DIGITAL IMPEDANCE RELAYING FOR POWER SYSTEM PROTECTION

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ABSTRACT

Digital relays are increasingly employed in power systems due to its flexibility and compactness. Because of speed and increasing computational ability, computer based relay algorithms are being used for on-line relaying. This paper describes a digital impedance relay structure based on the Kalman Filter algorithm. It discusses the computational implications and system specifications based on an IBM compatible PC.

LIST OF PRINCIPAL SYMBOLS

M(n) : $\tilde{P}(t/t-1)$ - Predicted error covariance matrix
Z(n) : $\tilde{P}(t/t)$ - Covariance correction matrix.
$\tilde{P}(t)$: corrected error covariance
B(t) : driving function matrix (nxn)
U(t) : driving function
Y(t) : input measurement
C(t) : transmission matrix (Ixn)
V(t) : measurement noise
R_w : process noise covariance
R_v : measurement noise covariance

1.0 INTRODUCTION

Protective relays and relaying systems detect abnormal conditions like faults in electrical circuits and operate automatic switchgear to isolate faulty equipment or line from the system as quickly as possible (1). Thus the relay must be able to recognize an abnormal condition in the power system. Such a protective system must be: Fast, reliable, selective, and discriminatory over fault types.

Mann and Morrison (2) stated the demanding tasks on a digital relay system for protection viz: computer speed, cycle time and peripheral equipment. Miki et-al (3) included operating principles for relaying also as a demanding task. In this light algorithms for fast protection have been advanced (4) (5) (6). Girgis (7), sachdev (8) applied the Kalman filtering algorithm. The Kalman Filter is a recursive and optimal algorithm that can meet the speed requirement of a protective system. It responds to noise in measurements (9). Modelling of the filter is based on assumption of a Gaussian noise in its measurements.

Using the state space approach, a 3-state model was implemented to estimate both the current and voltage phasors.

The computer structure and system specification of a digital impedance relay structure was discussed based on the 3-state Kalman estimator.

Impedance relays respond to the voltage and current ratio as a quantity. The ratio is normally given by

$$Z = \frac{V_f}{I_f}$$

where V_f, I_f are fault voltage and current respectively.

During normal system conditions, the ration Z will have a large magnitude (and arbitrary phase angle) and will lie outside the circle of radius [Z_f] blocking the relay.

The method of calculation of line impedance involves the predictive calculation of peak current and peak voltage (2). For on line applications, sampling of the power line phasors at the time of fault occurrence is done and used for the computation of the line impedance. For accurate fault determination, it may not be feasible to use raw online calculations because of certain inherent quantities present on the phasors. For example Iron-Cored current transformers with resistive burdens transmit the full amount of offset in the primary fault current (2). This component takes some cycles to decay in some systems.

Quite a number of faults are transistory in nature and may vanish within a few cycles of the power line frequency. Thus it may not be economically wise to trip a fault which is transistory in nature and incapable of disturbing the system nor damage expensive equipment. From this line of reasoning, a relay that will be employed should be capable of discriminating between fault types so as to detect

and trip the system in the case of a dangerous fault. Some algorithms that use batch computation to predict the phasors has proposed but fail the speed requirements.

The Kalman Filter recursively computes the estimates of the peak current and voltage, using the present samples and past estimates. A highly discriminatory filter is obtained when the transitory faults and dc components are included in the model. Such a filter gives a high degree of accuracy of fault waveforms.

2.0 KALMAN FILTERS

The optimal behaviour of the Kalman filters depends on the Kalman gains. The process and measurement models are given below respectively.

$[V(n+1)] = [A]\,[V(n)] + [B]\,[\Delta V(n)]$

where V(n+1) is the future state that depends on V(n) the present state. $\Delta V(n)$ is the driving function and represents the change in voltage phasor from present time to future time.

[A] is the state transition matrix, [B] is the driving function matrix which advances $\Delta V(n)$ by one sampling interval. Both matrices [A] and [B] are the Jacobian of the sinusoid for a 2-state model, while for a 3-state model it includes the dc exponential function $e^{\lambda T}$. For higher order filters, the harmonics and other fault representations are used.

$$[A] = [B] = \begin{pmatrix} \cos\omega\Delta T & -\sin\omega\Delta T & 0 \\ \sin\omega\Delta T & \cos\omega\Delta T & 0 \\ 0 & 0 & e^{\lambda T} \end{pmatrix}$$

The measurement model is given by

$[Vs(n)] = [C]\,[V(n)] + b(n)$ 3

where $V_s(n)$ is the instant of voltage sampled at $n\Delta t$. [C] is the measurement matrix, b(n) is the measurement noise at time $n\Delta t$. The Kalman gains are listed as

$[K(n)] = [M(n)]\,[C]^T\,[[C]\,[M(n)][C]^T + R_v]$ 4

$[Z(n)] = [I-[K(n)]\,[C]]\,[M(n)]$ 5

$[M(n+1)] = [A]\,[Z(n)]A^T + [B]\,[R_w]\,[B]^T$ 6

The sampled power line signals contain an addition of the phasor information, process noise and measurement errors. The measurement error is due mainly to the quantizing effects of the sample and hold circuit which decreases as the precision increases. The estimated voltage phasor is thus given in terms of the Kalman gains as ;

$[V(n)] = [A]\,[V(n-1)] + [K(n)]\,[[V_s(n)] - [C]\,[A]\,[V(n-1)]]$ 7

The analysis and design of the Kalman Filter model for the 3-state current phasor, is similar to the voltage phasor except that the transistional variance will vary with the degreee of phasor distortion experienced during faults.

2.1 3-State Kalman model

Equation (7) is the augmented Kalman Filter equation which can be expanded in a three state equation as:

$$\begin{pmatrix} \hat{V}_r(n) \\ \hat{V}_i(n) \\ \hat{V}_{dc}(n) \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{pmatrix} \begin{pmatrix} \hat{V}_r(n-1) \\ \hat{V}_i(n-1) \\ \hat{V}_{dc}(n-1) \end{pmatrix} + \begin{pmatrix} K_{11}(n) \\ K_{21}(n) \\ K_{31}(n) \end{pmatrix}$$

$$\left([V_s(n) - [C_{11}\ C_{12}\ C_{13}]] \right) \begin{pmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{pmatrix} \begin{pmatrix} \hat{V}_r(n-1) \\ \hat{V}_i(n-1) \\ \hat{V}_{dc}(n-1) \end{pmatrix}$$

The states include the complex voltage phasor comprising the real and imaginary phasors and the offset dc component introduced by the instrument transformers.

On careful observation, one will notice that these equations do not include any system measurements. Therefore the Kalman gains can be calculated off line in advance and stored for use during real time calculations. It is noteworthy that the Kalman gains computed here are stationary and need be computed once. This attribute is responsible for the speed of the algorithm making it much suited for online applications.

In the three state model, the initial covariance matrix is represented by the variance of prefault to post-fault estimates and the process noise covariance matrix R_w is represented by the variance of the process uncertainty at fault transients. This is a prelude to an effective impedance relay scheme which has been proposed. Since initial state estimate affects speed of convergence, a-prior knowledge of approximate fault onset data will be highly useful in a practical installation. Convergence of 6ms has been typical for the simulation presented here.

We note also that the use of a complex fault detection algorithm is reduced as a substantial change in computed line impendance is enough indication of fault onset.

3.0 DISTANCE PROTECTION SCHEME

The relay structure proposed and simulated is based on the assumption that the harmonic distortion is minimum even on long lines and doesn't exist on short lines.

We propose three state estimators for both the voltage and current phasors. Both filters were modelled differently in relation to their peculiarities at fault transients.

The matrices for the three-state voltage model are augmented as given below:
The process noise variance R_w represents component inaccuracies in power line phasor which is brought about by variation in load swings. Assuming a standard deviation of +/- 0.3 per unit (pu) giving a variance of 0.09 for the phasor and +/- 0.03pu for the dc offset voltage and +/-0.1pu for dc offset current.

$$[Rw] = \begin{matrix} 0.09 & 0.0 & 0.0 \\ 0.0 & 0.09 & 0.0 \\ 0.0 & 0.0 & 0.03 \end{matrix}$$

$[C] = [1\ 0\ 1]$. For an A/D of 8-bit precision, we assume measurement inaccuracy of +/- 0.03 deviation to give $R_v = 0.09$. At fault onset, the current magnitude is assumed to be three times the normal value over one standard deviation, therefore the initial predicted error covariance matrix is assumed to be

$$[M(1)] = \begin{matrix} 9 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 3 \end{matrix}$$

The matrices for the three state current model are augmented as given below: $[C] = [1\ 0\ 1]$, $R_v = 0.09$

$$[Rw] = \begin{matrix} 0.09 & 0 & 0 \\ 0 & 0.09 & 0 \\ 0 & 0 & 0.1 \end{matrix}, \quad [M(1)] = \begin{matrix} 9 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 21 \end{matrix}$$

Notice that $M(1)_{33}$ current component is worse than its voltage component. From the estimated states, the rms values of the phasor is obtained from

$$V=\sqrt{(V_{real}^2+V_{imag}^2)}$$

, and the phase obtained from

$$\phi=\tan^{-1}\left(\frac{V_{imag}}{V_{real}}\right)$$

3.1 Computer Implementation

For a 3-phase transmission line, the complete protective scheme for all types of faults requires seven signals. The signals include three line currents, three phase voltlages and the residual current. These are supplied by seven current and voltage transducers. The protection scheme is such as to sample the seven analog signals and convert them to digital data by seven independent A\D converters. As input data streams in for two cycles, the fault processing program is initiated. The algorithm is such that at any point in time, two cycles of data are stored in the memory.

3.2 Fault Detection

Each input waveform is assigned a 3-state Kalman estimator. Each line voltage and current estimators send estimates of peak values of current and voltage to an impedance calculation routine. The impedance calculation routine compares the present value with that a cycle before. For any abnormal change, a counter is set up indicating a fault or transient disturbance. The routine then monitors this situation for a quarter of a cycle. For a distance protection scheme, the line impedance is caluculated per sample and compared with a threshold value. Once the line impedance is below this threshold, the fault detection routine is activated and if the fault is persistent up to the 13th sample, a trip decision is made. Further processing is made to determine the fault distance. This criteria is used to detect and ignore transistory faults. However for severe faults the system needs to bypass the criteria to engage the trip routine (not on flowchart).

The impedance and phase are calculated from

$$Z=\left(\frac{V}{I}\right), \quad \Phi_F = \Phi_v - \Phi_c$$

where f, v, c, indicate fault, voltage, and current components. (8), (20) both have considered different algorithms for fault classification, zone computation and distance computation. Any of these and others could be programmed and used for efficient application. This has not been considered here as various lines and systems require different approaches.

This is one inherent flelxibility offered by digital relays as each system could be programmed on a case by case basis. The distance computation algorithm considered here is one of the most basic. It is shown in the flowchart in fig. 1 for a single phase line.

3.3 Microprocessor Structure

The most important constraint of computer application to real time processing is speed. The speed of the processor w.r.t. computational burden was considered. For recovery of input signal after processing, the Nyquist Criterion of sampling rate

has to be met. The task on any real time processing is that, it must complete each processing before the next sample. The hardware structure proposed here revolves around the computer (CPU) speed. Fig. 2 shows the simplified transmission line protection. The block diagram of the digital relay structure proposed is shown in fig. 3.

The low pass filters cut off the higher harmonics so as to prevents aliasing during sampling. Third order LPF's will provide good cut-off at acceptable time delay. The A/D's are usually selected to have a precision that is the same as the CPU data length given below. The CPU speed should be selected to allow fast sequential processing of current and voltage data.

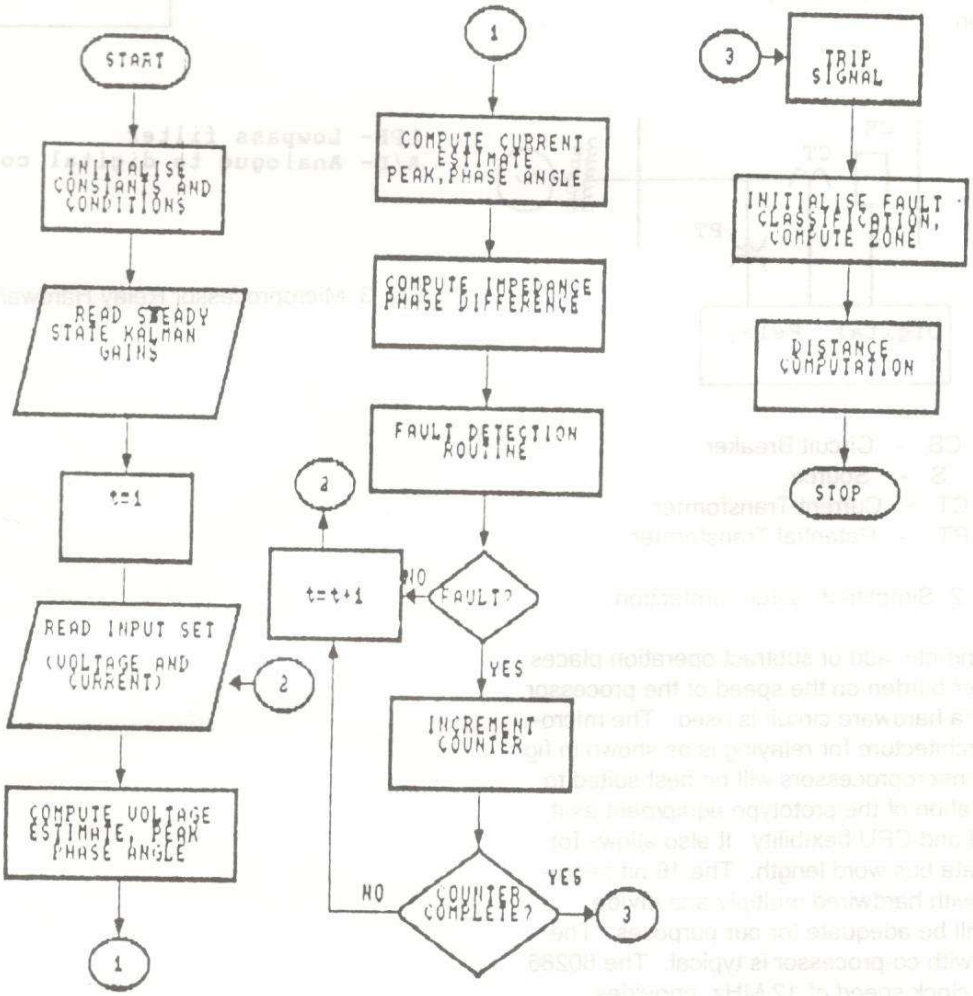
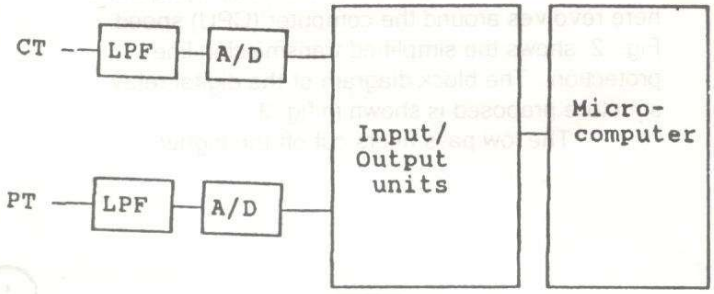


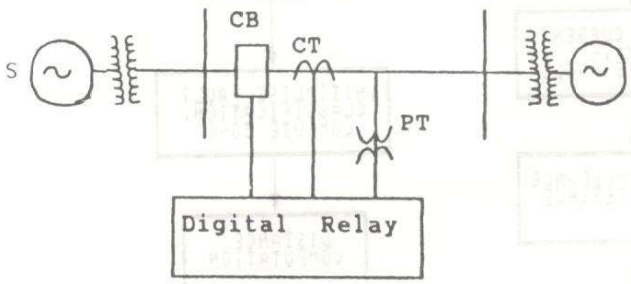
Fig.1 Flowchart of relay implementation.

The main specifications of a prototype protective relay equipment for the system of Fig,. 3 is given in Table 1. These specifications assume that Kalman gains are computed off-line and stored in memory. The multiplication is hardware configured. The three state filter requires 20 multiplications and 15 additions. For a sampling rate of 40 samples per cycle, the constraint that is placed on multiplication for each estimator is given by 1/Fs seconds, where Fs is the sampling frequency. The multiplier must therefore, have an execution time of less than or equal to (1/Fs*20) seconds for each multiplication.



LPF- Lowpass filter
A/D- Analogue to digital converter

Fig. 3 Microprocessor Relay Hardware.



CB - Circuit Breaker
S - Source
CT - Current Transformer
PT - Potential Transformer

Fig. 2 Simplified system protection.

Arithmetic add or subtract operation places a much lower burden on the speed of the processor especially if a hardware circuit is used. The microcomputer architecture for relaying is as shown in fig. 4. Bit slice microprocessors will be best suited to the configuration of the prototype equipment as it gives speed and CPU flexibility. It also allows for choice of Data bus word length. The 16 bit microprocessors with hardwired multiply and divide capability will be adequate for our purposes. The intel 80286 with co-processor is typical. The 80286 with a CPU clock speed of 12 MHz, priovides signed/unsigned multiply, divide, add and subtract facilities.
This implies a state time of 0.08 μ secs. or 0.16 μ secs. for single and double phase clock input respectively. For a multiply time of about 10 μsecs., the maximum sampling period to be obtained from an 80286 for a 3-state filter is about 200 secs., which gives a sampling frequency of 5000 Hz or 100 samples per cycle of power line frequency. Multiply times for CPU with co-processor is about 4 μ secs. or lower.

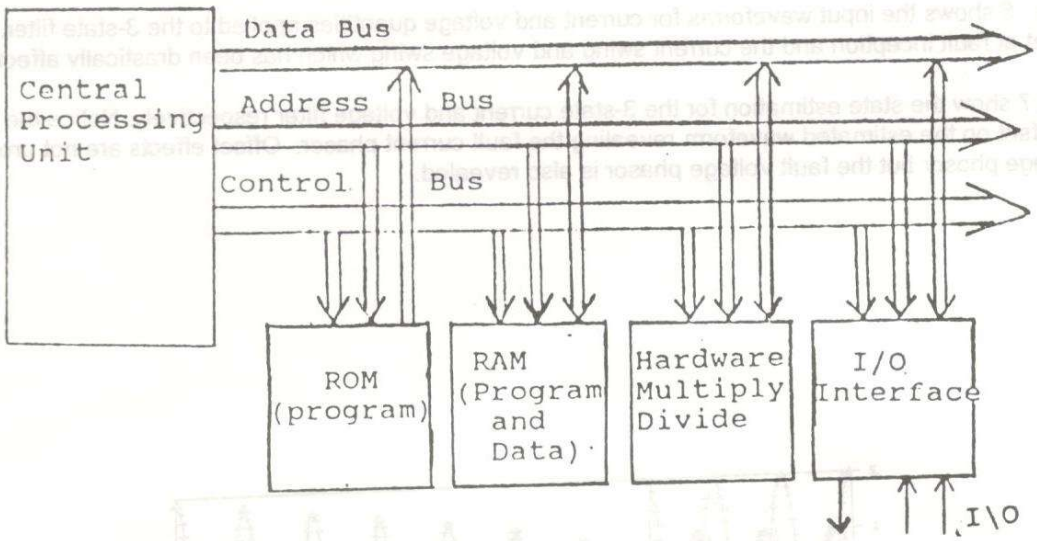


Fig.4 Microprocessor system architecture for relaying.

Table 5.1 System Specifications

Components of Microcomputer		Specification
CPU	Basic instruction cycle	Depends on CPU clock
	Control Structure	Microprogram
	Arithmetic unit	>/ 16 bits
	Execution time: Addition	\<(Fs x 15*N)
	Multiplication	\<(Fs x 20*N)
	;N_ Number of states.	
Hardware (Multiply/ Divide Circuit)	Word length	>/ 16 bits
	Execution time: Addition	\< (Fs x 15xN)
	Multiplication	\< (Fs x 15xN)
Memory	Word length Structure	
	Rom Size	2k words maximum
	Ram size	2k words maximum

4.0 KALMAN FILTER RESPONSE AND DISCUSSION

Fig. 5 shows the input waveforms for current and voltage quantities applied to the 3-state filter. Notice the dc offset at fault inception and the current swing and voltage swing which has been drastically affected by the fault.

Figs. 6 and 7 show the state estimation for the 3-state current and voltage filter respectively. Notice the removal of the dc offset on the estimated waveform revealing the fault current phasor. Offset effects are not pronounced on the voltage phasor but the fault voltage phasor is also revealed.

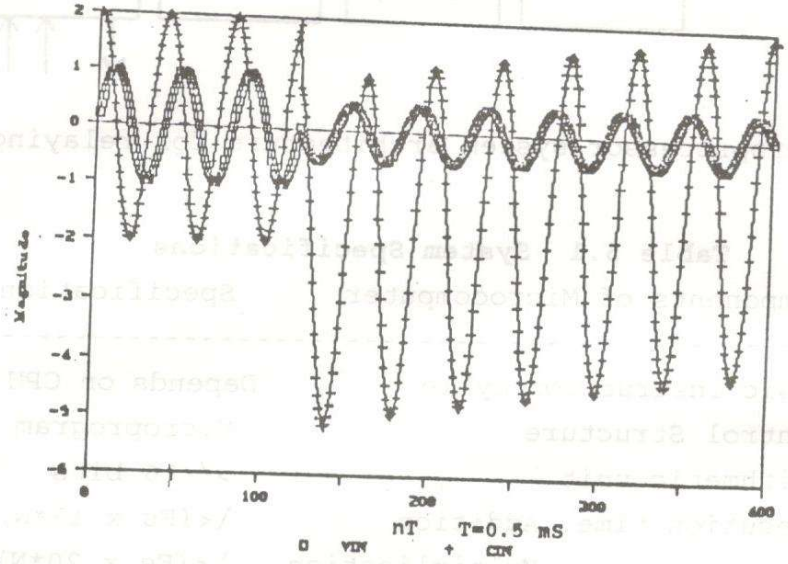


Fig.5 Input waveforms

Effects of line quantities $\frac{X}{R}$ ratios Fig. 8 show a dependance of the Kalman Filter model on line quantities. Line quantities represent reactive and resistive components inherent in the transmission line. It suggests that the model be designed explicitly based on a-priori information of the line. This is because shift in line parameters, shifts the model and distorts its estimates.

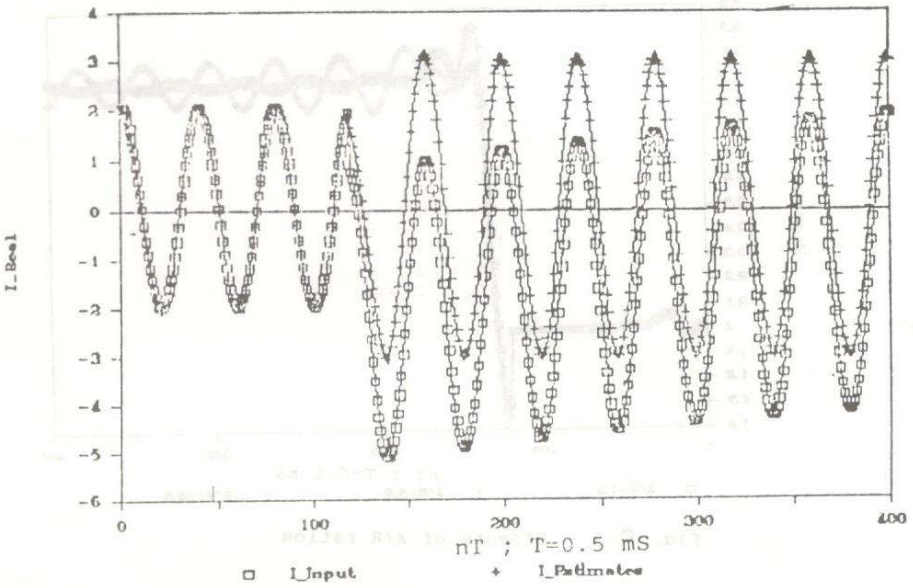


Fig.6 State estimation for 3-state current filter

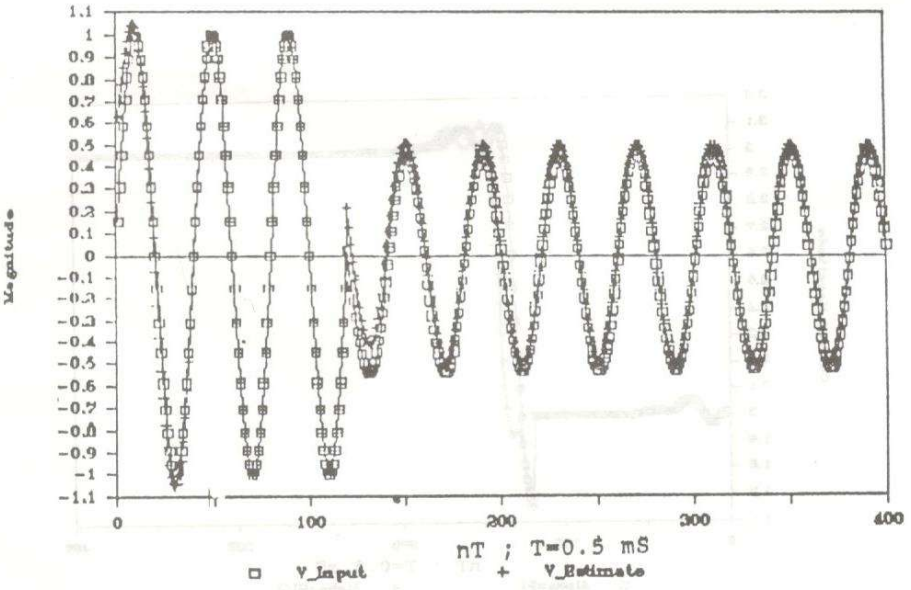


Fig.7 State estimation for 3-state voltage filter

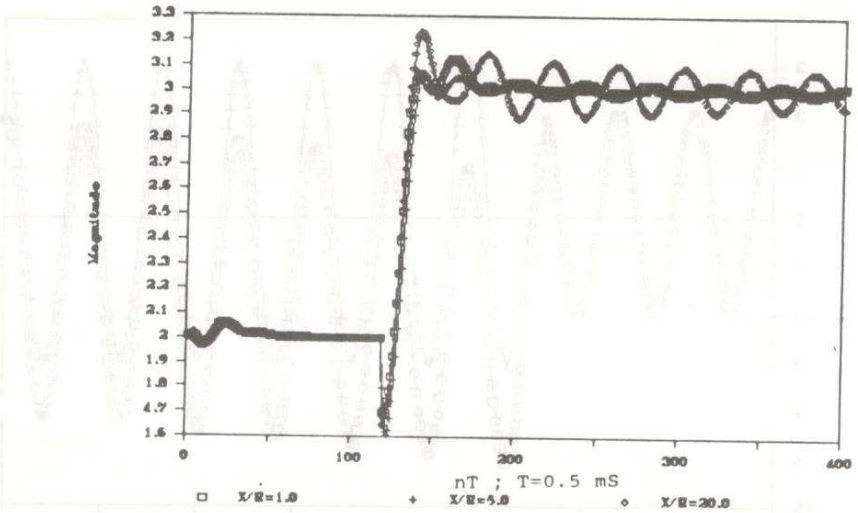


Fig. 8 Effects of X/R ratios

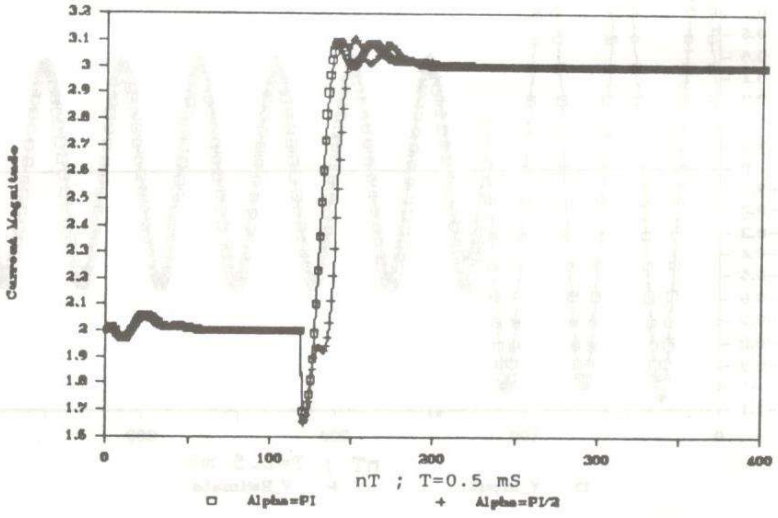


Fig. 9 Effects of change in fault inception angle

Angle of fault inception can delay convergency Fig. 9 but the worst case is still within acceptable limits of speed of relay operation. Notice the lag in the transient region for an angle of . The effect is not the fault of the filter but from an actual delay in the waveform itself.

5.0 CONCLUSIONS

It can be seen that the Kalman algorithm optimally estimates the power line phasors effectively removing all unwanted disturbances which have been included in the model. The simulated filters converged to reliable estimates in 12 samples for a 50 Hz Power line input sampled at 2000Hz or 40 samples per cycle. This gives a time of 6 ms. This implies that the relay algorithm has enough information to trip or block the relay. Thus online application requirement is adequately met.

The distance relay structure proposed and simulated for a single phase line demonstrated the applicability of the Kalman algorithm for online installation.

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