Processing Power System Signals for Digital Distance Protection

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Abstract : This paper outlines how power system voltages and currents under fault conditions are processed by the finite transform technique of solving the line differential equations. The application of the method in digital distance protection is described. Results of simulations are shown and it can be seen that very stable operation is achieved even in the presence of high frequency components arising from reflected travelling waves in the transmission line. As a high sampling rate is required in the algorithm, special effort is made to implement real time simulation so as to ensure that the required processing can be completed within strict time limits.

1 Introduction

Since the development of digital protection by Rockefeller [1] in 1969, many alternative digital relay algorithms and techniques have been developed [2], [3]. The algorithms developed in the early years usually employed a relatively low sampling rate and the fault impedance calculation was based on sinusoidal measurands. However during fault conditions, the range of system voltage and current waveforms encountered is extremely large. It depends on many factors, including the plant configuration and the location of fault. The post fault waveforms are usually distorted and consist of numerous harmonics and reflected travelling wave components [6]. Filters have to be used extensively to suppress these non-fundamental components in order to achieve a stable operation. The use of filters, plus the relatively low sampling rate (600 Hz) makes the response of the relay unattractive to conventional static distance relays.

The performance of the digital distance relay must be independent of the system waveforms. Measurements of the fault impedance must be accurate and have a high operating speed. To achieve the above goal, the algorithm employed must converge rapidly and the fault impedance must be calculated precisely by processing a small window of information. To facilitate hardware implementation, the algorithm must not involve too much computation.

The method described in this paper is based on the above objectives. The finite transform technique [4] is used to calculate the line impedance, which is the basis of distance protection of transmission lines. On-line evaluation of the Fourier Transform is carried out using a data window imposed on a small section of voltage and current waveforms (Fig. 1) at the relaying point. As the data window progresses with time, a new transform is obtained by modifying the old transformed values. Because most of the transform values inside the data window remain unchanged, each new transform is obtained with relatively few additional computation.

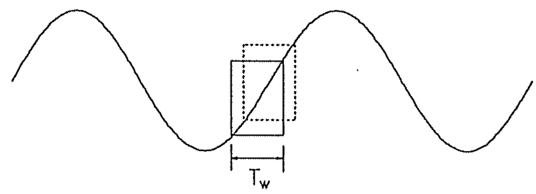
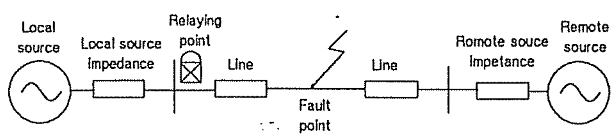


Figure 1 Data window on waveform

The study case is based on a 400 kv line of length 128 km interconnecting two power sources as shown in Fig.2.



Fault level at relaying end = 35 GVA
Fault level at remote end = 35 GVA
Pre-fault relaying end busbar voltage = $1.0 \angle 0°$
Pre-fault remote end busbar voltage= $1.0 \angle 0°$
Total line impedance = $36.8 \angle 86° \ \Omega$

Figure 2 System diagram for study case

2 Finite transform technique

As the digital relay is processing signals for a fixed window length T_w, transforming the system voltage v_r at the relaying point gives

$$\bar{v}_r(j\omega_e,t) = \int_{t-T_w}^{t} v_r(\tau)\exp(-j\omega_e\tau)d\tau \tag{1}$$

This is the transform of the following unit step function,

$$\bar{v}_r(j\omega_e,t) = \int_{-\infty}^{\infty}[H(\tau-(t-T_w))-H(\tau-t)]\,v(\tau)\exp(-j\omega_e\tau)d\tau \tag{2}$$

Similarly,

$$\bar{i}_r(j\omega_e,t) = \int_{t-T_w}^{t} i_r(\tau)\exp(-j\omega_e\tau)\,d\tau \qquad (3)$$

The finite Fourier integral extracts the spectral component at a chosen frequency $f_e = w_e/2\pi$ from the time variation of the voltage $[v_r(t)]$ and current $[i_r(t)]$ within a finite time T_w preceding any time t at which computation is implemented (Fig. 4) [5]. The fundamental advantage of the finite transform method is its insensitivity to transient waveform distortion [4].

3 Fault impedance measurement

The following transmission line equation is used as the basis of calculation:-

$$V_r(t) = R\,i_r(t) + L\,di_r(t)/dt \qquad (4)$$

Although the system voltages and currents do not conform exactly to equation (4), it is a close approximation based on the Positive Phase Sequence series inductance and resistance of the line at power frequency provided high frequency components caused by fault induced travelling waves are prefiltered [5].

Eqn.(4) has been solved by other authors in different way, but this paper presents a new approach. The finite Fourier transform of it gives

$$\begin{aligned}\bar{v}_r(j\omega_e,t) &= R\,\bar{i}_r(j\omega_e,t) + j\omega_e L\,\bar{i}_r(j\omega_e,t)\\ &+L\,\{i_r(t)\exp(-j\omega_e t) - i_r(t-T_w)\exp[-j\omega_e(t-T_w)]\}\end{aligned} \qquad (5)$$

The last term in the RHS of eqn. (5) accounts for the sudden drop to zero of the time function at the beginning and at the end of the window duration. Decomposing eqn. (2) & (3) into their real and imaginary parts gives,

$$\bar{v}_r(j\omega_e,t) = \bar{v}_{r1} - j\bar{v}_{r2} \qquad (6)$$

$$\bar{i}_r(j\omega_e,t) = \bar{i}_{r1} - j\bar{i}_{r2} \qquad (7)$$

where $\bar{v}_{r1}$, $\bar{v}_{r2}$, $\bar{i}_{r1}$, $\bar{i}_{r2}$ can be evaluated by the following equations

$$\bar{v}_{r1} = \int_{t-T_w}^{t} v_r(\tau)\cos(\omega_e\tau)\,d\tau \qquad (8)$$

$$\bar{v}_{r2} = \int_{t-T_w}^{t} v_r(\tau)\sin(\omega_e\tau)\,d\tau \qquad (9)$$

$$\bar{i}_{r1} = \int_{t-T_w}^{t} i_r(\tau)\cos(\omega_e\tau)\,d\tau \qquad (10)$$

$$\bar{i}_{r1} = \int_{t-T_w}^{t} i_r(\tau)\sin(\omega_e\tau)\,d\tau \qquad (11)$$

Eqn.(5) can then be arranged in the form,

$$\begin{bmatrix}\bar{v}_{r1}\\ \bar{v}_{r2}\end{bmatrix} = \begin{bmatrix}\bar{i}_{r1} & C_o\\ \bar{i}_{r2} & S_i\end{bmatrix}\begin{bmatrix}R\\ L\end{bmatrix} \qquad (12)$$

where

$$C_o = i_r(t)\cos(\omega_e t) - i_r(t-T_w)\cos[\omega_e(t-T_w)] + \omega_e\bar{i}_{r2} \qquad (13)$$

$$S_i = i_r(t)\sin(\omega_e t) - i_r(t-T_w)\sin[\omega_e(t-T_w)] - \omega_e\bar{i}_{r1} \qquad (14)$$

When the matrix of the above equation is inverted, R and L can then be expressed as

$$\begin{bmatrix}R\\ L\end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix}S_i & -C_o\\ -\bar{i}_{r2} & \bar{i}_{r1}\end{bmatrix}\begin{bmatrix}\bar{v}_{r1}\\ \bar{v}_{r2}\end{bmatrix} \qquad (15)$$

where $\Delta = \bar{i}_{r1}S_i - \bar{i}_{r2}C_o$.
Hence a measurement of the line impedance as seen from the relaying point has been achieved.

4 Technique for discrete digital signal processing

To achieve fast operation of the protective relay, real time calculation must be a minimum. Referring to eqn.(15), the first step is to calculate $\bar{v}_{r1}$, $\bar{v}_{r2}$, $\bar{i}_{r1}$, $\bar{i}_{r2}$. For the n-th elemental strip, the area A(n) is estimated by equation (16) to make use of the information conveyed by $\cos(\omega_e\tau)$.

$$A_n = \frac{1}{2}\{v_r(t_{n-1}) + v_r(t_n)\}\int_{t_{n-1}}^{t_n}\cos(\omega_e\tau)\,d\tau \qquad (16)$$

Therefore,

$$\bar{v}_{r1} = \frac{1}{2\omega_e}\sum_{n=1}^{N}\{[v_r(t_{n-1})+v_r(t_n)][\sin(\omega_e t_n)-\sin(\omega_e t_{n-1})]\} \qquad (17)$$

where N is the number of samples in one data window. To reduce the computing task, v_{r1} is calculated by modifying the previous integral as follows:

$$\begin{aligned}\bar{v}_{r1}(k) &= \bar{v}_{r1}(k-1) + [v_r(t_k)+v_r(t_{k-1})]*C(k)\\ &-[v_r(t_{k-N})+v_r(t_{k-1-N})]*C(k-N)\end{aligned} \qquad (18)$$

where $\bar{v}_{r1}(k-1)$ = the result calculated in last sample period and $C(k) = \sin(\omega_e t_n) - \sin(\omega_e t_{n-1})$.

In a similar way, $\bar{v}_{r2}(k)$, $\bar{i}_{r1}(k)$, $\bar{i}_{r2}(k)$, $S(k)$, $C(k)$, $D(k)(D(k)=\Delta(k))$ can be calculated. The measured resistance and reactance at the sample instant k are calculated from eqn. (15) as follows:

$$R(k) = [S_i(k)\,\bar{v}_{r1}(k) - C_o(k)\,\bar{v}_{r2}(k)]\,/\,D(k) \qquad (19)$$

$$X(k) = 2\pi f L(k) = 2\pi f[\bar{i}_{r1}(k)\bar{v}_{r2}(k) - \bar{i}_{r2}(k)\bar{v}_{r1}(k)]/D(k) \qquad (20)$$

5 Relay operation logic

A quadrilateral trip decision logic shown in Fig. 3 is selected for this study[5]. The operating region is divided into two zones: the increased counter rate region and the reduced counter rate region. The relay counter will start to accumulate from zero whenever the impedance calculated falls within the operating region from the instant of fault inception. A trip signal will be issued once the counter value has reached a predetermined value. Both regions of increased and reduced counter rate, rate of increase of counter, and the final counter value for relay trip can be adjusted for optimum performance. At present, the settings used are :

Reduced counter rate region = 80 % to 100 % of relay reach
Increased counter rate = 2
Reduced counter rate = 1
Decrease counter rate = -1
(impedance outside the relay operating zone)
Final counter value for relay trip = 8

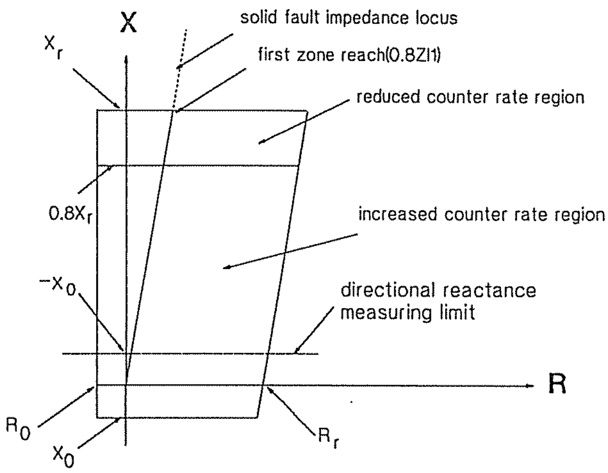


Figure 3 Relay tripping characteristic

The relay tripping characteristic can be defined by equation (21) and (22).

$$[X_0<X(k)<0.8X_r]\wedge[R_0<R(k)<R_r+K_1X(k)]\wedge[X_m(k)>-X_0] \quad (21)$$

$$[0.8X_r<X(k)<X_r]\wedge[R_0<R(k)<R_r+K_1X(k)]\wedge[X_m(k)>-X_0] \quad (22)$$

where $K_1 = Rl1/Xl1$
$X_m(k)$ = directional reactance

6 Performance of algorithm

The relay algorithm was simulated in a high level language. Fault transient voltage and current waveforms were generated by a method similar to that developed by A.T. Johns [6]. This method has an accurate representation of the frequency variance of line parameters and shows that even on lines which are electrically short, very severe transient conditions can exist. The typical line used for study here is a 400 kV double circuit overhead line, 128 km in length with a total line impedance of 36.8 $\angle$ 86° Ω. To protect 80 % of the line length, the relay reach is adjusted to :
$X = 29.4\Omega$; $X_0 = -4.0\Omega$; $R = 29.4\Omega$; $R_0 = -4.0\Omega$.
For a phase-A to earth fault at a distance 64 km away from the relaying point, the three phase voltage and current waveforms are shown in Fig.4.

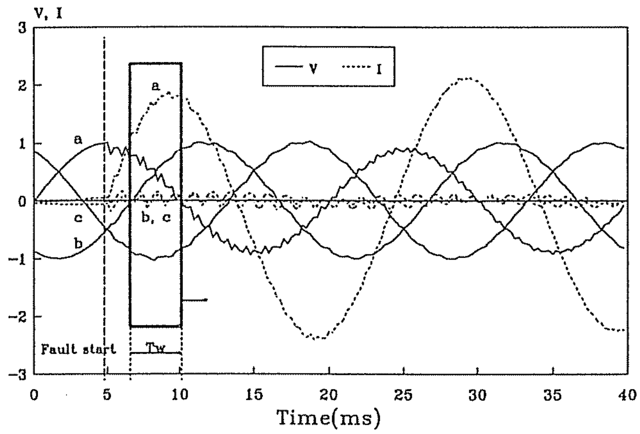


Figure 4 Voltage & current waveforms during line to earth fault on phase-a

In order to achieve an extra fast operating time, a sampling rate of 4 kHz is used. A simple analogue lowpass filter is simulated to filter any component above 2 kHz in order to eliminate the aliasing effect. As the low pass analogue filter has a high cut-off frequency, the time delay caused by the filter is a minimum. The resistance and reactance calculated for a fault at the above location by using a window length of 16 samples are shown in Fig. 5. The relay counter value is shown in Fig. 6 and it shows that the relay can complete the measurement within 5 ms.

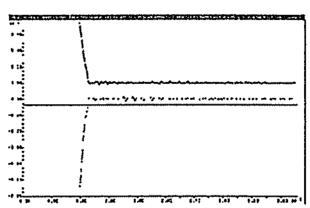


Figure 5 Calculated line reactance and resistance

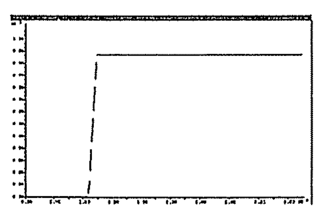


Figure 6 Relay counter

Fault at 64 km

In the worst case, for a fault at 92 km (in the reduced counter rate region) with a very weak source (5 GVA) at the relaying end, the relay operating time is slightly slower but it still operates in less than 7ms (Fig. 7, 8) although the voltage waveform (Fig. 6) is severely distorted by travelling wave components.

In the other respect, for those faults that fall outside the protective region (Fig.3), the simulation shows that the relay can restrain its operation reliably.

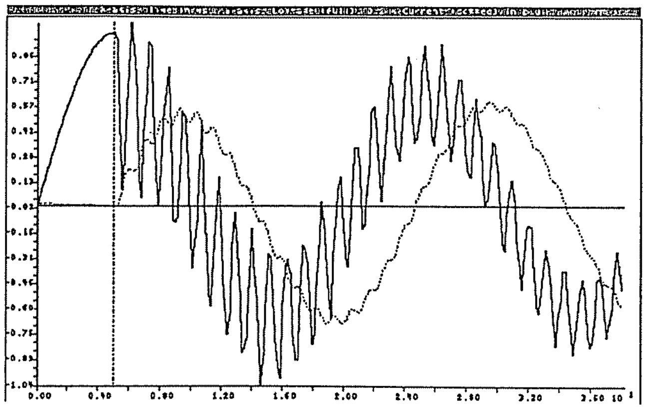


Figure 7 Voltage and current waveforms during fault with a very weak source at relaying end

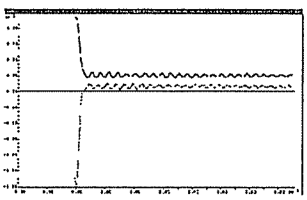


Figure 8 Calculated line reactance and resistance

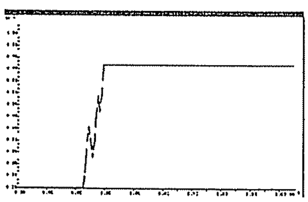


Figure 9 Relay counter

Fault at 92 km

7 Real time simulation

The simulation of the algorithm with high level language showed that satisfactory results are obtained by using a high sampling frequency (4kHz). However, under such a high sampling frequency, the microprocessor has to complete the calculation of R(k), X(k) and all trip logic judgment between the sampling interval (250 μs). To confirm that goal can be reached, real time simulation of the digital relay has been done on an IBM PC AT which has the same microprocessor as the target system. The relay function program has been developed which includes the calculation of R(k), X(k) and all trip logic judgment. The program is written in assemble language with the objective of cutting down the on-line processing time. The input data produced by the transient waveform simulation are converted to integer type in the main program. This will create the same processing environment as the planned target hardware system. When the execution of the relay function program is completed, the counter within the PC is read to give the exact processing time. The main program then displays the relay output.

The result of the real time simulation shows that all the required processing can be completed within 250 μs based on a 4 kHz sampling rate. A typical processing time is 150 μs on a 80286 CPU running at 12 MHz.

8 Conclusion

It is shown that the finite transform technique has a very strong filter function. Calculated results converged quickly and very stable operations can be achieved. The use of numerical integration technique largely reduces the processing work required by the main processor. The result of real time simulation shows that even a common microprocessor can handle all the necessary computation well within the time limit. The full digital approach further simplifies the hardware design and standard hardware can be used to reduce cost. All these make this technique very suitable for use in digital distance protection scheme in the power system.

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