AUTOMATIC TESTING OF POWER SYSTEM PROTECTION RELAYS.

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SUMMARY

The paper outlines the development of a portable computerised protection test set by the C.E.G.B. in the U.K. for field testing of protection relays. Design principles are given for the hardware of the equipment and flow diagrams are used to demonstrate the software for testing distance type protection relays. Typical results produced by the equipment are given for tests on both phase comparison and distance relays. Details are presented to show how the equipment by virtue of the way in which test signals are produced can be used to simulate complex waveforms such as those which occur during power swings or the D.C. decrement on fault inception. Finally operating experience with the equipment in the C.E.G.B. is presented.

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1. INTRODUCTION.

Modern high-voltage power systems need secure high performance protection devices which have a high speed of operation for internal system fault conditions and a high level of discrimination between internal and external system faults. To achieve the high performance required by the power system modern protection devices have, of necessity, become more complex, resulting in larger numbers of diverse types of electronic components being employed. This increase in component count inherently increases the probability of a random component failure causing protection mal-function. In order to guard against this, relay manufacturers have adopted stringent design constraints, manufacturing procedures and testing techniques, which historically has resulted in a very low level of component failures. Nevertheless, these failures can still lead to incorrect protection system operation even when applying protection relays in a 1 out of 2 tripping arrangement. Power system supply authorities periodically evaluate the condition of all protection systems to ensure no random component failure or wiring fault has degraded the protection performance

The need to guard against protection relay mal-function becomes increasingly more important to maintain system stability as power system loads increase. Traditionally this has meant that the power system plant is isolated and a series of secondary injection tests are performed by manual means on the protection relays. These tests and the results obtained are very dependent upon the time available for testing and the skill and familiarity of the test personnel with the protection relay being evaluated. Also this approach to protection evaluation can have an adverse effect on reliability due to human error causing damage or incipient faults in the protection. Additionaly, increased difficulty in obtaining access to power system plant for testing means that traditional techniques can no longer be considered adequate. The obvious solution to these limitations would be to automate the evaluation test process in order to obtain as much information as possible whilst minimising the human involvement. This would then enable the integrity of the system to be improved.

2. REQUIREMENTS OF AN AUTOMATIC TEST FACILITY.

The following requirements should be considered as a minimum for any automatic test facility used to evaluate a power system protection device.

Not degrade the protection reliability even in the event of a test facility failure.

Check the functional operation of the entire protection scheme or as much as is practicable, including the operate time.

Be easily interfaced to the protection relay being evaluated without risk of damage. This is particulary important if the test facility is removed after completion of testing.

Be capable of self-checking to ensure that the results are meaningful and be simple to use, thus avoiding human errors.

Aim to minimise the out-of-service time of the part of the power system protection under test, thus removing the need to take the protected plant out of service.

Rapidly accomplish the test program and present the information in a easily comprehended fashion so as to leave no doubt as to whether the relay under test is satisfactory or faulty.

Be capable of correct operation in the same enviromental conditions as the relay it is evaluating, electrical interference or surges should not cause damage or mal-operation.

These requirements could be met both by test equipment built in as an integral part of the relay, or relay scheme, or by a universal portable test set designed to be able to test more than one type of relay. The preponderance of relays installed on the CEGB system was of the type where built in test equipment was not available and the cost and upheaval of providing these facilities either in the relay panel or relay were considered prohibitive. Hence it was decided to develop a portable computerised test set for maintenance testing, the connection of the test set to the relay and the frequency of testing being determined by manual intervention.

As well as the requirements outlined above it was felt the equipment must be capable of testing relays to at least commissioning standard in a maximum time of 30 minutes. this performance it was considered would allow the testing of a relay by taking that relay out of service and leaving the primary plant still protected by the other main protections. Statistical analysis had shown that the risk of an uncleared or extended clearance system fault occuring where not significantly increased if the length of time for which a feeder was protected by one main protection was less than 2 1/2 hours per end per year. This meant that it was possible to perform a total of 10 tests on any combination of the 4 relays per year without taking the primary plant out of service. Thus the availability of the equipment would enable testing of relays to be performed more frequently than the yearly or two yearly primary plant outage period allowed.

3. MODE OF OPERATION.

The basic requirement for any relay test equipment is that the simulated power system quantities are changed until the required response of the relay is found. In normal test equipment the signals are typically derived from three-phase mains inputs, using variable transformers, etc., and manually adjusted until the relay operates.

In this test set, the test waveforms are produced mathematically by a computer. Digital to analogue converters are then used to convert these numerical waveforms into low level voltages, which are used to drive power amplifiers. These produce the necessary level of current and voltage to operate the relay. At the same time, the outputs of the relay are monitored by the computer so the effect of the injection is noted. Suitable strategies are used to change the injected signals until the required relay response is obtained.

The production of test signals by a combination of mathematical and electronic techniques allows complex current and voltage signals to be readily obtained. Thus this type of test equipment can more closely simulate power system disturbances than traditional test equipment.

The high speed of testing is achieved by the test equipment being "plugged into" test points available on the protection and injecting simulated power system signals into the appropriate voltage and current inputs of the relay. The various test points are then monitored as the injected currents and voltages are changed. Thus the equipment can ascertain and then display the characteristics of the relay. All of this is done automatically by the equipment, after the protection has been made available for testing by manually taking it out of service. The only involvement of the operator being to connect the equipment to the relay, inform the equipment which type of relay is to be tested, initiate the test, reinstate the protection to service and, most importantly, interpret the results to ensure the protection is healthy.

4. EQUIPMENT DESCRIPTION.

4.1 Hardware.

A block diagram of the equipment is given in figure 1. The computer is a propriety 16 bit word length machine, it is housed in a case and segregated from the rest of the equipment; this is to both improve the portability and to enable it to be shielded from the harsh electrical enviroment found in substations.

The injection part of the equipment is contained in a second case and is designed around commercially available power amplifiers. Four channels are provided, this number being the minimum required for testing of both phase comparison and distance type relays. For phase comparison relay testing three phase current is required, whilst for testing distance relays, a single phase current and three phase voltage is adequate. The switching of three of the power amplifiers between voltage and current sources and the phase selection of the fourth current source is performed by electromagnetic relays, which are controlled by the computer.

Negative feedback is provided around the power amplifiers to enable the equipment to maintain it's calibrated output when injecting relays of different burdens.

The protection interface is to enable the computer to monitor the relay during the test. It performs the function of conditioning the relay signals to the correct levels for the computer. More importantly, it provides surge suppression and electrical isolation, thus ensuring the safety of the relay during the test period.

4.2 Software.

The test routines are written in a compiled high level language thus easing the production of software and making the future enhancement of routines easier. Any software development necessary can be performed on the test set itself, no separate development system is necessary.

The method of producing waveforms to inject into a relay is based purely upon the mathematical description of the waveform, thus any complex waveform that can be mathematically described can be produced.

The speed of the software is such that four waveforms with 24 samples per cycle can be produced at 50 Hz., whilst monitoring one output from the relay. This allows a resolution of 0.833 mSec. on the measurement of relay operating times. The same performance can be achieved at 60 Hz. by using 20 samples per cycle. This reduction in sample rate having little effect on the purity of the injected waveforms, due to the action of the reconstituting filters between the D/A converters and the power amplifiers.

4.3 Test routines.

The routine which produces the injected AC signals is shown in flow chart form in figure 2. The inner loop of this routine is time critical in that it determines the frequency of the waveforms produced. As can be seen, each pass of the loop results in consecutive values of array A being output by the D/A converters. The loop is repeated 24 times (20 for 60 Hz.) to produce one cycle, and after each cycle a counter is incremented and compared with the desired number of cycles to be injected. The loop is only left if the desired number of cycles has been produced or if the digital input, which is monitored on every pass, changes state. This digital input is connected via the interface to a relay signal so that operation of the relay can be detected. The operate time of the relay can be found from the values of CYCLE and K when the routine is left.

The array A, which holds the instantaneous values of the waveforms at the sample intervals, has to be calculated before the injection routine is entered. It is formed using the set of equations:

$$A(K) = Va\ SIN(\omega K/4 + \phi a) + 2048$$

$$A(K+1) = Vb\ SIN(\omega K/4 + \phi b) + 2048$$

$$A(K+2) = Vc\ SIN(\omega K/4 + \phi c) + 2048$$

$$A(K+3) = I\ SIN(\omega K/4 + \phi i) + 2048$$

where ω is determined by the required frequency and sample rate of the waveform to be produced. The equations are shown for the production of three phase voltages and a single phase current, as used for distance relay injection, and are calculated for K=0,4,8,......92 (76 for 60 Hz.)

The magnitude of the D/A outputs is determined by the values used for Va, Vb, Vc, and I, 2048 giving the maximum output. The relative phase is determined by ϕa, ϕb, ϕc, and ϕi. The D/A converters are 12 bit devices scaled to use offset binary hence the addition of 2048 in the equations.

To test a relay the injection routine is used in conjunction with routines which vary the output of the equipment until the desired response of the relay is found. For finding the reach setting of a distance relay the injected waveforms are calculated so that the effective impedance presented to the relay is reduced until operation is found. The stategy used to achieve this is demonstrated in figure 3. Initially the faulted phase voltage and current are such that the impedance presented is at a maximum. If no operation occurs the subsequent injection uses an impedance reduced by the step size A. This is repeated until an operation is found. The next injection presents an impedance of B less than the last injection which did not cause operation. Injections continue using step size B until a second operation is found. Injection then starts above the second operation and continues using reductions of C on subsequent injections. This process is repeated using decreasing step sizes, thus enabling the operate level of the relay to be found with a high resolution with as few injections as possible. For testing distance relays it has been found that the use of five step sizes, each step size being 25% of that preceeding, gives the best compromise between speed and resolution. With phase comparison relays because of their smaller range of settings three step sizes are adequate.

The reduction in impedance presented to the relay can be achieved by two different methods:

1. by maintaining the injected current constant and reducing the faulted phase voltage
2. by changing both the injected current and the faulted phase voltage.

In using method 2 a source impedance has to be assumed in the calculation of the voltage and current. This is shown in figure 5 where Z1 is the impedance to be presented to the relay. The use of this method is limited by the maximum current which the equipment can produce (10 amps). Hence a minimum source-to-line impedance ratio occurs for a given relay reach below which this method can not be used. However, the main use of this method is in ensuring the correct operation of healthy phase crosspolarising circuits, which can be most easily tested with the low values of faulted phase voltage which occur for high source-to-line ratios. In both methods the healthy phase voltages are maintained at their nominal magnitude and phase relationship.

A flow diagram demonstrating the testing of a distance type relay is shown in figure 5. As can be seen it will find the reach of the relay at different phase angles between the faulted phase voltage and current. This allows the polar characteristic of the relay to be found.

5. TEST RESULTS.

Figure 6 shows the form of the test results produced by the equipment for a test on a distance type relay. In this case the ohmic reach of the relay is found for faults at the relays nominal characteristic angle in the forward and reverse directions. Thus both the calibration and directionality of the relay are proved. The reach of the relay in the resistive direction is also found using a source impedance which is selected according to the reach of the relay at it's characteristic angle. Knowing the source impedance and the reach of the relay the computer can then mathematically model the relay comparator and calculate what the reach should be in the resistive direction. Comparison of the actual and calculated reach then allows checking of the healthy phase cross polarising or whether the relay characteristic is tilted. These tests are repeated for each zone and phase of the relay.

The test continues by applying faults at 80% of the previously found reach of each zone and timing the operation of the relay. Checks are performed to check switch on to fault features and any acceleration or blocking logic included in the scheme. For a four zone phase and earth fault relay the total time for the equipment to perform these tests is twenty minutes.

Polar diagrams of the relay can also be found and an example is shown in figure 7. In this instance the thin line is the characteristic found by injection whilst the thick line is the characteristic the equipment has calculated that the relay should have at the source to line ratio used for injecting the relay.

Figure 8 shows part of the results obtained by the test routine for a power line carrier phase comparison relay. As well as measuring starter settings as shown the routine also checks starter operate, reset and dwell times. Further tests check the trip angle and ensure the correct operation of the carrier transmitter and receiver.

All of the results as shown are displayed on a CRT monitor as the various tests progress. After the test is complete the operator can recall the results to the screen or print them out on a printer or save them to the mass storage device on the equipment. (tape cartridge or disc)

6. THE PRODUCTION OF COMPLEX WAVEFORMS.

Injecting waveforms by continually cycling around one set of data values as shown in figure 2 in effect produces steady state waveforms. However by increasing the size of the array A such that it can contain an element for the whole sequence of instantaneous values in an injection and providing the waveform can be described it is possible to simulate transient phenomena. This is shown in figure 9 which is the output produced when the equation:

$$A(K+3) = e^{-\frac{R}{L}K} [-I\ \mathrm{SIN}(\theta - \phi i)] + I\mathrm{SIN}(\omega K/4 + \phi i)$$

is used to calculate the instantaneous values. By further adding the values produced by:

$$A(K+3) = I\ \mathrm{SIN}(\omega K/2 + \phi i)$$

to the array, the waveform shown in figure 10 is given. This output simulating a magnetising inrush condition.

Figure 11 shows the output when oscillatory currents such as occur during power swings are simulated. Outputs such as these have been used to investigate the anomalous pickup of starters in phase comparison schemes.

7. MANUAL TESTING.

Although the equipment was intended for automatic testing of relays, it can also be used in a manual mode. Routines have been written to allow continuous manual control of a particular parameter. This parameter can be:

Impedance presented to a distance relay (including or excluding the effect of source impedance.)

Phase angle between two output channels which can be either current or voltage.

Frequency of one channel variable between 45 and 65Hz.

Magnitude of three phase voltage or current.

In all of these programs, the variable parameter is controlled by "raise" and "lower" pushbuttons whilst fixed parameters are preselected by using a numeric keypad.

8. FIELD EXPERIENCE.

The initial conception and design of the equipment took place in 1982/83. The first test sets were used in the field in 1983 in the South Western Region of the C.E.G.B. for the maintenance testing of 2 types of modern static relay. At the present time in excess of 50 of the test sets are in use throughout the C.E.G.B. for both maintenance testing of existing relays and commissioning of new relay installations. Specialised interfaces and software have been produced for the fully comprehensive testing of a further 6 types of feeder protection relay, both of static and electromagnetic design. A further 2 software/interface packages are soon to be introduced to the field.

For testing the less common feeder protection relays found on the C.E.G.B system, where the cost of producing specialised software/interface packages could not be justified a generic program and general purpose interface are used. This allows automatic testing of any distance relay, again in a short period of time but it cannot test as thoroughly as can be achieved with the dedicated packages.

During the time the equipment has been used in the field a number of faults have been found with relays which if undiscovered would have led to non-operation or mal-operation on system faults. The faults which have been found have been both of component failure (of a random nature) and mal-adjustment or drift of settings. Some faults were of an intermittant nature and may have taken many years to find (if incorrect operation on a system fault did not show them up) if manual testing of 1 or 2 yearly frequency had still been the norm.

9. CONCLUSION.

The field experience with this equipment has shown that computerised automatic testing of relays has many advantages over manual testing, these include:

1. The speed of testing permits more frequent testing as tests can take place with the relay out of service whilst the primary plant is retained in service. This increases the ability to find relay faults before they can cause problems on system faults and thus leads to an increase in overall power system reliability.
2. The actual mechanics of executing the relay test procedure do not need to be performed by a protection specialist. Although of course the results produced by the equipment must be interpreted by a person with an intimate knowledge of the relay. This allows more efficient use to be made of skilled personnel.
3. Testing of relays is done to a common standard with the possibility of human induced errors and inaccuracies kept to a minimum.
4. The logistics of relay testing are eased by the use of one common equipment to test diverse types of relay.

10. ACKNOWLEDGMENTS.

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Figure 1
Block diagram of hardware

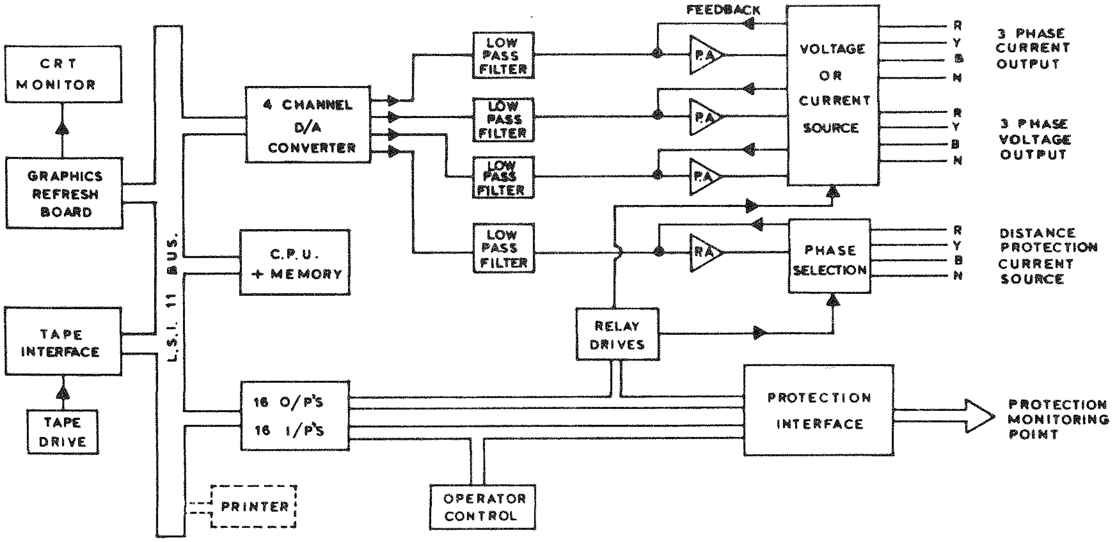


Figure 2
Injection routine

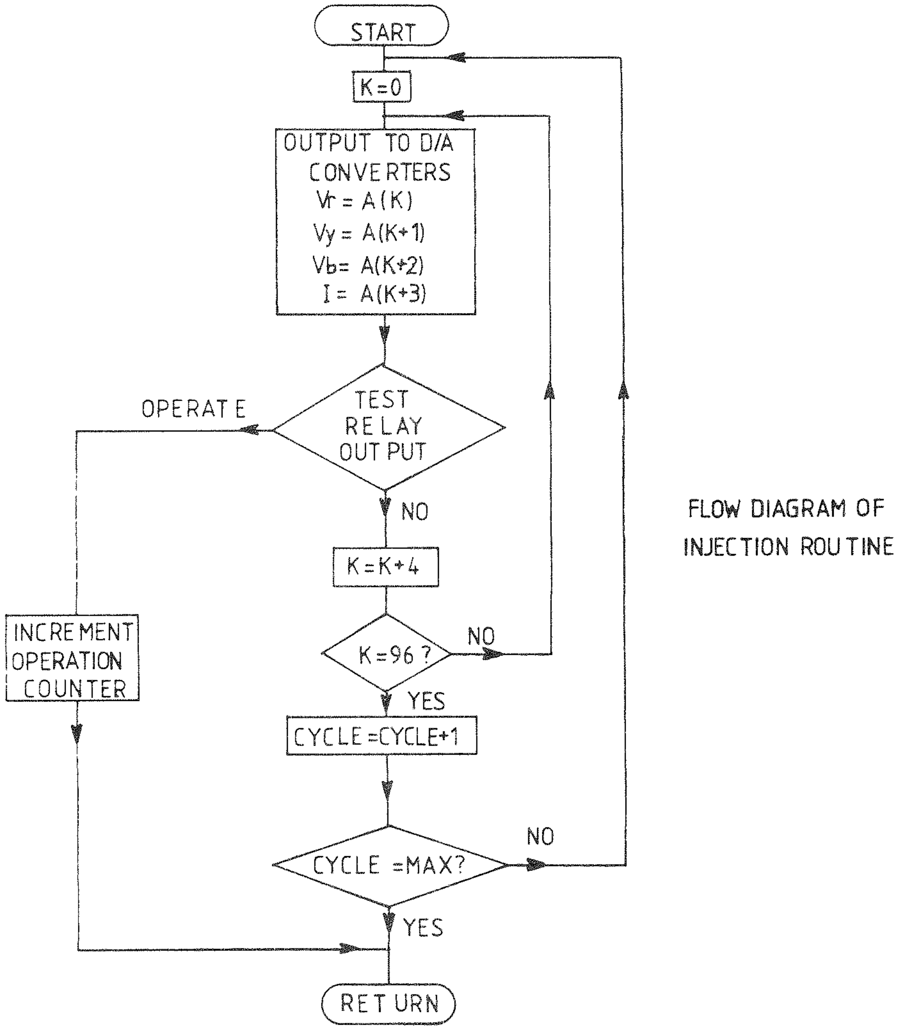
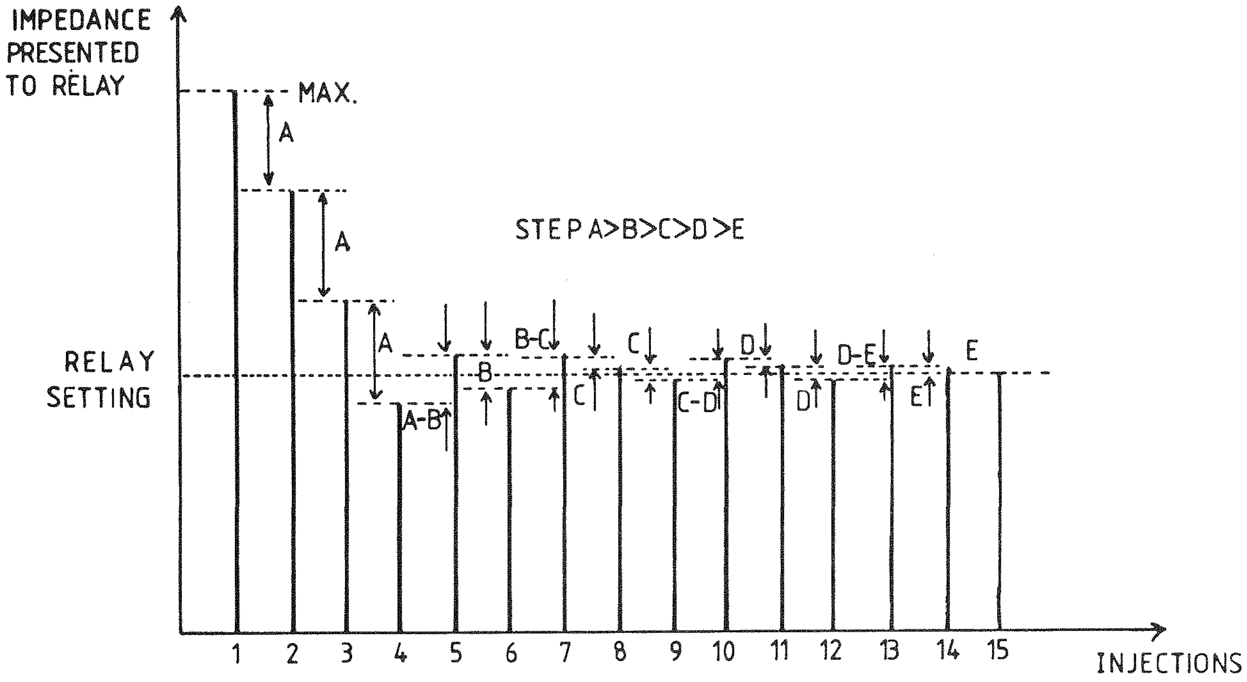
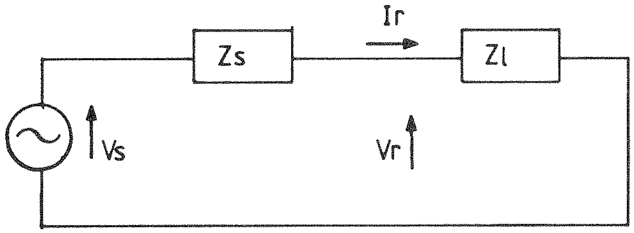


Figure 3
Strategy



DIAGRAMATIC REPRESENTATION OF STRATEGY FOR FINDING A RELAY SETTING

Figure 4
Calculation of volts & current



IMPEDANCE PRESENTED TO RELAY = $V_r / I_r = Z_l$

WHERE $V_r = \frac{V_s \cdot Z_l}{Z_l + Z_s}$

CALCULATION OF FAULTED PHASE VOLTAGE & CURRENT FOR UNBALANCED FAULTS

Figure 5
Finding distance relay setting

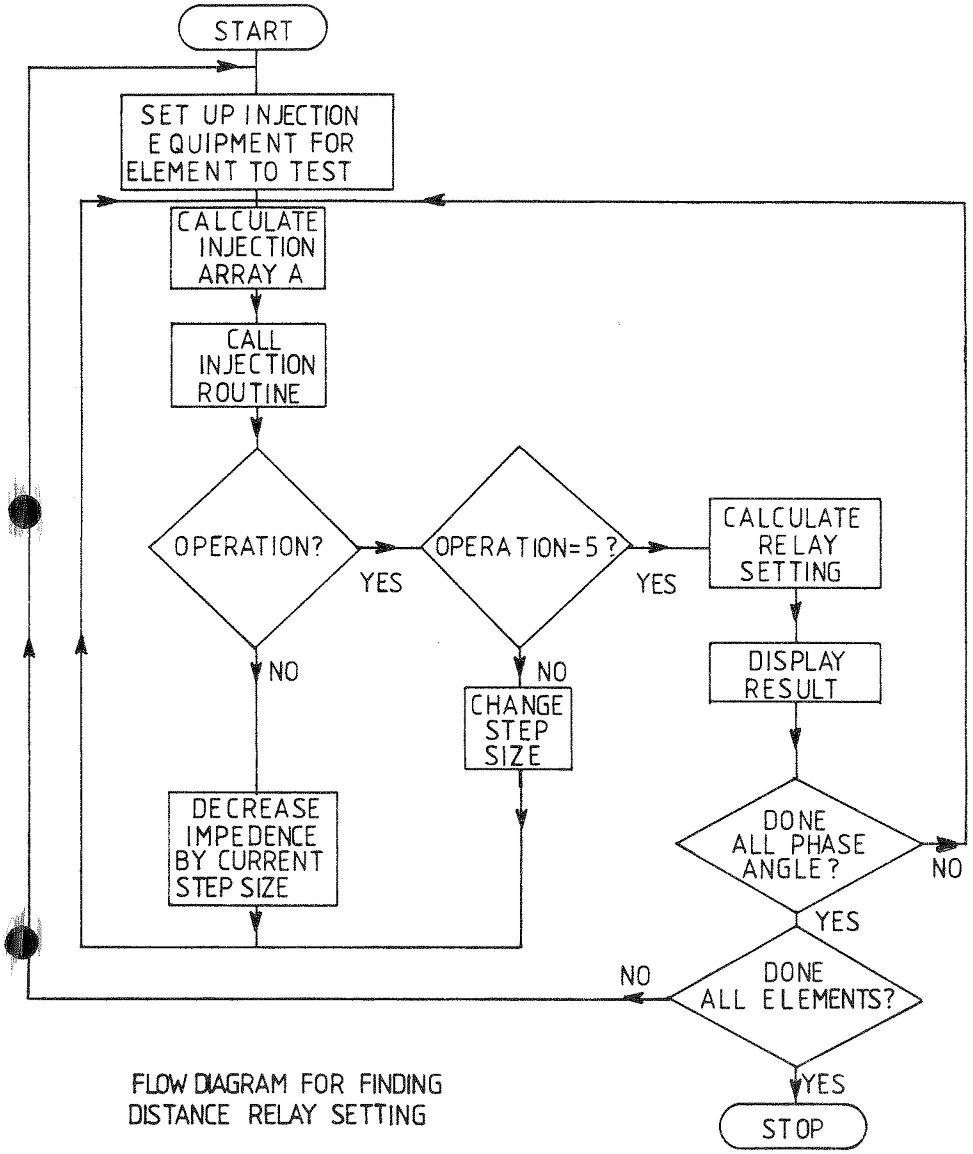


Figure 6
Reach tests for Distance Delay

```
           R-E ELEMENT

ZONE ONE
    9.66 OHMS AT    75 DEGS.
       NO OP. AT   255 DEGS.
    8.78 OHMS AT     0 DEGS.
    9.28 OHMS CALCULATED AT 0 DEGS.

ZONE TWO
   19.48 OHMS AT    75 DEGS.
       NO OP. AT   255 DEGS.
   13.08 OHMS AT     0 DEGS.
   13.68 OHMS CALCULATED AT 0 DEGS.

ZONE THREE
   29.22 OHMS AT    75 DEGS.
    2.44 OHMS AT   255 DEGS.
   12.42 OHMS AT     0 DEGS.
   12.58 OHMS CALCULATED AT 0 DEGS.
```

Figure 7
Polar diagram for Distance relay

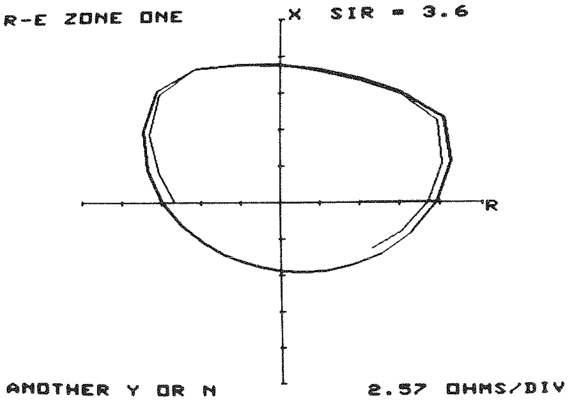


Figure 8
Setting tests for phase comparison relay

```
              P.P.S.  STARTERS
H.S.  SETTING =   30.9 %  LS.  OP.  OK.
L.S.  SETTING =   14.5 %
              N.P.S.  STARTERS
H.S.  SETTING =   10.5 %  LS.  OP.  OK.
L.S.  SETTING =    7.1 %
        NON-IMPULSE STARTERS
H.S.  SETTING = 19.7 %  LS.  OP.  OK.
L.S.  SETTING = 13.2 %
```

Figure 9
Output for 100% offset current X/R = 50

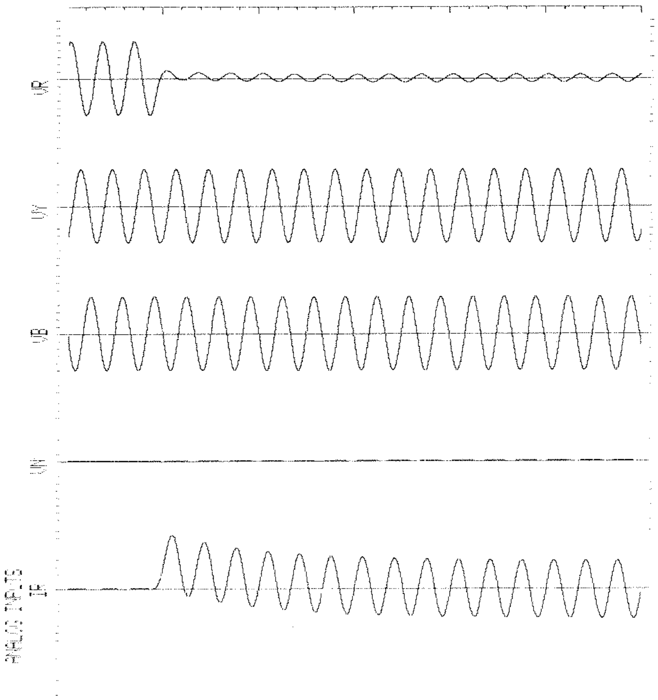


Figure 10
As Figure 9 but with 2nd Harmonic added.

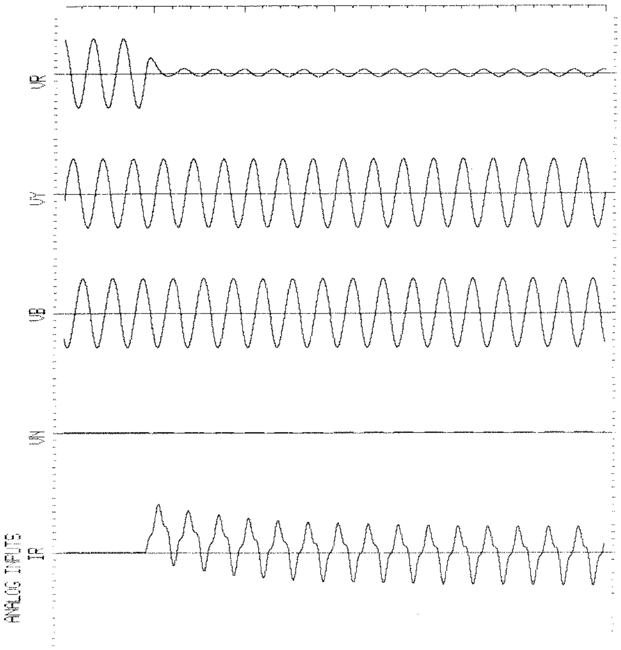


Figure 11
Output to simulate power swing conditions