TO ESTIMATE THE FAULT IN TRANSMISSION LINE USING HAAR FUNCTION

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Abstract

In order to estimate the fault occurrence quickly and fast identification of the type of fault, the algorithm based on Haar function is proposed herewith. In this paper, the sine and cosine Fourier co-efficient are expressed in terms of Haar co-efficient. The Haar co-efficient and the data samples in post fault period give the Fourier coefficients by using simple mathematical operations. Thus the amplitude of different harmonics is determined in terms of Haar functions. Haar functions have amplitude characteristics which is very suitable for fast computation. It has constant amplitude (plus or minus) over the entire period.

In case of transmission line, the relative value of the combined amplitude of the second and fifth harmonics compared to the amplitude of the fundamental waveform forms the basis of the fault detection. Also by identifying the dominance of a particular harmonics, the type of fault can be confirmed.

Keywords

Haar function, Haar co-efficient, fourier series, fundamental, second and fifth harmonics etc.

Introduction

There are different methods for quick estimation of fault occurrence. Some of these methods are Cross-correlation method, Least square curve fitting method, Fourier algorithm and Walsh algorithm.

Cross-correlation method involves the convolution of normal waveform with the wave-form under fault condition. This takes much computation time and so it is slow in response. Least square curve fitting method is lengthy and so computation time for this method as well is high. Fourier algorithm is straight forward for estimating the harmonic contents but cumbersome and hence computational time is high. Walsh algorithm suffers from the problem of slow convergence.

Haar functions have amplitude characteristics which is very suitable for fast computation. It has constant amplitude (plus or minus) over the entire period. This simplifies the mathematical operations as compared to that in case of Fourier algorithm.

The mathematical operation in estimating particular Fourier coefficient merely requires N multiplications and (N-1) additions, so computational burden is less. This helps in fast estimation of the fault current which in turn helps in isolating the faulted area. This algorithm can be further simplified by normalizing the function and neglecting the Haar co-efficient of higher order. This has been done, by using:-

[1] Approximate Haar algorithm and
[2] Modified Haar algorithm.

It can be observed that computational burden reduces as the number of effective Haar co-efficient gets reduced. Fast computation for fault estimation is very essential in case of high power handling electrical equipment where fault persistence even for a fraction of second can cause tremendous damage. The proposed algorithm in this paper is concentrated on this fact and therefore, attempts have been made to reduce the fault detection time as less as possible so that protective devices can be activated immediately after fault occurrence. The simplifications at different stages may introduce error in estimation of the harmonic components to the exact value but the estimated value still lies in the vicinity of the exact value. Hence, the fault current is estimated very quickly and at the same time with satisfactory precision.

Properties of Haar functions

[1]They are rectangular functions and orthogonal functions as well.

[2]A given periodic function can therefore be represented by linear combination of Haar functions of different order and

[3]The computational efficiency is improved due to simplicity of Haar function wave form.

Estimation of harmonic components using Haar function

Any periodic function f(t) with normalized time period of unity and spread over $0 \leq t \leq 1$ can be expressed as infinite summation series of Haar function of different orders as-

$$f(t) = \sum_{n=0}^{\infty} C_n HAR_{(n.t)} \qquad \text{.....(1)}$$

$$\text{Where } C_n = \int_0^1 f(t)\, HAR_{(n.t)}\, dt \qquad \text{..... (2)}$$

is called Haar coefficient.

Extraction of fundamental and harmonic components

The amplitude and phase of any frequency component of a signal can be obtained by calculating its sine and cosine components. The sine and cosine components of any harmonics are calculated from the Haar coefficients using the Haar-Fourier relationship can be developed as follows:-

A given periodic continuous function f(t) within the interval $0 \leq t \leq 1$ can be expressed in the Fourier series as:-

$$f(t) = \sum_{n=0}^{\infty} a_n \cos nwt + \sum_{n=0}^{\infty} b_n \sin nwt \qquad \text{.....(3)}$$

Where,

$$a_n = 2/1 \int_0^1 f(t) \cos nwt dt$$

$$a_n = 2 \int_0^1 f(t) \cos nwt dt \qquad \text{.....(4)}$$

and

$$b_n = 2/1 \int_0^1 f(t) \sin nwt dt$$

$$b_n = 2 \int_0^1 f(t) \sin nwt dt \qquad \text{..... (5)}$$

Where, a_n and b_n are called Fourier coefficients.

Combining relationship (4) with (1), coefficient a_n can be expressed as:-

$$a_n = 2 \int_0^1 \sum_{n=0}^{\infty} [c_n\, HAR_{(n,t)}] \cos 2n\pi t dt \qquad \text{.....(6)}$$

And combining relationship (5) with (1) the coefficient b_n can be expressed as:-

$$b_n = 2 \int_0^1 \sum_{n=0}^{\infty} [c_n\, HAR_{(n,t)}] \sin 2n\pi t dt \qquad \text{.....(7)}$$

The results derived in equations (6) and (7) are Haar–Fourier relationship and enables in determining Fourier coefficients in terms of Haar coefficients. For example, a_1 can be expressed considering the first 16 Haar functions as:-

$$a_1 = 2\int_0^1 [\sum_{n=0}^{15} c_n\, HAR_{(n,t)}] \cos 2\pi t dt \qquad \text{.....(8)}$$

$$= 2[\int_0^1 C0\, HAR_{(0,t)} \cos 2\pi t dt \ldots\ldots + \int_0^1 C_{15} HAR_{(15,t)} \cos 2\pi t dt] \qquad \text{..... (8a)}$$

Similarly,

$$b_1 = 2 \int_0^1 [\sum_{n=0}^{15} c_1 \, HAR_{(n,t)}] \sin 2\pi t dt \quad \ldots\ldots(9)$$

$$= 2[\int_0^1 C0 \, HAR_{(0,t)} \sin 2\pi t dt \ldots + \int_0^1 C_{15} HAR_{(15,t)} \sin 2\pi t dt] \quad \ldots\ldots (9a)$$

Calculation of the Fourier coefficients for fundamental components from equation (8a) $a_1 = 2[\int_0^1 C_0 HAR_{(0,t)}\cos 2\pi t dt + \int_0^1 C_1 HAR_{(1,t)}\cos 2\pi t dt] +2[\int_0^1 C_2 HAR_{(2,t)}\cos 2\pi t dt + \int_0^1 C_3 HAR_{(3,t)}\cos 2\pi t dt] +2[\int_0^1 C_4 HAR_{(4,t)}\cos 2\pi t dt + \int_0^1 C_5 HAR_{(5,t)}\cos 2\pi t dt] +2[\int_0^1 C_6 HAR_{(6,t)}\cos 2\pi t dt + \int_0^1 C_7 HAR_{(7,t)}\cos 2\pi t dt]+2[\int_0^1 C_8 HAR_{(8,t)}\cos 2\pi t dt + \int_0^1 C_9 HAR_{(9,t)}\cos 2\pi t dt] +2[\int_0^1 C_{10} HAR_{(10,t)}\cos 2\pi t dt + \int_0^1 C_{11} HAR_{(11,t)}\cos 2\pi t dt]+2[\int_0^1 C_{12} HAR_{(12,t)}\cos 2\pi t dt + \int_0^1 C_{13} HAR_{(13,t)}\cos 2\pi t dt] +2[\int_0^1 C_{14} HAR_{(14,t)}\cos 2\pi t dt+ \int_0^1 C_{15} HAR_{(15,t)}\cos 2\pi t dt]$.

After evaluating the involved integrals and simplifying the results-

$a_1 =0.90(C_2-C_3) + 0.2636(C_4+C_5- C_6-C_7) + 0.0524 (C_8+C_{11}- C_{12}-C_{15}) + 0.1266 (C_9+C_{10}- C_{13}-C_{14})$ ……..(10)

And from result (9a)

$b_1 = 2[\int_0^1 C_0 HAR_{(0,t)} \sin 2\pi t dt + \int_0^1 C_1 HAR_{(1,t)} \sin 2\pi t dt] +2[\int_0^1 C_2 HAR_{(2,t)} \sin 2\pi t dt + \int_0^1 C_3 HAR_{(5,t)} \sin 2\pi t dt] +2[\int_0^1 C_4 HAR_{(4,t)} \sin 2\pi t dt + \int_0^1 C_5 HAR_{(5,t)} \sin 2\pi t dt]+2[\int_0^1 C_6 HAR_{(6,t)} \sin 2\pi t dt + \int_0^1 C_7 HAR_{(7,t)} \sin 2\pi t dt]+2[\int_0^1 C_8 HAR_{(8,t)} \sin 2\pi t dt+ \int_0^1 C_9 HAR_{(9,t)} \sin 2\pi t dt] +2[\int_0^1 C_{10} HAR_{(10,t)} \sin 2\pi t dt+ \int_0^1 C_{11} HAR_{(11,t)} \sin 2\pi t dt]+2[\int_0^1 C_{12} HAR_{(12,t)} \sin 2\pi t dt+ \int_0^1 C_{13} HAR_{(13,t)} \sin 2\pi t dt]+2[\int_0^1 C_{14} HAR_{(14,t)} \sin 2\pi t dt + \int_0^1 C_{15} HAR_{(15,t)} \sin 2\pi t dt]$

After evaluating the integrals and then simplifying co-efficient b1, is obtained as-

$b_1= 1.2732C_1 + 0.2636(-C_4+C_5+C_6-C_7) + 0.1266(-C_8+C_{11}+ C_{12}-C_{15}) + 0.0524(-C_9+C_{10}+C_{13}-C_{14})$………..(11)

Calculation of the Fourier coefficient for second harmonics

Coefficient a_2 is derived as:-

$$a_2 = 2 \int_0^1[\sum_{n=0}^{15} C_1 \, HAR_{(n,t)}] \cos 4\pi t \, dt$$

$= 2[\int_0^1 C_0 HAR_{(0,t)}\cos 4\pi t dt + \int_0^1 C_1 HAR_{(1,t)}\cos 4\pi t dt]+2[\int_0^1 C_2 HAR_{(2,t)}\cos 4\pi t dt+ \int_0^1 C_3 HAR_{(3,t)}\cos 4\pi t dt]+2[\int_0^1 C_4 HAR_{(4,t)}\cos 4\pi t dt+ \int_0^1 C_5 HAR_{(5,t)}\cos 4\pi t dt]+2[\int_0^1 C_6 HAR_{(6,t)}\cos 4\pi t dt+ \int_0^1 C_7 HAR_{(7,t)}\cos 4\pi t dt]+2[\int_0^1 C_8 HAR_{(8,t)}\cos 4\pi t dt+ \int_0^1 C_9 HAR_{(9,t)}\cos 4\pi t dt] +2[\int_0^1 C_{10} HAR_{(10,t)}\cos 4\pi t dt+ \int_0^1 C_{11} HAR_{(11,t)}\cos 4\pi t dt]+2[\int_0^1 C_{12} HAR_{(12,t)}\cos 4\pi t dt+ \int_0^1 C_{13} HAR_{(13,t)}\cos 4\pi t dt] +2[\int_0^1 C_{14} HAR_{(14,t)} \cos 4\pi t dt+ \int_0^1 C_{15} HAR_{(15,t)}\cos 4\pi t dt]$.

Evaluating the integrals and on simplification-

$a_2 =0.6366 (C_4-C_5+ C_6-C_7) + 0.1863 (C_8+C_9- C_{10}-C_{11}+C_{12} +C_{13}-C_{14}-C_{15})$……………………………..(12)

Similarly,

$$b_2 = 2 \int_0^1[\sum_{n=0}^{15} C_n \, HAR_{(n,t)}] \sin 4\pi t \, dt$$

$= 2[\int_0^1 C_0 HAR_{(0,t)} \sin 2\pi t dt + \int_0^1 C_1 HAR_{(1,t)} \sin 2\pi t dt]+2[\int_0^1 C_2 HAR_{(2,t)} \sin 4\pi t dt+ \int_0^1 C_3 HAR_{(3,t)} \sin 4\pi t dt]+2[\int_0^1 C_4 HAR_{(4,t)} \sin 4\pi t dt + \int_0^1 C_5 HAR_{(5,t)} \sin 4\pi t dt]+2[\int_0^1 C_6 HAR_{(6,t)} \sin 4\pi t dt+ \int_0^1 C_7 HAR_{(7,t)} \sin 4\pi t dt]+2[\int_0^1 C_8 HAR_{(9,t)} \sin 4\pi t dt+ \int_0^1 C_9 HAR_{(9,t)} \sin 4\pi t dt]+2[\int_0^1 C_{10} HAR_{(10,t)} \sin 4\pi t dt + \int_0^1 C_{11} HAR_{(11,t)} \sin 4\pi t dt] +2[\int_0^1 C_{12} HAR_{(10,t)} \sin 4\pi t dt + \int_0^1 C_{13} HAR_{(13,t)} \sin 4\pi t dt] +2[\int_0^1 C_{14} HAR_{(14,t)} \sin 4\pi t dt + \int_0^1 C_{15} HAR_{(15,t)} \sin 4\pi t dt]$

Evaluating the integrals and on simplification-

$b_2 = 0.9 (C_2-C_3) + 0.186 (-C_8+C_9+C_{10}-C_{11}-C_{12}+C_{13}+C_{14}-C_{15})$ ……………………..…………. (13)

Calculation of the Fourier coefficients for fifth harmonics

For this harmonics cosine coefficient a_5 is obtained as: -

$$a_5 =2 \int_0^1[\sum_{n=0}^{15} C_1 \, HAR_{(n,t)}] \cos 10\pi t dt$$

$= 2[\int_0^1 C_0 HAR_{(0,t)}\cos 10\pi t dt + \int_0^1 C_1 HAR_{(1,t)}\cos 10\pi t dt]+2[\int_0^1 C_2 HAR_{(2,t)}\cos 10\pi t dt + \int_0^1 C_3 HAR_{(3,t)}\cos 10\pi t dt]+2[\int_0^1 C_4 HAR_{(4,t)}\cos 10\pi t dt+ \int_0^1 C_5 HAR_{(5,t)}\cos 10\pi t dt] +2[\int_0^1 C_6 HAR_{(6,t)}\cos 10\pi t dt+ \int_0^1 C_7 HAR_{(7,t)}\cos 10\pi t dt]+2[\int_0^1 C_8 HAR_{(8,t)}\cos 10\pi t dt + \int_0^1 C_9 HAR_{(9,t)}\cos 10\pi t dt] +2[\int_0^1 C_{10} HAR_{(10,t)}\cos 10\pi t dt + \int_0^1 C_{11} HAR_{(11,t)}\cos 10\pi t dt]+2[\int_0^1 C_{12} HAR_{(12,t)}\cos 10\pi t dt + \int_0^1 C_{13} HAR_{(13,t)}\cos 10\pi t dt] +2[\int_0^1 C_{14} HAR_{(14,t)}\cos 10\pi t dt + \int_0^1 C_{15} HAR_{(15,t)}\cos 10\pi t dt]$.

Evaluating the integrals and on simplification-

$a_5 = 0.18C_2 + 0.3074 (-C_4 -C_5 +C_6 +C_7) + 0.46 (C_8 +C_{11} -C_{12} -C_{15}) +0.19(-C_9-C_{10} +C_{13} +C_{14})$ …………...

(14)

Similarly,

$$b_5 = 2\int_0^1 \left[\sum_{n=0}^{15} C_n\, HAR_{(n,t)}\right] \sin 10\pi t dt$$

$$= 2\left[\int_0^1 C_0\, HAR_{(0,t)} \sin 10\pi t dt + \int_0^1 C_1 HAR_{(1,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_2\, HAR_{(2,t)} \sin 10\pi t dt + \int_0^1 C_3 HAR_{(3,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_4 HAR_{(4,t)} \sin 10\pi t dt + \int_0^1 C_5 HAR_{(5,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_6 HAR_{(6,t)} \sin 10\pi t dt + \int_0^1 C_7 HAR_{(7,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_8\, HAR_{(8,t)} \sin 10\pi t dt + \int_0^1 C_9 HAR_{(9,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_{10}\, HAR_{(10,t)} \sin 10\pi t dt + \int_0^1 C_{11} HAR_{(11,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_{12}\, HAR_{(12,t)} \sin 10\pi t dt + \int_0^1 C_{13} HAR_{(13\,t)} \sin 10\pi t dt\right] + 2\left[\int_0^1 C_{14}\, HAR_{(14,t)} \sin 10\pi t dt + \int_0^1 C_{15} HAR_{(15,t)} \sin 10\pi t dt\right].$$

Evaluating the integrals and on simplification-

$$b_5 = 0.254C_1 + 0.307\,(C_4 - C_5 - C_6 + C_7) + 0.19\,(C_8 - C_{11} - C_{12} + C_{15}) + 0.46\,(-C_9 + C_{10} + C13 - C_{14}) \quad \ldots\ldots\ldots\ldots (15)$$

Application of Haar function to transmission line/transformer fault detection

In this paper, the trip decision is based on the estimation of the relative of the fundamental compared to the combined amplitude of the second and fifth harmonics. The trip signal is issued when the computed ratio falls below a particular set value. The relative amplitude (K_1, K_2) can be determined by using either of the following formula.

$$K_1 = \frac{\sqrt{a_1^{2} + b_1^{2}}}{\sqrt{a_2^{2} + b_2^{2}} + \sqrt{a_5^{2} + b_5^{2}}} \quad \ldots\ldots\ldots\ldots (16)$$

$$K_2 = \frac{\text{Max}\,(a_1, a_2)}{\text{Max}\,(a_2, a_2) + \text{Max}\,(a_5, a_5)} \quad \ldots\ldots\ldots\ldots (17)$$

For demonstration of relative amplitudes K_1 or K_2 16 samples are selected beginning with the onslaught of fault on the transmission line. Such samples have been selected to match with 16 samples taken over a period for Haar function for determination with 16 samples taken over a period for Haar function for determination of harmonic coefficients. For determination of K_1 or K_2 the fault current / voltage transient curve is considered. It can be seen in the figure that the fault occurs at time t = 5ms. From this instant of time, total of 16 samples are taken at a sampling interval of 1 ms. These samples together with Haar coefficients give harmonic components, which are calculated as follows:

Calculation of Fourier coefficients from Haar coefficient (when fault takes place at voltage maximum):-

Sample Table - 1

t_k(ms)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
x_k(p.u.)	0.75	0.17	0.42	-0.18	0.08	-0.04	-0.23	-0.08	-0.11	-0.25	-0.18	-0.11	-0.05	0.08	0.17	0.19
C1s	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}

From equation (10) and Table 1:-

$a_1 = 0.90(c_2 - c_3) + 0.2636\,(c_4 + c_5 - c_6 - c_7) + 0.0524\,(c_8 + c_{11} - c_{12} - c_{15}) + 0.1266\,(c_9 + c_{10} - c_{13} - c_{14})$

$= 0.90(0.42+0.18) + 0.2636(0.08-0.04+0.23+0.08) + 0.0524\,(-0.11-0.11+0.05-0.19) + 0.1266(-0.25-0.18-0.08-0.17)$

$= 0.63226 - 0.104952$

$= 0.5273$

From equation (11) and Table 1: -

$b_1 = 1.2732\,C1 + 0.2636\,(-c_4 + c_5 + c_6 - c_7) + 0.1266\,(-c_8 + c_{11} + c_{12} - c_{15}) + 0.0524\,(-c_9 + c_{10} + c_{13} - c_{14})$

$= 1.1732 \times 0.17 + 0.2636\,(-0.08-0.04-0.23+0.08) + 0.1266\,(0.11-0.11-0.05-0.19) + 0.0524\,(-0.25-0.18+0.08-0.17)$

$= 0.145272 - 0.057632$

$= 0.08764$

From equation (12) and Table 1: -

$a_2 = 0.6366\,(c_4 - c_5 + c_6 - c_7) + 0.1863\,(c_8 + c_9 - c_{10} - c_{11} + c_{12} + c_{13} - c_{14} - c_{15})$

$= 0.6366\,(0.08+0.04-0.23+0.08) + 0.1863\,(-0.11-0.25+0.18+0.11-0.05+0.08-0.17-0.19)$

$= -0.093618$

From equation (13) and Table 1: -

$b_2 = 0.9\,(c_2 - c_3) + 0.186\,(-c_8 + c_9 + c_{10} - c_{11} - c_{12} + c_{13} + c_{14} - c_{15})$

$= 0.9\,(0.42+0.18) + 0.186\,(0.11-0.25-0.18+0.11+0.05+0.08+0.17-0.19)$

$= 0.5214$

From equation (14) and Table 1: -

$a_5 = 0.18\, c_2 + 0.3074\,(-c_4 - c_5 + c_6 + c_7) + 0.46\,(c_8 + c_{11} - c_{12} - c_{15}) + 0.19\,(-c_9 - c_{10} + c_{13} + c_{14})$

$= 0.18 \times 0.42 + 0.3074\,(-0.08+0.04-0.23-0.08) + 0.46\,(-0.11-0.11+0.05-0.19) + 0.19\,(0.25+0.18+0.08+0.17)$

$= -0.06839$

From equation (15) and Table 1:-

$b_5 = 0.254\, c_1 + 0.307\,(c_4 - c_5 - c_6 + c_7) + 0.19\,(c_8 - c_{11} - c_{12} + c_{15}) + 0.46\,(-c_9 + c_{10} + c_{13} - c_{14})$

$= 0.254 \times 0.17 + 0.307\,(0.08+0.04+0.23-0.08) + 0.19\,(-0.11+0.11+0.12+0.19) + 0. 46\,(0.25-0.18+0.08+0.17)$

$= 0.33217$

From empirical formula relative amplitude (K_1) in equation (16):-

$$K_1 = \frac{\sqrt{(0.5273)^2 + (0.08764)^2}}{\sqrt{(-0.093618)^2 + (0.5214)^2} + \sqrt{(-0.06839)^2 + (0.33217)^2}}$$

$$= \frac{0.5345}{0.5297 + 0.3391} = 0.6152$$

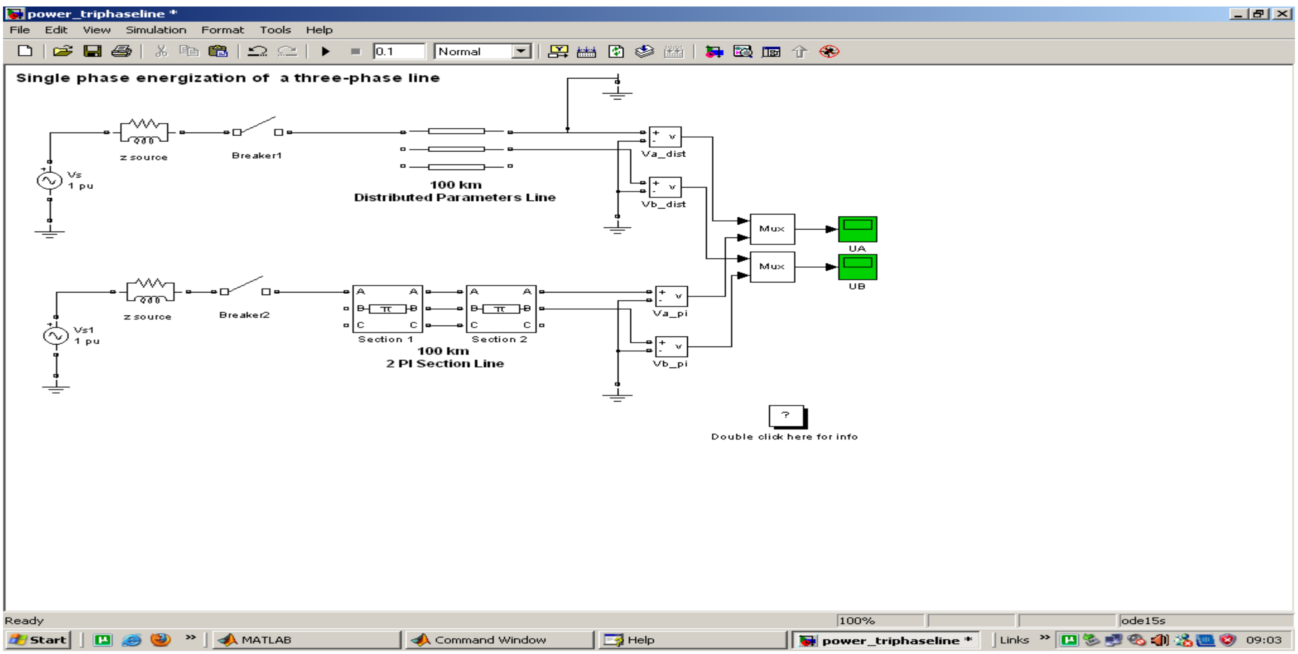
During pre-fault period K_1 assumes very high value (ideally, infinite) and as soon as the fault occurs the value of K_1 falls and the relay will sense it when K_1 becomes less than a particular set value (say 1.0).

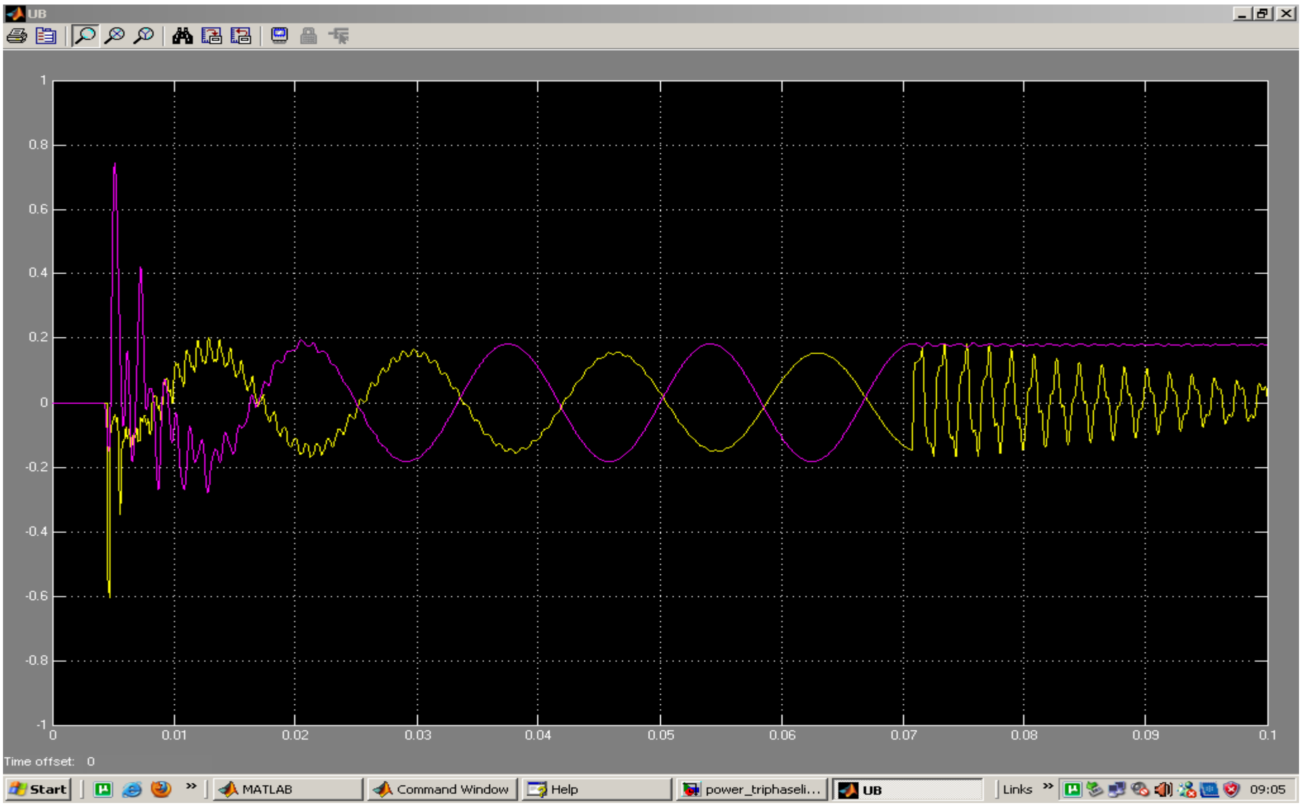
From empirical formula for relative amplitude (K_2) in equation (17): -

$$K_2 = \frac{0.5273}{0.5214 + 0.3321} = 0.6178$$

Again, the relay would respond to the fault as K_2 would become less than 1.0 and finally will actuate the circuit breaker to isolate the transmission line from the power system so that the fault is cleared.

It can be observed that the amplitude of the second harmonics is 0.5297p.u. The amplitude of the fifth harmonics is 0.3391p.u. and the amplitude of the fundamental is 0.5345p.u. Both the harmonics are dominant since they are comparable or even more than fundamental. Their combined amplitude is 0.8688p.u. This is more than the fundamental component. The comparative p.u. value of the fundamental relative to the combined amplitude (called relative amplitude, K_1 or K_2) forms the basis of the fault detection. Here, the value of the relative amplitude has come out as 0.6152, which is less than the relay setting (K = 1.0) of the differential relay, hence the relay would detect the internal fault and activate the CB clear it at the earliest.





CONCLUSIONS

Haar function and its applications to harmonic components determination have been discussed in this paper. This concept has been applied to a three phase transmission line (100 Km ling) energized with single phase supply constructed in MAT LAB for fault analysis and protection whose voltage and current wave forms have been shown under fault (Line to ground) conditions. Based on the analysis therein the following conclusions have been derived as under:-

[1] The algorithm based on Haar function involves less computation time it becomes still less if modified Haar algorithm is used.
[2] Using a threshold level of K=1.0, an accurate and fast discriminations between inrush current and internal fault can be made.
[3] The convergence feature of this algorithm is satisfactory as sufficiently accurate estimation of fault current is achieved by considering the first sixteen Haar functions.
[4] The amplitudes of the second harmonics and the fifth harmonics are comparable to that for the fundamental in case of internal fault. For inrush currents, the amplitude of the second harmonics is about 62% of the fundamental and the contribution of the fifth harmonics is insignificant. These observations help in differentiating the faults.

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