DEVELOPMENT OF ALGORITHM BASED ON BLOCK PULSE FUNCTION FOR NUMERICAL DIFFERENTIAL PROTECTION OF SYNCHRONOUS GENERATOR

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Abstract*—A synchronous generator, which is major and very important equipment in a power system, requires very efficient and reliable protection scheme. Percentage differential relays of electromagnetic and static type are conventionally used for protection of synchronous generator against internal faults. With the advent of fast and sophisticated microprocessor and special purpose processor, there is a growing trend it design and develop digital processing relays. The main features of digital relay are there economy, compactness and improved performance over conventional relays. In digital relaying scheme processor acquires the digitized samples of relaying signals and processors under the elaborate program control to extract the fault discriminate. The digital filtering algorithms for differential protection of synchronous generator extract the fundamental and second harmonic frequency components of the differential current it provide the operating and restraint signals respectively. The work described in this paper deals with the development of a digital filtering algorithms based Block Pulse Function (BPF) for the differential protection of synchronous generator for its high speed of response, computational burden, simplicity and accuracy and the capability to extract the fundamental and other harmonic components from post fault signal and to check the suitability of the algorithm for the digital differential protection of synchronous generator. In the present work an attempt has been made to calculate fundamental component and second harmonic component by relationship developed between Fourier and BPF coefficients. By choose test signal, it has been found that BPF algorithm is suitable for the numerical differential protection of synchronous generator.

Index Terms*—Block Pulse Function (BPF); synchronous generator, Digital filtering technique;

I. INTRODUCTION

The increase growth of power system both sizes and complexity has brought about the need for fast and reliable protection scheme for major equipment like synchronous generator. The synchronous generator is a major and vital component in power system. Any fault in the very source of power, i.e. synchronous generator may hamper the available power to the great extent. For the protection of synchronous generator, high-speed protective relay and associated switch gear is necessary. The electromechanical, electronic and static relays have not been able to provide require high speed, simplicity, flexibility, sensitivity and reliability. These features can be achieved very easily in the digital protection scheme, especially in the microprocessor (i.e. minicomputer or PC based) relaying schemes, with an additional self-checking feature. In the recent years there has been a growing interest regarding the application of discrete orthogonal transform to digital signal processing for differential protection of synchronous generator. The emergence of microprocessor and PC has acted as catalyst to the general field of data processing. Numerous discrete orthogonal transform are available today, here we used only few of them such as Discrete Fourier Transform (DFT), Fast Walsh Hadamard Transform (FWHT), Haar Transform (HT) and Block Pulse Function (BPF) are used for extracting the fundamental and second harmonic components from the complex post faults signal.

A. Need for Protective Systems

An electrical power system consists of generator, transformer, transmission line and distribution line, Short circuit and other abnormal conditions often occur in power system. The heavy current associated with short circuit is suitable protective relays and circuit breakers are not provided for protection of the each section of power system. A protective scheme includes circuit breaker and protective relays to isolate the faulty section of the system from the healthy sections. A circuit breaker can disconnect the faulty element of the system when it is called upon to do so by the protective relay. The function of the protective relay is to detect and isolate the fault and issued a command to the circuit breaker to disconnect the faulty element.

The cost of the protective equipment generally works out to be about 5% of the total cost of the system.

B. Scope of the present work

For differential protection of synchronous generator several digital filtering algorithms for extracting fundamental and second harmonic components, but they involve time consuming multiplication which make of the relay using digital processor rather difficult. Up till now several digital algorithms are used for development of digital differential protection of synchronous generator. The work presented in this paper is concerned with the development of a digital filtering algorithm based on BPF for harmonic restraint differential protection of synchronous generator and test to check whether suitable algorithm for the numerical differential protection of synchronous generator. The BPF coefficients are computed using the sampled values of the current signal and then by correlating these coefficients with Fourier coefficients, the real and imaginary parts of fundamental and second harmonic components of the current are computed. This program used 16 samples of current signal acquired over a data window of one full cycle to calculate the fundamental and harmonic frequency components and this components are then utilized to check the tripping condition and to detected whether the relay should operate or not. The Block Pulse functions algorithm presented here is computationally simpler and faster than others and that is why BPF is most suitable algorithm for numerical differential protection of synchronous generator.

II. ALGORITHM BASED ON BLOCK FUNCTIONS

In a digital relaying scheme, the processor acquires the digitized sample of the relaying signals and processes them using digital algorithm to extract the fault discriminates. The digital filters based on different algorithms extract the fundamental frequency component and the second components of the differential current to provide operating and restraint signals respectively. The algorithm for extracting the fundamental frequency component and second harmonic component, from post fault current signal is based on Block pulse function (BPF). The algorithm is computationally simple and flexible to use with any sampling frequency. The post fault current signal contains fundamental frequency component as well as harmonic component, which are extract by using the algorithm and operating conditions of relay is decided according to the values of these frequency components. The current samples acquired over a full cycle data window at the sampling rate of 16 samples per cycle. The BPF coefficients are obtained by merely calculating the value of current samples.

C. Block pulse function

A set of Block pulse function on a unit time interval (0, 1) is defined as:

$$\phi_n(t) = \begin{cases} 1 & \text{for } (n-1)/N < t \le n/N \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

$$\text{where } n = 1,2,3,....,N$$

Where N is no. of samples chosen in one cycle

If there is a function f (t), which is integrable in (0, 1) can be approximated using BPF as

$$f(t) \approx \sum_{n=1}^{N} a_n \phi_n(t) \qquad (2)$$

Where the coefficient and are Block pulse function coefficients determined so that the following integral square error is minimized

$$\varepsilon = \int_0^1 (f(t) - \sum_{n=1}^{N} a_n \phi_n(t))^2 \, dt \qquad (3)$$

For such a least error square fit and is given by

$$a_n = N \int_{(n-1)/N}^{n/N} f(t)dt \qquad (4)$$

=average value of f (t) in the interval (n-1)/N< t≤ n/N

Here, the number of samples chosen is 16 samples per cycle. Number of samples chosen is decided by sampling theorem, which dictates that the sampling frequency should be at least twice the largest frequency content in the sampled information. In this work, the presence of fifth harmonic has been considered as the largest frequency. Therefore the sampling frequency of 800 Hz i.e. a sampling rate of 16 samples acquired over one cycle window is suitable.

From the above equations, it is obvious that the Block pulse function a1, a2, a3… a16 are the sampled values of function f (t).

For a no. of samples N=16, it is clear from eqn. (1) that on a unit time interval (0,1) block pulse function are twelve blocks of magnitude one as shown in fig.(1) for interval(0 to 1/16),(1/16 to 2/16),(3/16 to 4/16),……………..(15/16 to 16/16).

The approximation in eq. (2) gives the best N segment piecewise constant approximation of f (t) and is unique.

Block pulse functions have following useful properties.

$$\int_0^1 \phi_n(t)\,\phi_m(t)\,dt = 0 \qquad \text{For all } n \neq m \text{ (orthogonality)}$$

$$\phi_n(t)\,\phi_m(t) = 0 \text{ For all } n \neq m \text{ (disjoint property)}$$

$$= \phi_n(t)$$

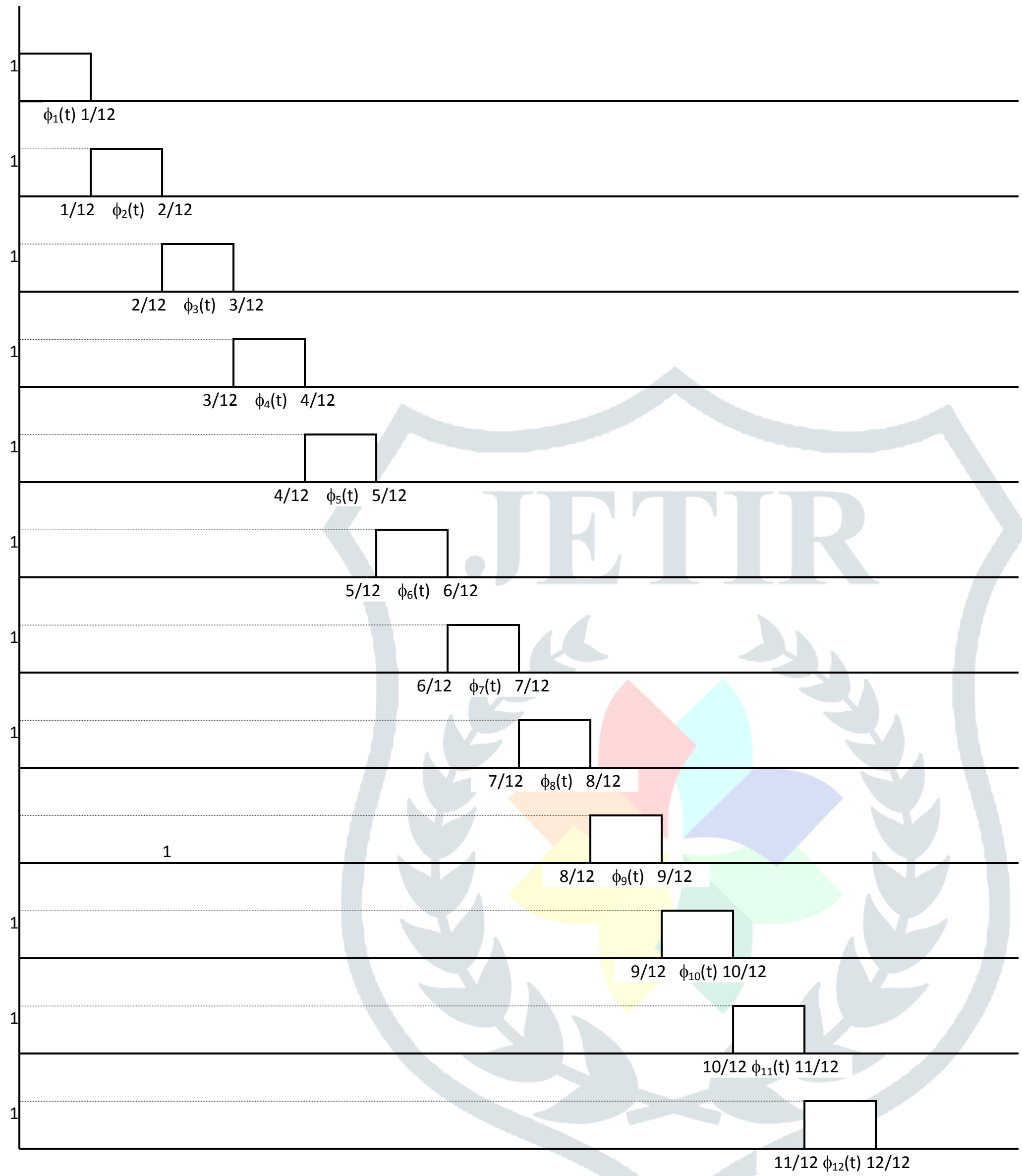


Fig.1 Blocks Pulse Function

D. Digital filtering technique using BPF

In this case, the algorithm for extracting the fundamental frequency component, second harmonic components from distorted post faults current signal in based on block pulse function. The function i (t) is the post fault current signal which contains the fundamental and harmonic components and Block pulse function coefficients (an) will be equal to the sample value of current.

Relationship to express fundamental, seconds Fourier sine and cosine coefficients in term of the BPF coefficients has been derived. The fundamental Fourier sine and cosine coefficients, which are respectively equal to the real and imaginary components of fundamental frequency phasor and computed by simple calculations with Block pulse function coefficients, similarly second harmonic component are equal to the real and imaginary component of the second phasor. The algorithm has been developed with a sampling rate of 16 samples per cycle, i.e. a sampling frequency of 600 Hz for the 50 Hz power frequencies.

Using the Discrete Fourier Transform, the phasors representation of the current in rectangular from can also be obtained directly as described in previous chapter by correlating the incoming data sample with the stored samples of reference sine and cosine waves. But this method involves time consuming multiplication. Therefore, instead of obtaining components of current phasor directly, if the data samples are used to calculate the BPF coefficients (which are simply current data samples), and thereby the corresponding Fourier sine and cosine coefficients are calculated, the overall computation complexity is drastically reduced. Relationship between Fourier and BPF coefficients and extraction of fundamental and harmonic components are described in further section.

E. Relationship between Fourier and BPF coefficients

a) Fundamental frequency components

Taking the fundamental period as 1, current i (t) which is given time function can be expressed in terms of Fourier coefficients as

$$i(t) = A0 + \sqrt{2}A1\sin(2\pi t) + \sqrt{2}B1\cos(2\pi t) + \sqrt{2}A2\sin(4\pi t) + \sqrt{2}B2\cos(4\pi t) + \ldots \quad (5)$$

Where A1 and B1 are fundamental frequency sine and cosine Fourier coefficients A1 is given by

$$A_1 = \sqrt{2}\int_0^1 i(t)\sin(2\pi t)dt \quad (6)$$

$$B_1 = \sqrt{2}\int_0^1 i(t)\cos(2\pi t)dt \quad (7)$$

From equation (2), i (t) can be expressed in term of BPF coefficients, which are simply the current data samples. So

$$i(t) \approx \sum_{n=1}^{N} a_n \phi_n(t) \quad (8)$$

Putting this equation in eq. (6) we obtain

$$A_1 = \sqrt{2}\int_0^1 \left[\sum_{n=1}^{N} a_n \phi_n(t)\right]\sin(2\pi t)dt \quad (9)$$

At this stage it can be observed that N can take any integral value in equation (9), while using BPF. However, in other algorithms there are some hard restrictions while selecting the value N. for example when algorithm based on Haar and Walsh transform, N has to be integral power of 2 i.e. 16. So this is a beneficial point when using block pulse functions.

Taking N=12, eq. (9) can be simplified as follows

$$A_1 = \sqrt{2}\int_0^1 \left[\sum_{n=1}^{N} a_n \phi_n(t)\right]\sin(2\pi t)dt$$

$$A_1 = \sqrt{2}\int_0^1 [a1\phi1(t) + a2\phi2(t) + a3\phi3(t) + a4\phi4(t) + a5\phi5(t) + a6\phi6(t) + a7\phi7(t) + a8\phi8(t) + a9\phi9(t) + a10\phi10(t) + a11\phi11(t) + a12\phi12(t) +$$

$$a13\phi13(t) + a14\phi14(t) + a15\phi15(t) + a16\phi16(t)] \sin(2\pi t)\, dt$$

Since

$\phi1(t) = 1$ from 0 to 1/16
$= 0$ otherwise

$\phi2(t) = 1$ from 1/16 to 2/16
$= 0$ otherwise

$\phi3(t) = 1$ from 2/16 to 3/16
$= 0$ otherwise

$\phi4(t) = 1$ from 3/16 to 4/16
$= 0$ otherwise

$\phi5(t) = 1$ from 4/16 to 5/16
$= 0$ otherwise

$\phi6(t) = 1$ from 5/16 to 6/16
$= 0$ otherwise

$\phi7(t) = 1$ from 6/16 to 7/16
$= 0$ otherwise

$\phi8(t) = 1$ from 7/16 to 8/16
$= 0$ otherwise

$\phi9(t) = 1$ from 8/16 to 9/16
$= 0$ otherwise

$\phi10(t) = 1$ from 9/16 to 10/16
$= 0$ otherwise

$\phi11(t) = 1$ from 10/16 to 11/16
$= 0$ otherwise

$\phi12(t) = 1$ from 11/16 to 12/16
$= 0$ otherwise

$\phi13(t) = 1$ from 12/16 to 13/16
$= 0$ otherwise

$\phi14(t) = 1$ from 13/16 to 14/16

=0 otherwise

$\phi15(t) = 1$ from 14/16 to 15/16

=0 otherwise

$\phi16(t) = 1$ from 15/16 to 16/16

=0 otherwise

Therefore,

$$A_1 = \sqrt{2}\begin{bmatrix} \int_0^{1/16} a_1 \sin(2\pi t)\,dt + \int_{1/16}^{2/16} a_2 \sin(2\pi t)\,dt + \int_{2/16}^{3/16} a_3 \sin(2\pi t)\,dt + \\ \int_{3/16}^{4/16} a_4 \sin(2\pi t)\,dt + \int_{4/16}^{5/16} a_5 \sin(2\pi t)\,dt + \int_{5/16}^{6/16} a_6 \sin(2\pi t)\,dt + \\ \int_{6/16}^{7/16} a_7 \sin(2\pi t)\,dt + \int_{6/16}^{8/16} a_8 \sin(2\pi t)\,dt + \int_{8/16}^{9/16} a_9 \sin(2\pi t)\,dt + \\ \int_{9/16}^{10/16} a_{10} \sin(2\pi t)\,dt + \int_{10/16}^{11/16} a_{11} \sin(2\pi t)\,dt + \int_{11/16}^{12/16} a_{12} \sin(2\pi t)\,dt + \\ \int_{12/16}^{13/16} a_{13} \sin(2\pi t)\,dt + \int_{13/16}^{14/16} a_{14} \sin(2\pi t)\,dt + \int_{14/16}^{15/16} a_{15} \sin(2\pi t)\,dt + \\ \int_{15/16}^{16/16} a_{16} \sin(2\pi t)\,dt \end{bmatrix}$$

$$A_1 = \sqrt{2}\begin{bmatrix} a_1\{-\cos(2\pi t)/2\pi\}_0^{1/16} + a_2\{-\cos(2\pi t)/2\pi\}_{1/16}^{2/16} + a_3\{-\cos(2\pi t)/2\pi\}_{2/16}^{3/16} + \\ a_4\{-\cos(2\pi t)/2\pi\}_{3/16}^{4/16} + a_5\{-\cos(2\pi t)/2\pi\}_{4/16}^{5/16} + a_6\{-\cos(2\pi t)/2\pi\}_{5/16}^{6/16} + \\ a_7\{-\cos(2\pi t)/2\pi\}_{6/16}^{7/16} + a_8\{-\cos(2\pi t)/2\pi\}_{7/16}^{8/16} + a_9\{-\cos(2\pi t)/2\pi\}_{8/16}^{9/16} + \\ a_{10}\{-\cos(2\pi t)/2\pi\}_{9/16}^{10/16} + a_{11}\{-\cos(2\pi t)/2\pi\}_{10/16}^{11/16} + a_{12}\{-\cos(2\pi t)/2\pi\}_{11/16}^{12/16} + \\ a_{13}\{-\cos(2\pi t)/2\pi\}_{12/16}^{13/16} + a_{14}\{-\cos(2\pi t)/2\pi\}_{13/16}^{14/16} + a_{15}\{-\cos(2\pi t)/2\pi\}_{14/16}^{15/16} + \\ a_{16}\{-\cos(2\pi t)/2\pi\}_{15/16}^{16/16} \end{bmatrix}$$

$$A_1 = 0.0171(a1+a8-a9-a16) + 0.0488(a2+a7-a10-a15) + 0.073(a3+a6-a11-a14) + 0.0171(a4+a5-a12-a13) \quad (10)$$

Similarly from eqn. (7) and eqn. (8), we obtained as

$$B_1 = \sqrt{2}\int_0^1 i(t)\cos(2\pi t)\,dt$$

$$B_1 = \sqrt{2}\int_0^1 \left[\sum_{n=1}^{N} a_n \phi_n(t)\right]\cos(2\pi t)\,dt$$

$B_1 = \sqrt{2}\int_0^1$ [a1ϕ1(t) + a2ϕ2(t) + a3ϕ3(t) + a4ϕ4(t) + a5ϕ5(t) + a6ϕ6(t) + a7ϕ7(t)+a8ϕ8(t) + a9ϕ9(t) + a10ϕ10(t) + a11ϕ11(t) + a12ϕ12(t) + a13ϕ13(t) + a14ϕ14(t) + a15ϕ15(t) + a16ϕ16(t)] Cos (2πt) dt

$$B_1 = \sqrt{2}\begin{bmatrix} \int_0^{1/16} a_1 \cos(2\pi t)\,dt + \int_{1/16}^{2/16} a_2 \cos(2\pi t)\,dt + \int_{2/16}^{3/16} a_3 \cos(2\pi t)\,dt + \\ \int_{3/16}^{4/16} a_4 \cos(2\pi t)\,dt + \int_{4/16}^{5/16} a_5 \cos(2\pi t)\,dt + \int_{5/16}^{6/16} a_6 \cos(2\pi t)\,dt + \\ \int_{6/16}^{7/16} a_7 \cos(2\pi t)\,dt + \int_{6/16}^{8/16} a_8 \cos(2\pi t)\,dt + \int_{8/16}^{9/16} a_9 \cos(2\pi t)\,dt + \\ \int_{9/16}^{10/16} a_{10} \sin(2\pi t)\,dt + \int_{10/16}^{11/16} a_{11} \sin(2\pi t)\,dt + \int_{11/16}^{12/16} a_{12} \sin(2\pi t)\,dt + \\ \int_{12/16}^{13/16} a_{13} \cos(2\pi t)\,dt + \int_{13/16}^{14/16} a_{14} \cos(2\pi t)\,dt + \int_{14/16}^{15/16} a_{15} \cos(2\pi t)\,dt + \\ \int_{15/16}^{16/16} a_{16} \cos(2\pi t)\,dt \end{bmatrix}$$

$$B_1=\sqrt{2}\begin{bmatrix} a_1\{\sin(2\pi t)/2\pi\}_0^{1/16}+a_2\{\sin(2\pi t)/2\pi\}_{1/16}^{2/16}+a_3\{\sin(2\pi t)/2\pi\}_{2/16}^{3/16}+ \\ a_4\{\sin(2\pi t)/2\pi\}_{3/16}^{4/16}+a_5\{\sin(2\pi t)/2\pi\}_{4/16}^{5/16}+a_6\{\sin(2\pi t)/2\pi\}_{5/16}^{6/16}+ \\ a_7\{\sin(2\pi t)/2\pi\}_{6/16}^{7/16}+a_8\{\sin(2\pi t)/2\pi\}_{7/16}^{8/16}+a_9\{\sin(2\pi t)/2\pi\}_{8/16}^{9/16}+ \\ a_{10}\{\sin(2\pi t)/2\pi\}_{9/16}^{10/16}+a_{11}\{\sin(2\pi t)/2\pi\}_{10/16}^{11/16}+a_{12}\{\sin(2\pi t)/2\pi\}_{11/16}^{12/16}+ \\ a_{13}\{\sin(2\pi t)/2\pi\}_{12/16}^{13/16}+a_{14}\{\sin(2\pi t)/2\pi\}_{13/16}^{14/16}+a_{15}\{\sin(2\pi t)/2\pi\}_{14/16}^{15/16} \\ +a_{16}\{\sin(2\pi t)/2\pi\}_{15/16}^{16/16} \end{bmatrix}$$

B_1=0.086(a1-a8-a9+a16) + 0.073(a2-a7-a10+a15) + 0.0488(a3-a6-a11+a14) +0.0171(a4- a5-a12+a13) (11)

The amplitude of fundamental current component $\mathrm{Im1}=\sqrt{2}\sqrt{A_1^2+B_1^2}$ (12)

The r.m.s value of the fundamental components of current= $\sqrt{A_1^2+B_1^2}$

a) Second Harmonic Component

In equation (5) for current i(t), A2 and B2 are second harmonic sine and cosine components (Fourier series). A2 and B2 are given by

$$\mathrm{A}_2=\sqrt{2}\int_0^1 i(t)\sin(4\pi t)dt \qquad (13)$$

And $$\mathrm{B}_2=\sqrt{2}\int_0^1 i(t)\cos(4\pi t)dt \qquad (14)$$

In equation (13), substituting i(t) in term of BPF coefficients from equation (8), we obtain

$$\mathrm{A}_2=\sqrt{2}\int_0^1 i(t)\sin(4\pi t)dt$$

$$\mathrm{A}_2=\sqrt{2}\int_0^1\left[\sum_{n=1}^{N}a_n\phi_n(t)\right]\sin(4\pi t)dt$$

$A_2=\sqrt{2}\int_0^1$ [a1ϕ1(t) + a2ϕ2(t) + a3ϕ3(t) + a4ϕ4(t) + a5ϕ5(t) + a6ϕ6(t) + a7ϕ7(t)+ a8ϕ8(t) + a9ϕ9(t) + a10ϕ10(t) + a11ϕ11(t) + a12ϕ12(t) + a13ϕ13(t) + a14ϕ14(t) + a15ϕ15(t) + a16ϕ16(t)] sin (4πt) dt

$$A_2=\sqrt{2}\begin{bmatrix} \int_0^{1/16}a_1\sin(4\pi t)dt+\int_{1/16}^{2/16}a_2\sin(4\pi t)dt+\int_{2/16}^{3/16}a_3\sin(4\pi t)dt+ \\ \int_{3/16}^{4/16}a_4\sin(4\pi t)dt+\int_{4/16}^{5/16}a_5\sin(4\pi t)dt+\int_{5/16}^{6/16}a_6\sin(4\pi t)dt+ \\ \int_{6/16}^{7/16}a_7\sin(4\pi t)dt+\int_{6/16}^{8/16}a_8\sin(4\pi t)dt+\int_{8/16}^{9/16}a_9\sin(4\pi t)dt+ \\ \int_{9/16}^{10/16}a_{10}\sin(4\pi t)dt+\int_{10/16}^{11/16}a_{11}\sin(4\pi t)dt+\int_{11/16}^{12/16}a_{12}\sin(4\pi t)dt+ \\ \int_{12/16}^{13/16}a_{13}\sin(4\pi t)dt+\int_{13/16}^{14/16}a_{14}\sin(4\pi t)dt+\int_{14/16}^{15/16}a_{15}\sin(4\pi t)dt+ \\ \int_{15/16}^{16/16}a_{16}\sin(4\pi t)dt \end{bmatrix}$$

$$A_2 = \sqrt{2}\begin{bmatrix} a_1\{-\cos(4\pi t)/4\pi\}_0^{1/16} + a_2\{-\cos(4\pi t)/4\pi\}_{1/16}^{2/16} + a_3\{-\cos(4\pi t)/4\pi\}_{2/16}^{3/16} + \\ a_4\{-\cos(4\pi t)/4\pi\}_{3/16}^{4/16} + a_5\{-\cos(4\pi t)/4\pi\}_{4/16}^{5/16} + a_6\{-\cos(4\pi t)/4\pi\}_{5/16}^{6/16} + \\ a_7\{-\cos(4\pi t)/4\pi\}_{6/16}^{7/16} + a_8\{-\cos(4\pi t)/4\pi\}_{7/16}^{8/16} + a_9\{-\cos(4\pi t)/4\pi\}_{8/16}^{9/16} + \\ a_{10}\{-\cos(4\pi t)/4\pi\}_{9/16}^{10/16} + a_{11}\{-\cos(4\pi t)/4\pi\}_{10/16}^{11/16} + a_{12}\{-\cos(4\pi t)/4\pi\}_{11/16}^{12/16} + \\ a_{13}\{-\cos(4\pi t)/4\pi\}_{12/16}^{13/16} + a_{14}\{-\cos(4\pi t)/4\pi\}_{13/16}^{14/16} + a_{15}\{-\cos(4\pi t)/4\pi\}_{14/16}^{15/16} + \\ a_{16}\{-\cos(4\pi t)/4\pi\}_{15/16}^{16/16} \end{bmatrix}$$

A_2 = 0.033(a1+a4-a5-a8+a9+a12-a13-a16) + 0.0796(a2+a3-a6-a7+a10+a11-a14-a15) (15)

In equation (14), substituting i(t) in term of BPF coefficients from eq.(8), we obtain

$$B_2 = \sqrt{2}\int_0^1 \left[\sum_{n=1}^{N} a_n \phi_n(t)\right]\cos(4\pi t)dt$$

$$B_2 = \sqrt{2}\int_0^1 [a1\phi1(t) + a2\phi2(t) + a3\phi3(t) + a4\phi4(t) + a5\phi5(t) + a6\phi6(t) + a7\phi7(t) + a8\phi8(t) + a9\phi9(t) + a10\phi10(t) + a11\phi11(t) + a12\phi12(t) + a13\phi13(t) + a14\phi14(t) + a15\phi15(t) + a16\phi16(t)]$$

$$B_2 = \sqrt{2}\begin{bmatrix} \int_0^{1/16} a_1\cos(4\pi t)dt + \int_{1/16}^{2/16} a_2\cos(4\pi t)dt + \int_{2/16}^{3/16} a_3\cos(4\pi t)dt + \\ \int_{3/16}^{4/16} a_4\cos(4\pi t)dt + \int_{4/16}^{5/16} a_5\cos(4\pi t)dt + \int_{5/16}^{6/16} a_6\cos(4\pi t)dt + \\ \int_{6/16}^{7/16} a_7\cos(4\pi t)dt + \int_{6/16}^{8/16} a_8\cos(4\pi t)dt + \int_{8/16}^{9/16} a_9\cos(4\pi t)dt + \\ \int_{9/16}^{10/16} a_{10}\sin(4\pi t)dt + \int_{10/16}^{11/16} a_{11}\sin(4\pi t)dt + \int_{11/16}^{12/16} a_{12}\sin(4\pi t)dt + \\ \int_{12/16}^{13/16} a_{13}\cos(4\pi t)dt + \int_{13/16}^{14/16} a_{14}\cos(4\pi t)dt + \int_{14/16}^{15/16} a_{15}\cos(4\pi t)dt \\ + \int_{15/16}^{16/16} a_{16}\cos(4\pi t)dt \end{bmatrix}$$

$$B_2 = \sqrt{2}\begin{bmatrix} a_1\{-\sin(4\pi t)/4\pi\}_0^{1/16} + a_2\{-\sin(4\pi t)/4\pi\}_{1/16}^{2/16} + a_3\{-\sin(4\pi t)/4\pi\}_{2/16}^{3/16} + \\ a_4\{-\sin(4\pi t)/4\pi\}_{3/16}^{4/16} + a_5\{-\sin(4\pi t)/4\pi\}_{4/16}^{5/16} + a_6\{-\sin(4\pi t)/4\pi\}_{5/16}^{6/16} + \\ a_7\{-\sin(4\pi t)/4\pi\}_{6/16}^{7/16} + a_8\{-\sin(4\pi t)/4\pi\}_{7/16}^{8/16} + a_9\{-\sin(4\pi t)/4\pi\}_{8/16}^{9/16} + \\ a_{10}\{-\sin(4\pi t)/4\pi\}_{9/16}^{10/16} + a_{11}\{-\sin(4\pi t)/4\pi\}_{10/16}^{11/16} + a_{12}\{-\sin(4\pi t)/4\pi\}_{11/16}^{12/16} + \\ a_{13}\{-\sin(4\pi t)/4\pi\}_{12/16}^{13/16} + a_{14}\{-\sin(4\pi t)/4\pi\}_{13/16}^{14/16} + a_{15}\{-\sin(4\pi t)/4\pi\}_{14/16}^{15/16} + \\ a_{16}\{-\sin(4\pi t)/4\pi\}_{15/16}^{16/16} \end{bmatrix}$$

B_2 = 0.0796(a1-a4-a5+a8+a9-a12-a13+a16) + 0.033(a2-a3-a6+a7+a10-a11-a14+a15) (16)

The amplitude of second harmonic current component Im2=√2 $\sqrt{A_2^2 + B_2^2}$ (17)

The r.m.s value of second harmonic fundamental frequency component of current = $\sqrt{A_2^2 + B_2^2}$

In this way all Fourier coefficients are expressed in term of BPF coefficients. If the Fourier coefficients are determined directly then it required a lot of complex computation process. But with the help of BPF coefficients are determined with simple computation.

These Fourier coefficients are utilized in the filtering of fundamental, second harmonic components of post fault current signal. After checking the operating conduction, the operation of relay takes place.

a) Real Time Implementation of Algorithm

In the real time implementation, the occurrence of the fault is to be checked continuously at every sampling instant. For this purpose, to calculate all the current components, it requires the present sample and the immediate past 15 samples before the sampling instant at which the fault is being checked. The generalized expressions for the Fourier coefficients of three current components at the k_{th} sampling instant in terms of BPF coefficients (i.e. current simples) work out as

A1k = 0.0171(a1k+a8k-a9k-a16k) + 0.0488(a2k+a7k-a10k-a15k) + 0.073(a3k+a6k-a11k-a14k) +.0171(a4k+a5k-a12k-a13k)

B1k = 0.086(a1k-a8k-a9k+a16k) + 0.073(a2k-a7k-a10k+a15k) + 0.0488(a3k-a6k-a11k+a14k) +0.0171(a4k- a5k-a12k+a13k)

Where A1k and B1k are fundamental Fourier coefficients at k_{th} sampling instant

A2k = 0.033(a1k+a4k-a5k-a8k+a9k+a12k-a13k-a16k) + 0.0796(a2k+a3k-a6k-a7k+a10k+a11k-a14k-a15k)

B2k = 0.0796(a1k-a4k-a5k+a8k+a9k-a12k-a13k+a16k) +0.033(a2k-a3k-a6k+a7k+a10k-a11k-14k+a15k)

Where A2k and B2k are the second harmonic Fourier coefficients at k_{th} sampling instant and ank is BPF coefficient, which is equal to the $(k\text{-}N\text{+}n)_{th}$ current sample. Where N is sampling rate

For real time implementation the sampling interval should be such that all the harmonic components can be computed and tripping condition be checked during one sampling interval.

One of the most prominent advantages of algorithm using BPF coefficient is that the sampling rate can be any positive integer. There is compulsion in other methods like in Haar and Walsh transform, where one is compelled to use sampling rates that are equal to integral powers of two.

III. RESULTS AND DISCUSSIONS

The post fault current signal contains several harmonic components. The main components are fundamental and second harmonic components. The other harmonic components are negligibly small so they are not considered in case of synchronous generator protection. Our attention is to extract the fundamental and second harmonic component from the post faults currents signal, which is required for differential protection. For extraction of fundamental frequency and harmonic components from the post fault current signal, we used BPF filtering techniques for these purpose in our discussion. The study yield that the BPF is the suitable algorithm for protecting synchronous generator.

Software based on BPF has been made in MATLAB programming. The flowchart is provided in the appendix. The frequency response graph determines the validity of algorithms, when the frequency is changed from normal fundamental frequency.

A. Numerical Experimentation

To evaluate the performance of all the algorithms with respect to estimating harmonic amplitude and phase and we take the post fault current signal of synchronous generator contains besides the fundamental and higher order harmonics of the 2nd 5th etc and decaying DC component. The pre fault test signal is represented by:

i (t) =2.0Sin (wt-80)

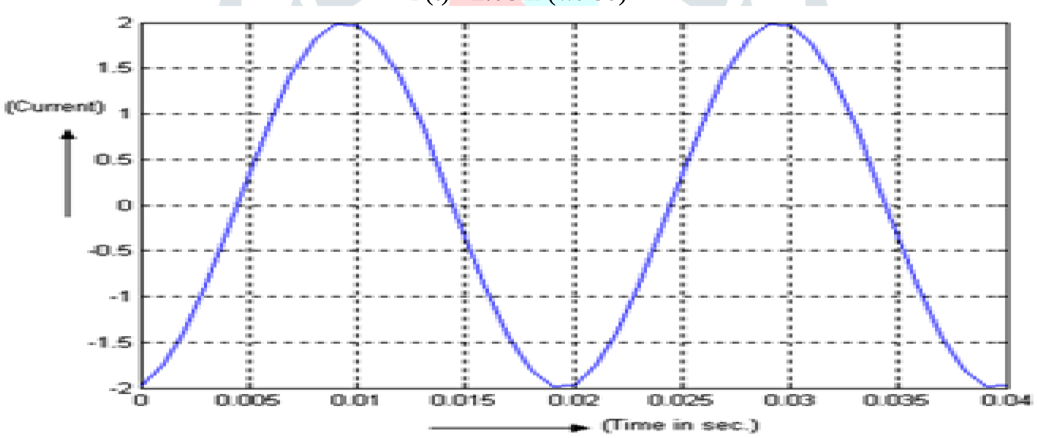


Fig. 2 Pre Fault Current Signal

And post fault current signal may be represented by-

i(t)=Im1Sin(wt-φ1)+Im2Sin(2wt-φ2)+Im5Sin(5wt-φ5)+Id exp(-t/τ)

Where the term used are as follows:

Im1=maximum value of fundamental current component

Im1=maximum value of second harmonic current component

Im1=maximum value of fifth harmonic current component

φ1=angle lag from reference for fundamental component

φ2=angle lag from reference for second harmonic component

φ5=angle lag from reference for fifth harmonic component

Id=maximum value of dc decaying component

τ =time constant associated with decaying dc component

i(t)=2.0Sin(wt-80)+0.5Sin(2wt-27)+0.3Sin(5wt-18)+0.07exp(-t/0.01)

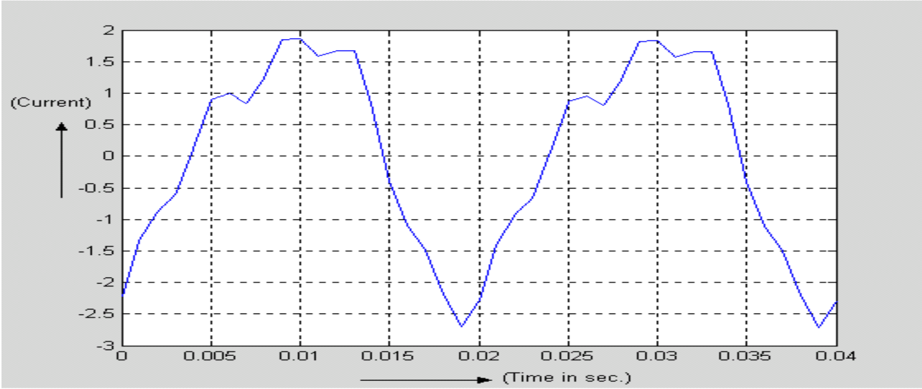


Fig. 3 Post Fault Current Signal

The pre fault and post fault current signal is sampled by taking the full cycle data window having sampling interval 0.00125 second and taken 16 samples for full cycle data window. Graph of the pre fault and post fault have been giving in Fig.2 and Fig.3 respectively.

B. Result of Block Pulse Function (BPF)

Imc1 = 1.9872

Imc2 = 0.4872

angle1 = 80.2500

angle2 = 26.8100

BPF = BLOCK PULSE FUNCTION

GAIN = ACTUAL IMPLITUDE/FUNDAMENTAL AMPLITUDE AT 50Hz

RESULT:-

ANALYSIS OF FREQUENCY RESPONSE OF FULL WAVE DATA WINDOW

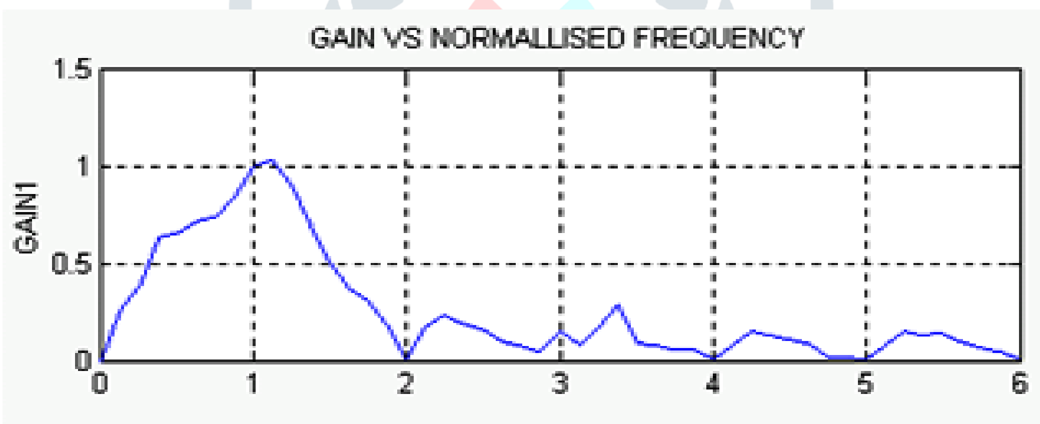
NF	GAIN1	GAIN2
0.0000	0.000000	0.000000
0.1250	0.259890	0.120870
0.2500	0.378028	0.279853
0.3750	0.625761	0.246633
0.5000	0.655586	0.287200
0.6250	0.712349	0.378723
0.7500	0.733471	0.330425
0.8750	0.833859	0.266800
1.0000	0.993587	0.243624
1.1250	1.021045	0.163473
1.2500	0.901280	0.286367
1.3750	0.688584	0.541782
1.5000	0.507679	0.713847
1.6250	0.372857	0.817827
1.7500	0.309880	0.857354
1.8750	0.178269	0.913514
2.0000	0.000000	0.974495
2.1250	0.172699	1.008877
2.2500	0.236639	0.924070
2.3750	0.195287	0.735132
2.5000	0.166083	0.569181
2.6250	0.101863	0.406196
2.7500	0.076271	0.142163
2.8750	0.044530	0.231686
3.0000	0.149038	0.000000
3.1250	0.074282	0.145918
3.2500	0.174097	0.223990
3.3750	0.282092	0.234195
3.5000	0.088382	0.210518
3.6250	0.076354	0.267147
3.7500	0.057899	0.113654
3.8750	0.058771	0.086320
4.0000	0.000000	0.000000

4.1250	0.073599	0.085153
4.2500	0.149566	0.172685
4.3750	0.129351	0.153272
4.5000	0.112162	0.136439
4.6250	0.084068	0.103690
4.7500	0.020353	0.038961
4.8750	0.011801	0.018667
5.0000	0.000000	0.000000
5.1250	0.082056	0.089778
5.2500	0.150437	0.164021
5.3750	0.133566	0.145308
5.5000	0.135705	0.148915
5.6250	0.103903	0.118008
5.7500	0.066186	0.077464
5.8750	0.042155	0.082384
6.0000	0.000000	0.146174

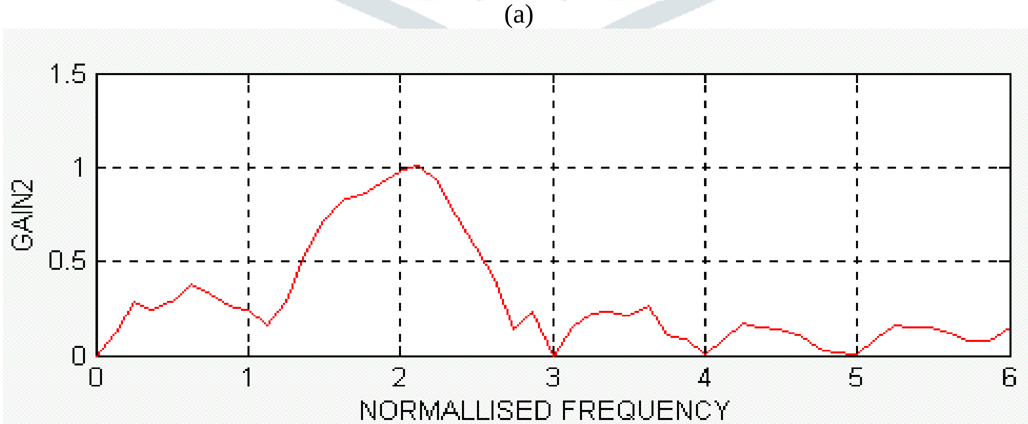
Time Elapsed= 0.110000 Seconds

C. Frequency response:

The frequency response for the fundamental and second harmonic filters for test signal has been drawn. Frequency response is curve drawn between normalized frequency and gain, where normalized frequency is assumed frequency divided by power frequency and gain is calculated value of current component at the assumed frequency divided by actual current component. Their responses to all undesired frequencies are non-zero, but very small. The efficacious of the filters is clear from the responses as it is shown that for a filter of particular frequency, the corresponding frequency component is extracted and other are almost rejected.



(a)



(b)

Fig. 4 Frequency Response of BPF algorithm (a) Fundamental (b) Second Harmonic current

Limitations:

- Though they measure accurately the magnitude of harmonics, which are multiple of supply frequency, but the argument of harmonic components of input data signal does not measured accurately.
- As shown in frequency response graph of algorithms, as used directly numerical relay are sensitive to frequency swing, what effect accuracy of measurements and consequently, the overall performance of protective relay. Generator and their step up transformer may

operate in comparative wide range of frequencies. Therefore to provide satisfactory protection, it becomes necessary to track the system frequency and apply certain correction on the measuring algorithm.

IV. CONCLUSIONS

In this paper an attempt has been made to present an algorithm for harmonic restraint differential relaying based on the BPF. Software has been developed to calculate the Fourier coefficients and thereby magnitude of currents from BPF coefficients on the basis of post faults current signal. This algorithm is able to extract the fundamental and other harmonic components from the fault signal. It is found that the BPF algorithm gives the suitable result in term of accuracy and speed, for digital implementation of the differential relay for synchronous generator. The frequency response of the algorithm has been shown. The maximum values of fundamental with all harmonic current, for all algorithms are very close to the actual test signal. The errors for calculating the different frequency components on the basis of BPF are very small and do not affect the accuracy of the algorithm. The frequency response of the fundamental filter and second harmonic filter are very good and shows a good filtering characteristic of algorithm using the differential protection scheme based on BPF. The relay can protect the synchronous generator without any loss.

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