DIGITAL OVERCURRENT RELAY WITH STANDARD CHARACTERISTICS

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ABSTRACT

In this paper, the implementation of a novel digital overcurrent relay with standard time-current curves is presented. The curves are modelled based on the direct data storage and curve fitting techniques. The relay is provided with several features to make it universal. The basis for selecting the sampling rate, scaling factors, analog and digital filter parameters are given. The relay hardware consists mainly of a data acquisition board interfaced with a digital processing board. The relay is tested for steady state and variable fault currents. The experimental results validate the efficacy of proposed digital relay performance.

Keywords: *Digital protection, Digital overcurrent relays, Modelling of overcurrent relays, Microprocessor-based overcurrent relays.*

I. INTRODUCTION

Over the past fifteen years several papers concerning the real time implementation of digital overcurrent relays (OCR) have been presented. The earliest one reported in the 1980s represented a digital thermal OCR used for the motor or cable protection [1]. This relay has been modified for feeder protection and generalised for various utility applications [2]. Although, this relay is provided with a standard time-current (t_r-I) curve in the form of a number of linear portions, the family of curves deviated from the standard ones [2]. On the other hand, the implementation of an OCR with an ideal inverse characteristics using a pre-defined mathematical form has been considered [3-6]. A look-up table with logarithmic values of fault current has been implemented in the microprocessor to overcome the complicity of the mathematical form [3]. Based on the same concept, a controlled gain amplifier is proposed to improve the relay resolution [4]. In order to account for the time variation in the fault current, a voltage to frequency (V/f) converter has been proposed in the implementation of a multi-curve OCR [5]. Although, the design and test results show agreement to the mathematical form [6], no means has been mentioned to assure that the tripping signal is based on the magnitude of the fundamental component only. In addition, two analytical models for the digital OCR have been presented [7,8]. Reference [7] is concerned with the real time implementation of an ideal inverse characteristic. On the other hand, reference [8] presents how a computer simulation can be used for the development of an OCR with standard characteristics. There exists a need to report the details of the development and implementation of a versatile digital overcurrent relay.

This paper presents the real time implementation of a digital OCR showing a good agreement between the proposed and the standard curves of the Westinghouse overcurrent relay type CO11. The relay can be adjusted easily to work at either 60 or 50 Hz. The curves are modelled using only one look-up table and a number of coefficients. The hardware of the relay includes a data acquisition board and a data processing board. The relay algorithm is adapted to account for the time variation of the fault current magnitude. Also, the resetting features of the relay can be instantaneous, linear, or

exponential with the possibility of changing the resetting time.

II. RELAY HARDWARE

The relay hardware consists mainly of a data acquisition board (DAB) interfaced with the digital processing board (DPB). The DPB board includes the Texas Instruments TMS32010 digital signal processor (DSP) in addition to a number of peripheral devices, e.g. a 12-bit A/D converter with an input of 10 V peak value, analog and 16-bit digital I/O ports, a clock, etc. Figure (1) shows the schematics of the relay hardware. The two oscillators are used to keep 16 samples per cycle, whether the specifying frequency is 60 Hz or 50 Hz. Four typical circuits are used for conditioning the three phases and the neutral current signals. Each circuit includes a low pass filter (LPF) cascaded to a scaling circuit and terminated with a sample and hold (S/H) circuit (LF398 with a holding capacitor 0.01μF). The four analog signals are then multiplexed and the output of the multiplexer (HI508) is connected to the digital processing board.

A. Logic Switches

The logic switches are employed to enable the operator to adjust the relay without going through the relay algorithm. Setting the logic switch high or low digitally can be interpreted to indicate the desirable setting. Six switches have been categorized for the adjustment of the time dial setting (*TDS*) value. So, 63 t_r-I curves can be accessed by the relay which permits a smaller step value of *TDS*. One switch is used to define the working frequency, high for 60 Hz and low for 50 Hz. Finally, eight switches are used for defining the desirable resetting feature and its speed of resetting. That is in addition to one push button switch used as a software-reset of the relay after tripping rather than the program hardware-reset switch which is used to reset the program itself to re-adjust the relay with new settings if required.

B. Analog Scaling Circuit and LPF

The scaling circuit is used to control the value of the output signal of the isolating current transformer. Changing the gain and/or varying the shunt resistor with the isolating transformer is equivalent to the changing of the current tap of the electro-mechanical relay. Also, if the neutral current is calculated from the phase currents, this gain will be helpful in substituting the errors arising from the difference in the current transformer (CT) characteristics.

The low pass filter is used to minimise the possibility of occurrence of aliasing in the digital system. This requires maximum pass band of the filter to be lower than the half of the sampling frequency (f_s) which is selected to be 960 Hz for this relay. As the t_r-I relations are based on the fundamental component of the current which may be 60 Hz or 50 Hz, a Butterworth filter is selected for this design. This filter permits a flat gain for the pass band, and has sufficient roll off characteristics. Also, the filter parameters are selected carefully to guarantee a fast response during switching to insure synchronization between the input and output signals. This factor, in particular, has substantial effect on the error associated with the small tripping time and the dynamic performance of the relay.

In order to satisfy all these requirements, a fourth order Butterworth filter consisting of two cascaded bi-quad circuits is found to be adequate for this task. One quad operational amplifier (LF 347) is employed per phase to implement the analog scaling circuit and the LPF. Fig. 1 shows the values of the filter parameters. The cut-off frequency for this filter is approximately 100 Hz.

III. ANALYTICAL BASIS OF OVERCURRENT PROTECTION

Usually, the magnitude of the fault current varies with time. To account for this variation, a general equation describing the tripping time-current relationship has been developed as [6,8],

$$\int_0^{t_r} \Psi(t).dt = 1 \qquad (1)$$

where $\Psi(t) = 0 \quad I < I_{pu}$ (minimum pick up value).

$\Psi(t) = 1/t_r(t) \quad I \geq I_{pu}$

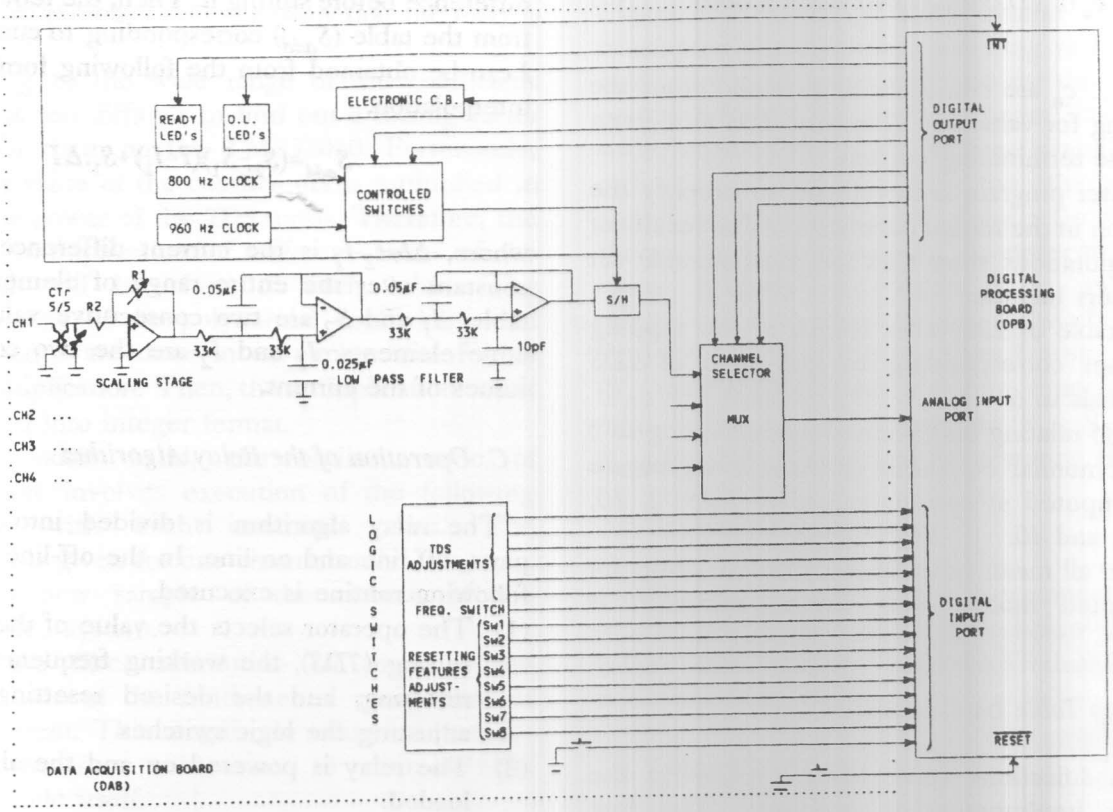

Figure 1. Schematic diagram of the relay hardware.

In (1), $t_r(t)$ is the tripping time of the relay corresponding to the current value I at instant t, and t_r is the overall tripping time. For a discrete system with a constant sampling rate of Δt interval, (1) can be re-written for $I \geq I_{pu}$ as,

$$\sum_{j=1}^{N} \frac{Q.\Delta t}{t_{rj}} = Q \qquad (2)$$

where Q is a scaling factor employed to guarantee execution of (2) on the fixed point microprocessor TMS32010, t_{rj} is the tripping time at sample number j, and N is an unknown determined from $N=t_r/\Delta t$

If the current value is greater than or equal to I_{pu}, the corresponding $Q.\Delta t/t_{rj}$ term is computed or obtained from a pre-stored look-up table. This value is added to a counter which is compared with the threshold Q to find out the tripping signal instant.

IV. RELAY ALGORITHM

A. Modelling of the Relay Curves

The standard curves of Westinghouse overcurrent relay type CO11 is selected to highlight the characteristics of the proposed prototype relay. The model of these curves consists of two parts [9]: *i*) stored table corresponding to one of the t_r-I overcurrent relay curves *ii*) a number of coefficients. The t_r-I curve corresponding to the stored table is taken as base curve and its time-current is denoted by t_b-I. In order to find the coefficients, all the tripping times of the twelve overcurrent relay curves are calculated as a time percentage (T_p) of t_b, i.e. $T_p=t_r/t_b$. Then, each T_p-I relation is approximated by a number of linear portions which are terminated at fixed current values for the twelve relations. This gives rise to develop a polynomial equation of *nth* degree to relate the T_p and *TDS* at each current value terminating the linear portions. The form of the proposed polynomial is given below as,

the microprocessor sends a high pulse to activate remote LED's to show that the relay is ready.

According to the wide range of the coefficient values, it is too difficult to find out a scaling factor suitable for them on the TMS32010. Fortunately, the lowest value of the coefficients is multiplied in the highest power of the *TDS* terms. Therefore, the results of multiplication of different terms of the polynomial will be close to each other. The representations of the polynomial coefficients and the *TDS* terms are done in an exponential format before multiplication. Then, the multiplication result is converted into integer format.

On the other hand, the on-line mode of computations involves execution of the following subroutine with each interrupt pulse. The description is given for one channel only.

(1) Get a new sample of the current of the protected system.
(2) Call the filter subroutine to compute the magnitude of the fundamental component of the current. This magnitude value is squared.
(3) Call the root subroutine to estimate the magnitude itself.
(4) Compare the current value with the pick up value. If the current value is higher than the pick-up value, send a signal to activate the overload LED's indicators (O.L.), and proceed to step (5). If not, send low signal to the (O.L.) and branch out to the resetting subroutine.
(5) Convert the current value into an offset jump in the look-up table and get the corresponding value of S_{add}, using (4), and add it to the counter.
(6) Compare the counter value with the Q. If the counter value is higher than the threshold, then issue a tripping signal. If not, wait for the next interrupting clock pulse and repeat again from step (1). The maximum required time to process the four channel during this mode is below 940 μsec.

If the current magnitude falls below the minimum pick-up value, then a resetting subroutine reduces the counter to the zero state according to the selected re-setting feature.

V. RELAY RESETTING FEATURES

Three resetting features have been provided to the relay algorithm which are instantaneous, linear, and exponential resettings. An adjustable resetting time is adapted for the linear resetting feature from 20 msec. up to 60 hours and also for the exponential resetting from 1 sec. up to 60 hours. The adjustable wide range of the resetting time simplifies the co-ordination of the relay with the other relay types, and shows the suitability of the relay for different thermal protection systems. In order to implement these features the eight logic switches are categorized into three groups, 2 switches (S_{w1} and S_{w2}) for selecting the resetting feature, 2 switches (S_{w3} and S_{w4}) for the resetting time (msec., sec., min., or hours.), and 4 switches (S_{w5}, S_{w6}, S_{w7}, and S_{w8}) for multiplication of the resetting time.

A. Instantaneous Resetting

If S_{w1} and S_{w2} are low, the instantaneous resetting is selected. If the current falls below the pick-up value, the counter will be reduced to zero instantaneously.

B. Linear Resetting

If S_{w1} is high and S_{w2} is low, the linear resetting is selected. Then, a fixed value will be subtracted from the counter as the current is below the pick-up value. Four values are stored in the program to bring the counter down from its maximum value to zero in 20 msec., 1 sec. 1 min., or 1 hour according to the read digital word from S_{w3} and S_{w4}. If the resetting time is required to be multiples from the previous values according to S_{w5}, S_{w6}, S_{w7}, and S_{w8}, the assigned value by S_{w3} and S_{w4} will be divided by the required multiple, stored and used during the on-line operation.

C. Exponential Resetting

If S_{w2} is high and S_{w1} is in any state, the exponential resetting is selected. A normalised exponential function is stored in the program in the form of five straight lines between time values of 0, 0.6, 1.4, 2, and 3 times the time constant of 1 second. If the selected resetting time constant is higher than 1 sec., the time values are multiplied to keep the same percentage to the selected time constant. To simplify the execution of the exponential resetting during the on-line period, the

subtracted value from the counter is kept constant, proportional to the initial counter value before resetting. On the other hand, the change in the slope of the straight lines with the time can be matched by varying the number of samples elapsed before subtracting the value.

VI. SAMPLING RATE AND SCALING FACTOR SELECTION

Equation (3) shows that increasing Q and reducing Δt will improve the accuracy of the data in the look-up table. Therefore, Q is selected with the maximum possible positive number which can be represented on the processor. This number is *7FFFFFFFH*. The sampling rate is selected to be *16* samples per cycle. This rate is relatively high compared with *4* samples per cycle in references [1,2,8], because the minimum value of t_r depicted by the standard curves of CO11 is approximately 20 msec. If *4* samples per cycle is selected, it will result in errors about 20% to 25%, and the resultant curves will take a strange shape. This will be very clear with t_r values below *0.1* sec.

VII. DIGITAL FILTER AND MAGNITUDE ESTIMATION

The Discrete Fourier Transform (DFT) algorithm is employed in the digital filter for this relay. The basic advantage of the DFT is the zero gain for both the dc component and the integer higher order frequencies. However, the estimated magnitude of the fundamental is obtained from the addition of the squared values of the sine and cosine terms. In order to get the amplitude itself, an iterative magnitude estimation is designed. This is summarised as follow:

(1) Multiples of *2* up to 2^n are stored in the RAM where 2^n is equal to or higher than one half the maximum expected value of the root.
(2) Start the iteration by assuming the root as 2^n. Then it is squared and compared with the resultant value from the filter subroutine.
(3) If the absolute comparison result is below the assumed root value, the root is 2^n. If it is higher or lower than the assumed root value, add or subtract 2^{n-1} from the assumed root, respectively and assume it as the new root.
(4) Repeat steps (1) and (2) with the new assumed value with consecutive reduction of n till the required root value is obtained.

The maximum number of trials to get the root at any time will be $n+1$ which is equal to 12 in this proposed relay.

VIII. EXPERIMENTAL SET-UP AND RESULTS

A. Steady State Fault Current Tests

The relay has been tested using the Universal Protective Relay Tester Model (*SR-51A*). It was loaned to the Faculty by the Newfoundland and Labrador Hydro. The maximum current rating of this tester is 500 A. Also, the timer counter can be adjusted to seconds or cycle range with two decimal number resolution. Ten msec. is the minimum measured time and it is also the rate of the counter increment. Therefore, the measured time less than 0.5 sec. was conveniently obtained by the oscilloscope. The tester current is converted into an equivalent voltage signal using an isolating CT having 5/5 ratio and a variable 0.3 ohm resistor is connected across the transformer secondary side. Figure (2) shows the measured and the standard curves of the overcurrent relay. From Figure (2), it is obvious that the relay tripping time is very close to standard characteristics. The deviation in the small tripping times is referred to the long window of the DFT which requires 16.66 msec. on 60 Hz basis, to define exactly the input signal. Also, similar results to that one given in Figure (2) are obtained for a simulated 50 Hz fault current.

Moreover, the relay is examined when the fault current has a dc offset, or when it has higher order harmonics. Figure (3) shows the effect of the dc offset on the relay performance. For the same relay settings and with a dc offset value equal to 100% of the fundamental peak, the tripping time is found to be very close to the tripping time for the same input magnitude without the dc offset as given by Figure (3). This feature shows the effectiveness of the relay in catering for the dc offset arising from the fault current, the current transducers, the operational amplifiers, etc. Also, the relay immunity against harmonics is tested. Figure (4a) depicts the relay behaviour for a simulated fault current of a square waveform. It has a fundamental component magnitude of 10.1 pu. However, Figure (4b) shows the delay time for a pure sinusoidal current of 10.1 pu. The recorded delay times are 0.348 sec. and

0.342 sec., respectively.

The resetting features are tested by accessing the stored number in the counter to the analog output port via an D/A converter. Figure (5) depicts the counter contents during an exponential resetting for a resetting time constant of 1 sec.

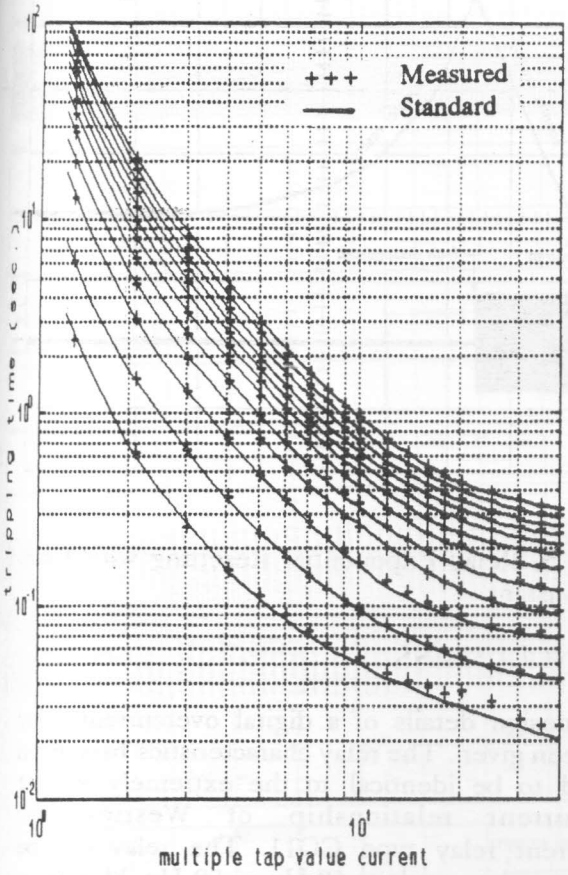

Figure 2. Measured and standard curves of the proposed relay.

B. Relay Dynamic Tests

The importance of the dynamic tests has been mentioned in reference [6,10,11]. The purpose of these tests is to measure the relay performance with a time variable fault current. To simulate this condition, the relay current is switched between two different levels with a constant modulation frequency. For this waveform of input current, the tripping time can be given in the following form as,

$$t_r = 2.\frac{t_{r1}t_{r2}}{t_{r1}+t_{r2}} \qquad (5)$$

where, t_{r1} and t_{r2} are the tripping times corresponding to each level individually.

The test circuit to realize this input shape consists of an ac voltage source shunted by two variable resistors connected in series, a clock signal representing the modulation frequency, and an analog switch (AD7590). The level magnitude and the speed of switching are controlled by the resistors value and the clock frequency, respectively. The relay is tested with different values of modulation frequency and current levels. The measured relay tripping times are very close to the calculated ones. This can be observed from Figures (6a), (6b), and (6c) which depict the tripping times for the individual low level, high level, and the switching between the two level inputs, respectively. In Figure (6c), the relay measured tripping

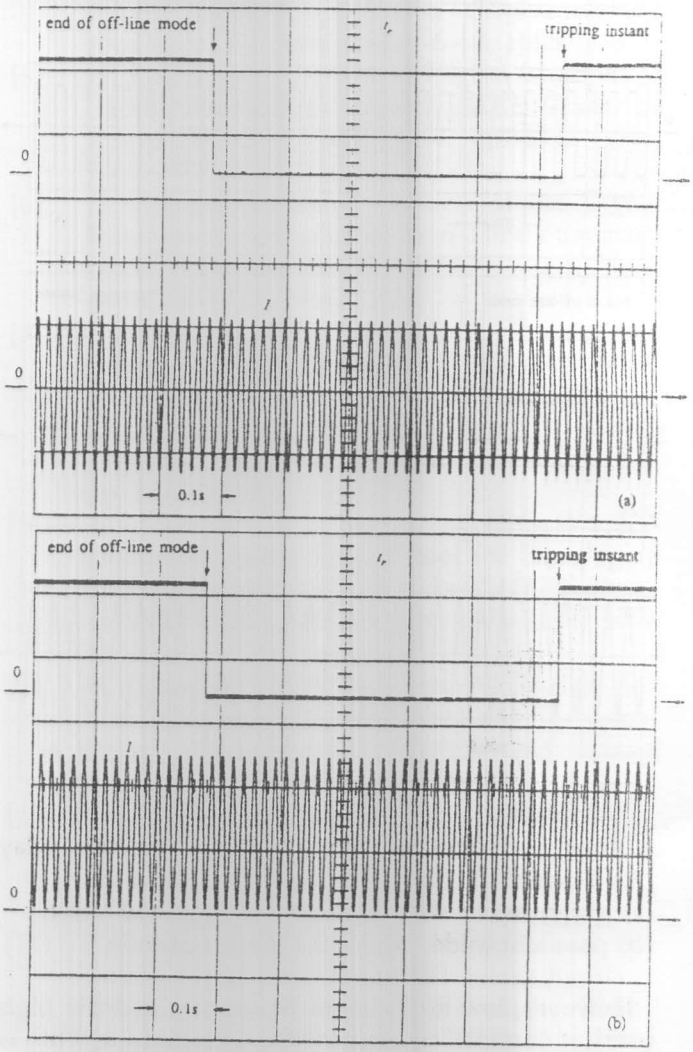

Figure 3. Effect of the dc offset on the relay. performance (a) pure sinusoidal (b) 100% dc offset.

time is 0.602 sec. for a modulation frequency of 30 Hz and current levels of 7.6 pu and 3.52pu. The tripping times for applying each level individually are 0.38 sec. and 1.44 sec. as given in Figures (6a) and (b), respectively. This yields expected tripping time of 0.601 sec. by manipulating the expression in (5). This shows excellent dynamic performance of the relay.

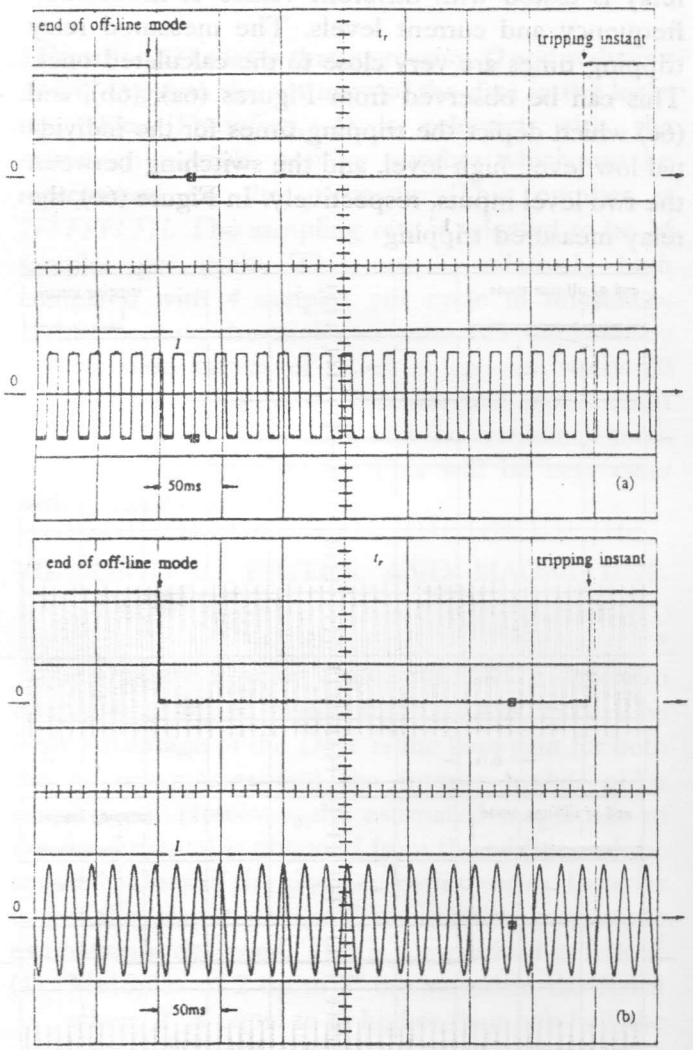

Figure 4. Effect of the harmonics on the relay performance.
(a) square wave with 10.1 pu fundamental value
(b) pure sinusoidal with 10.1 pu magnitude.

However, low modulation frequency and the high level of currents cause variable time delays. This is because the tripping time corresponding to these levels is very close to the cycle time of the modulation frequency. In order to obtain a steady time delays, the over all tripping time should be at least twenty times the modulation period.

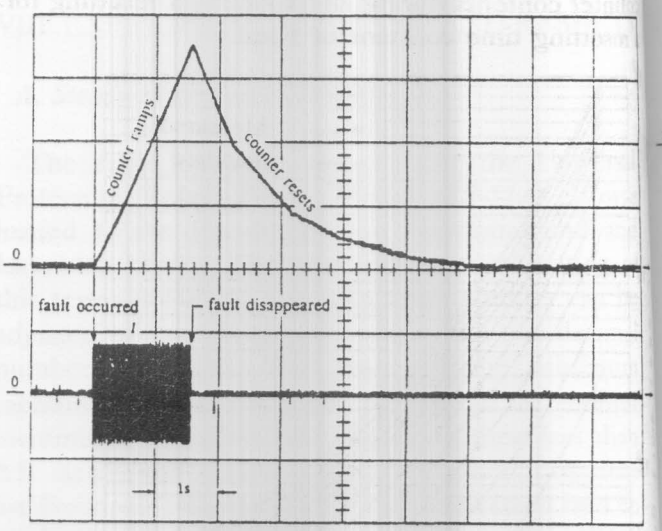

Figure 5. Relay Exponential Resetting with 1 sec. time constant.

X. CONCLUSIONS

The design details of a digital overcurrent relay have been given. The relay characteristics have been adapted to be identical to the extremely inverse time-current relationship of Westinghouse overcurrent relay type CO11. The relay can be programmed to work at 60 Hz or 50 Hz. Moreover, the relay can access 48 time-current curves according to the setting requirements. The *TDS* can be adjusted from *0.25* to *12* in *0.25* steps. The relay algorithm has been developed to account for the fluctuations in the fault current. Also, the resetting can be accomplished instantaneously, linearly, or exponentially. A TMS 32010 DSP board interfaced with a data acquisition board is used in implementing the prototype relay hardware. A number of logic switches have been provided to facilitate external adjustment of the relay settings without going through the relay algorithm. The relay performance has been examined experimentally under steady and variable fault currents. The immunity of the relay against the dc component and higher order harmonics have been verified. The experimental test results validate the efficacy of the proposed relay performance.

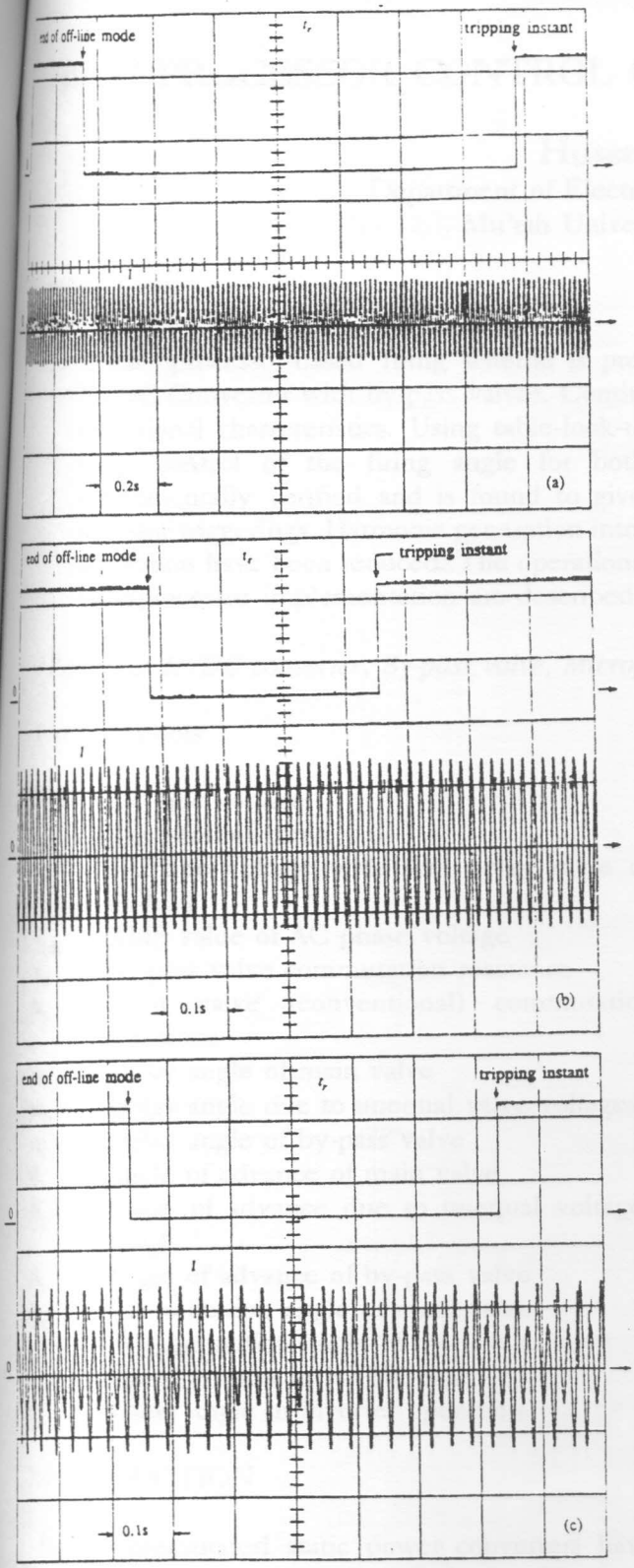

Figure 6. Relay dynamic test.
(a) low level of 3.52pu
(b) high level of 7.6 pu
(c) switchable mode

XI. REFERENCES

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