset" and "clock" circuits, are universally applicable.

The requirement for surge suppressors to protect power supplies and communication line equipment may or may not be regarded as a "weak link", but is certainly in accordance with accepted design practices.

9.3 Noise Levels in Switchyards

A paper by Hicks and Jones[2] was quoted in the Introduction, wherein the opinion was expressed that electronic equipment should be designed to withstand 3 kV noise voltages on input/output cables. However, the differential ground potential tests showed that voltage levels above 2 kV caused flashover at the edge connector terminals of some of the printed circuit boards. These terminals are located on a 0.156 in. pitch, and have 0.066 in. clearance between adjacent terminals.

An obvious remedy to this problem would be to use connectors whose terminals were spaced further apart. However, this requires large, clumsy and expensive connectors, and still does not eliminate the flashover problem when, as time goes by, dust and grime accumulate on the circuit cards, thus lowering the flashover threshold.

A more satisfactory solution is to use surge suppressors, which can be sized for the kind of environment that is expected in each application. The preferred type would seem to be the metal oxide varistors, which are compact, economical and have a long life. For example, a small surge suppressor can easily withstand up to 5000 volts transients in the 0.2 to 2 megahertz frequency range with source impedances below 100 ohms.

9.4 Circuit Design Techniques for Noise Immunity

The conclusions above deal with problems that arose during the test program, and their solutions. Below is a short list of design techniques that proved successful during the tests:

9.4.1 The use of COS/MOS integrated circuits probably helped a great deal to allow the prototype system to function well during the tests.

9.4.2 All the printed circuit boards use two connectors; a front connector for input/output cables, and a rear connector for the data/address bus interface. That way noise on input/output lines was not allowed to couple into the logic wiring.

9.4.3 The cabinet was a CEMA-1 type enclosure, and as it was properly grounded, it provided good shielding against radiated noise.

9.4.4 From the experiments with the digital input circuits, it was learned that an isolator may be an isolator at DC, but not necessarily at 2 MHz. A typical optical isolator may have a coupling capacitance of a couple of picofarads, while an open realy contact may have 5 to 10 pF. Good quality high frequency capacitors should be used to decouple high frequency common mode noise..

10.0 SUGGESTIONS FOR FUTURE WORK

10.1 Quantitative Noise Measurements

It is certain that the noise levels at the test site at the Boucherville switchyard were very high, but their exact characteristics were not measured. These characteristics would include peak amplitude, typical waveshape, characteristic resonance frequency and repetition rate.

Measurements should be made to determine transients generated by circuit-breakers as opposed to line disconnectors, and to determine effects of different cable types and cable routing methods.

10.2 Test/Evaluation of Surge Suppressors

Since surge suppressors are required in high-noise environments, different types and makes should be compared for voltage limiting capability, rate of response, expected life, failure mechanism, ease of replacement, etc.

10.3 High Speed Data Link

The data link used two D.C. Keyers operating a 20 mA current loop between MTU and RTU at a speed of 300 bits per second. It would be desirable to test such a communication link at speeds up to 9600 bits per second, and higher as well. The operating speed of a data link needs to be considered in relation to the type of error detecting or correcting code being used by the system. The prototype control system used a cyclic polynomial error detecting code with 8 check bits for 32 data bits.

10.4 Analog Input Long Term Accuracy

Experience has shown that long term drift of Analog Input measuring systems can be very serious, and could be adversely affected by noise voltages on the input lines. Such a study could be carried out with a computer on line to statistically analyze the incoming data and perform drift rate calculations in addition to calculating the normal statistical parameters.

10.5 Surge Voltage Generator

Such a generator should generate high voltage decaying oscillations from a low impedance source. It has apparently been difficult to achieve a low enough output impedance (50 Ohms is required) in this type of circuit (the oscillations should decay to 50% of the initial peak amplitude after 5 periods), and a thorough study of the problems involved would be worthwhile.

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(5) The Hydro-Electric Power Commission of Ontario, "Specification for Transient Interference Immunity Tests on Electronic Equipment". Ontario Hydro Designation No. C-5043-74.

(6) J.O. Tvedt, and V.V. Vaidya, "Supervisory Control Systems for Megavolt Environments", presented at IEEE, Canadian Communications and Power Conference Montreal, November 1974 IEEE Cat. No. 74 CHO 894-6 REG 7, pp 176, 177.

(7) J.O. Tvedt, V.V. Vaidya, D. Mukhedkar, "Noise Immune Digital Input System For High Voltage Switchyard Environment," presented at IEEE Conference, PES Summer Meeting San Francisco, July 1975. IEEE Conference Paper No. A75 557-9

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APPENDIX 1

RELIABILITY CALCULATIONS

A demonstration of system reliability was not part of this testing program. However, since the digital input modules had been subjected to a particularly rigorous testing sequence, it was reasonable to check the reliability of this module. The table below lists the average failure rates for the components of one 16-channel digital input module.

The resultant average MTBF for the digital input board works out to 282,500 hours if maximum component stress factors are considered. A calculation with the actual stress factors will tend to double the MTBF figure. The MTBF can be further increased by using MIL spec. integrated circuits rather than the industrial grade integrated circuits used in this project.

Qty	Description	Failure/in 10^6 Hours
24	Integrated Circuits	1.477
57	Capacitors	0.941
32	Diodes	0.416
81	Resistors	0.656
16	Jumper Wires	0.050
	TOTAL:	3.540

Therefore, module MTBF = 282,500 hours.

At the date of this writing, about 100 of these modules have been operating for about 7 months of full time operation without any failures. This corresponds to 5000 hours, or 500,000 module hours, which tends to confirm the predicted MTBF, especially when bearing in mind that the majority of the failures will take place during the later periods of the life of the equipment.