© September 2021 | IJIRT | Volume 8 Issue 4 | ISSN: 2349-6002

Extraction of Negative Phase Sequence Quantities from Three-Phase Measurements Using a New Numerical Relay Algorithm

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***Abstract*- An issue that has been plaguing protection engineers for a considerable amount of time is the extraction of negative phase sequence components from three-phase alternating current voltages and currents. In this research, a unique numerical three-phase filtering approach is presented for the purpose of extracting the negative phase sequence components from sampled three-phase observations. In order to calculate either the absolute value of the negative phase quantity or the relative value of the negative phase sequence to the positive phase sequence measured at the operating point, the algorithm has been designed to be appropriate for use in a numeric relay. This is because the method has been developed to be suitable for use in its intended application. The purpose of this study is to illustrate the capabilities of the method by presenting findings that indicate that the amount of negative phase sequence components can often be retrieved within thirty milliseconds after a disturbance by using a simple post-extraction smoothing filter. A notional sampling rate of 1200 samples per second was used in this example, together with an automated frequency tracking method, in order to ensure that the sampling clock and the power system frequency remained in perfect sync with one another.**

***Index Terms*- Relay algorithm, Negative phase sequence, Three-phase measurements.**

I. INTRODUCTION

The presence of negative phase sequence components in the current or voltage signals of a three phase system might indicate that the system is either faulty or that it is being operated in an abnormal condition. In the case of power transformers, motors, and generators, the existence of negative phase sequence components always results in overheating. In an ideal scenario, this overheating leads to protective tripping, which isolates the plant in question from the rest of the power supply network.When it comes to collecting negative phase sequence components, the conventional methods include the use of specific hardware filters that contain phase shifting components. The majority of the time, they are connected to electromechanical relays and early static designs.

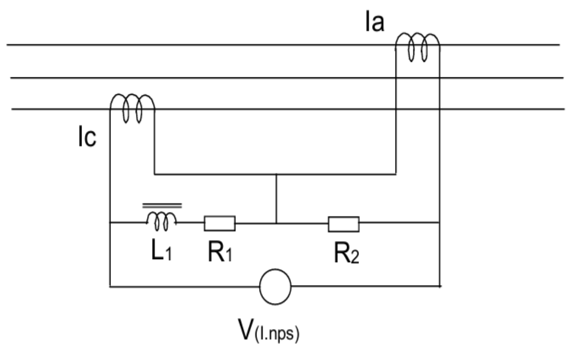

Figure 1. Basic Negative Phase Sequence Current Filter

In figure 1, we have an example of one of the more fundamental filter designs[1]. In this particular design, the output is obtained by adding the values of Ia and Ic at a 60-degree angle. This solution has a flaw in that it also produces an output for zero sequence components, which is a drawback. Figure 2 depicts a design that is more advanced [1] and that has the ability to circumvent this issue. For the sole purpose of determining the value of the negative phase sequence current, this makes use of the three phase electrical currents. Both of these methods are vulnerable to fluctuations in the frequency of the power system to which they are sent. This technique enabled improved phase shifting and mixing circuits, which resulted in more effective filters. Similar negative phase sequence filters were created for the analogue static relays. However, this technology was more effective than the alternatives.

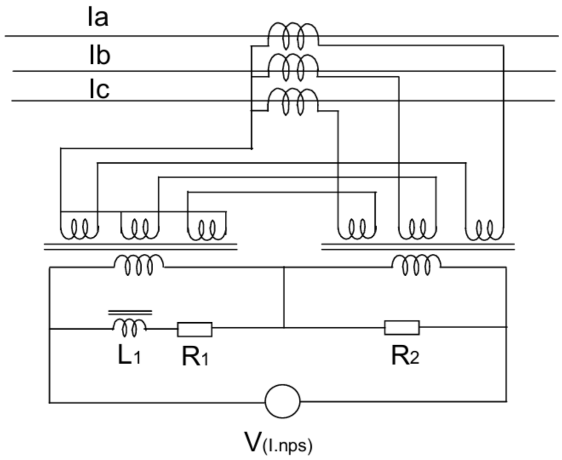

Figure 2. Practical Negative Phase Sequence Current Filter

The development of general-purpose microprocessor relay platforms has resulted in the use of processors that are ever more powerful, as well as the implementation of numerical relaying algorithms with increasing frequency. Islam and Mostafa are responsible for the development of one of the few numeric relay techniques that has been reported for the purpose of extracting the negative phase sequence components [2]. The equation that is used to determine the negative phase sequence current I_2 is as follows:

$$I_2 = \frac{1}{3}(I_a \angle 0 + a^2 I_b \angle \theta_b + a I_c \angle \theta_c) \quad (1).$$

Simple algebraic manipulation then yields;-

$$I_{r2} = \frac{1}{3}(I_{ra} - 0.5 I_{rb} - 0.5 I_{rc} + \frac{\sqrt{3}}{2} I_{xb} - \frac{\sqrt{3}}{2} I_{xc}) \quad (2).$$

$$I_{x2} = \frac{1}{3}(-\frac{\sqrt{3}}{2} I_{rb} + \frac{\sqrt{3}}{2} I_{rc} - 0.5 I_{xb} - 0.5 I_{xc}) \quad (3).$$

and,

$$|I_2| = \sqrt{I_{r2}^2 + I_{x2}^2} \quad (4).$$

where:-

I_2 is the negative phase sequence current

I_{r2} and I_{x2} are the real and quadrature components of I_2 I_a,

I_b and I_c are the three phase currents Ira,

I_{rb} and I_{rc} and I_{xa}, I_{xb} and I_{xc} are the real and quadrature components of the three phase currents

Islam and Mostafa use an innovative sampling and time-multiplexed phase-sensitive rectification approach to ascertain the values of I_{ra}, I_{rb}, I_{rc}, I_{xa}, I_{xb}, and I_{xc}, therefore facilitating the determination of I_2. This circumvents complex signal processing, hence reducing the demands on the relay's CPU. Experimental findings using various simulated unbalanced waveforms demonstrated that the measurement accuracy was within ±5%.

Usta et al.[3] developed a novel digital relaying technique aimed at identifying asymmetrical faults by the observation of sinusoidal oscillations in the three-phase instantaneous power recorded at a generator's terminals. Under balanced circumstances, the instantaneous power is a constant DC component; however, any unbalanced elements add oscillatory components into the result, either at the power system frequency or at double that frequency. Their system then analyzes the direction of the negative sequence-reactive power flow at the machine terminal to differentiate between internal and external defects. Power system test investigations indicate that the new relay delivers rapid tripping for internal asymmetrical faults and supplementary protection for external asymmetrical fault scenarios.

II. THE NEGATIVE PHASE SEQUENCE ALGORITHM.

A numeric filter with three phases is used by the newly developed technique for negative phase sequence. Both the instantaneous power equation and the fourier series filter play a role in the operation of this. The fourier series filter is at the heart of its functioning. It has been developed to be implemented in the digital signal processing environment of a contemporary protection relay platform by using a sampling rate that is moderate and sampling points that are automatically locked to the frequency of the power system.

Using the separate instantaneous values of the voltage and current measurements, the instantaneous power equation is able to calculate a direct current value of the instantaneous three-phase power in a circuit. -!

$$P = i_a v_a + i_b v_b + i_c v_c = IV\cos(\theta) \quad (5).$$

This can be presented more generally as:-

$$S_R = s_a \sin(wt) + s_b \sin\left(wt + \frac{2\pi}{3}\right) + s_c \sin\left(wt + \frac{4\pi}{3}\right)$$

$$S_R = S\cos(\theta) \quad (6).$$

This represents the real part of the signal S and the quadrature term can be derived from:-

$$S_X = s_a \cos(wt) + s_b \cos\left(wt + \frac{2\pi}{3}\right) + s_c \cos\left(wt + \frac{4\pi}{3}\right)$$

$$S_X = S\sin(\theta) \quad (7).$$

The magnitude of signal S is derived from;-

$$|S| = \sqrt{S_R^2 + S_X^2} \quad (8).$$

This presumes that the input phasor set, sa, sb, and sc, comprises three-phase signals rotating in synchrony with the reference phasors sin(wt), sin(wt+2π/3), and sin(wt+4π/3), all possessing unit magnitude. Recognizing the improbability of balanced input phasors being in synchronism with the reference phasor set, filtering is used to focus on the power frequency component and remove components that do not rotate in synchronism with the reference phasors.

In this generalized formula, s_a, s_b, and s_c represent sampled three-phase current signals, whereas sin(wt), sin(wt+2π/3), and sin(wt+4π/3) constitute a three-phase set of unit magnitude reference phasors. S denotes the positive phase sequence current.

For the balanced components, the designations S_R and S_X are essentially direct current. Imbalanced elements in the input phasors produce sinusoidal signals at the power system frequency or its second harmonic.

Numerous filtering approaches exist for the extraction of these DC components, and several windowing procedures have been examined. The extraction methods for the aforementioned are represented as follows:

$$S_{DR} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n\left(s_{an}\sin(wn) + s_{bn}\sin\left(wn + \frac{2\pi}{3}\right) + s_{cn}\sin\left(wn + \frac{4\pi}{3}\right)\right)$$

$$S_{DX} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n\left(s_{an}\cos(wn) + s_{bn}\cos\left(wn + \frac{2\pi}{3}\right) + s_{cn}\cos\left(wn + \frac{4\pi}{3}\right)\right)$$

and;-

$$|S_D| = \sqrt{S_{DR}^2 + S_{DX}^2} \quad (9).$$

where:-

S_{DR} and S_{DX} are the derived real and quadrature values for S_D n is the sample, N is window length, F_n is the window function.

The window length is an integer multiple of power system frequency cycles, influencing the algorithm's reaction speed and the filter's frequency selectivity. The technique defined in equation (9) employs a positive rotating set of reference phasors, hence facilitating the extraction of the positive phase sequence components of s_a, s_b, and s_c. To extract the negative phase sequence components, a collection of negative rotating reference phasors is needed, namely:

sin(wt), sin(wt+4π/3) and *sin(wt+2π/3)*

The negative phase sequence extraction algorithm is:-

$$N_{DR} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n\left(s_{an}\sin(wn) + s_{bn}\sin\left(wn + \frac{4\pi}{3}\right) + s_{cn}\sin\left(wn + \frac{2\pi}{3}\right)\right)$$

$$N_{DX} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n\left(s_{an}\cos(wn) + s_{bn}\cos\left(wn + \frac{4\pi}{3}\right) + s_{cn}\cos\left(wn + \frac{2\pi}{3}\right)\right)$$

and;-

$$|N_D| = \sqrt{N_{DR}^2 + N_{DX}^2} \quad (10).$$

The zero phase sequence components are extracted in a similar manner using a static set of reference phasors i.e.:-

sin(wt), sin(wt) and *sin(wt)*

It is possible to deconstruct the zero phase sequence extraction method into the following:

$$Z_{DR} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n (s_{an} + s_{bn} + s_{cn}) \sin(wn)$$
$$Z_{DX} = \frac{1}{N}\sum_{n=-N}^{n=0} f_n (s_{an} + s_{bn} + s_{cn}) \cos(wn)$$

$$\left| Z_D \right| = \sqrt{Z_{DR}^2 + Z_{DX}^2} \quad (11).$$

III. THE NEGATIVE PHASE SEQUENCE ALGORITHM IS BEING IMPLEMENTED.

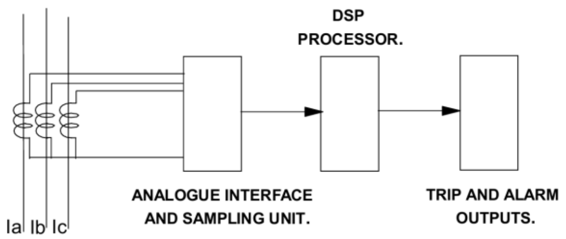

Figure 3. Block Diagram for the Numeric Relay

A relay platform that is based on a general-purpose microprocessor has been provided with the algorithms that have been created for implementation. The current inputs of a typical unit would be converted using 14-bit A/D conversion, and the unit would be based on a digital signal processor (DSP). The tests that were conducted for the demonstration were based on a power system that operated at 50Hz and used a sampling rate of 24 samples per cycle across all channels. Through the use of a numerical phase locked loop tracking technique, the sampling clock was coordinated with the frequency of the power supply system. A block schematic of such a system may be seen in figure 3, which can be found here.

As a result of the extensive number of functions that are accessible, selecting the appropriate windowing function turned out to be a challenging effort [4,5]. Following the examination of the performance of a number of distinct functions, the two cycle Kaiser window was ultimately selected as the optimal solution since it offers an appropriate speed of reaction while also exhibiting a minimal amount of overshoot. A possible signal extraction time of between 10 and 40 milliseconds was supplied as a result of this, in addition to an efficient filtering function.

IV. SIMULATION STUDIES.

MATLAB was used for simulations, and a model of a perfect three-phase synchronous generator feeding a balanced load through a feeder network was made. To show how the negative phase sequence algorithm works, a number of short circuit fault and broken wire situations were looked at.

Figure 4 shows what happens when a single phase to ground fault is put on the generator's connections after 0.1 seconds. After the fault, the program finds the new number in less than 36 ms.

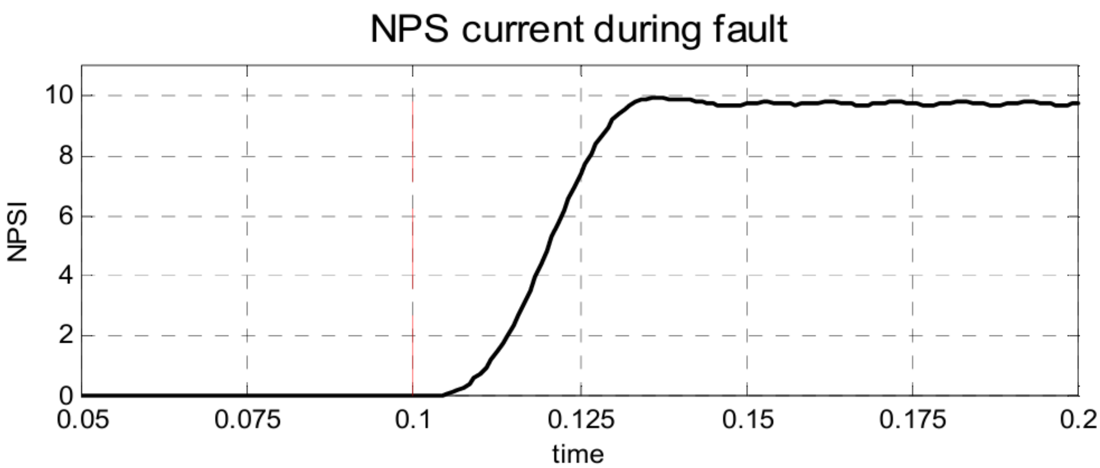

Figure 4. Single Phase to Ground Fault at the Generator Terminals

If there was a phase-to-phase fault on the generator's inputs, the reaction was the same, as shown in Figure 5.

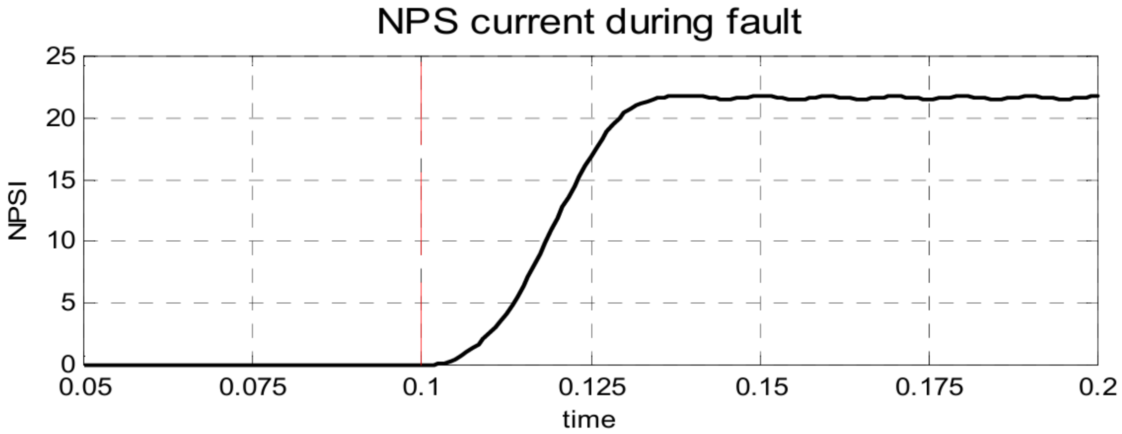

Figure 5. Phase to Phase Fault at the Generator Terminals

When there was a three-phase fault at the generator terminals, the response showed that during the algorithm's data capture period, which is equal to the length of the window, a negative phase sequence component was found. This could be confusing if the filter output was used without any further processing. Adding a 30 to 40 ms. check to the output to make sure that a transient like this doesn't cause annoying tripping will stop this problem. This would, of course, make the transfer work longer and the choice to trip take longer. In figure 6, you can see how to fix this fault.

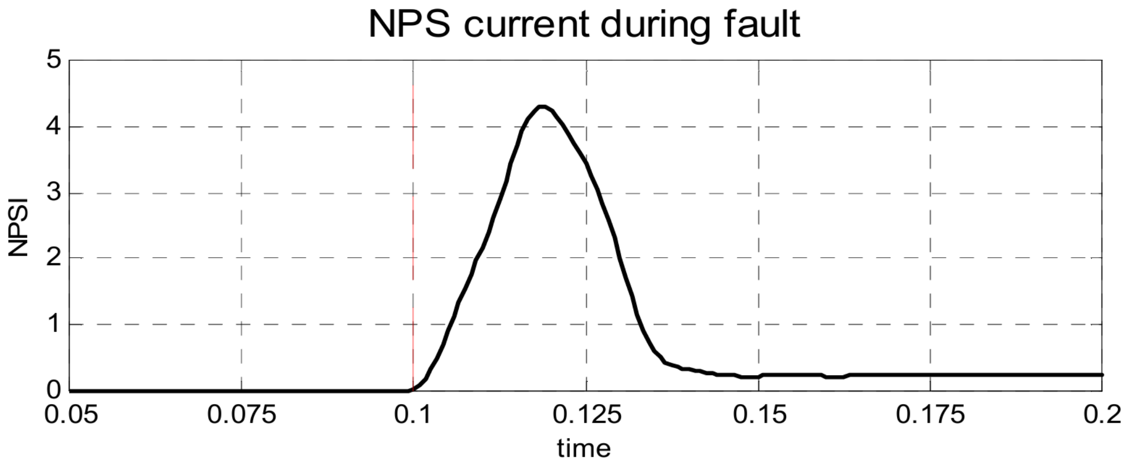

Figure 6. Three-Phase Fault at the Generator Terminals

The successful removal of a phase-to-phase fault is shown in Figure 7. The fault is put in place after 0.1 seconds and taken away after 0.15 seconds.

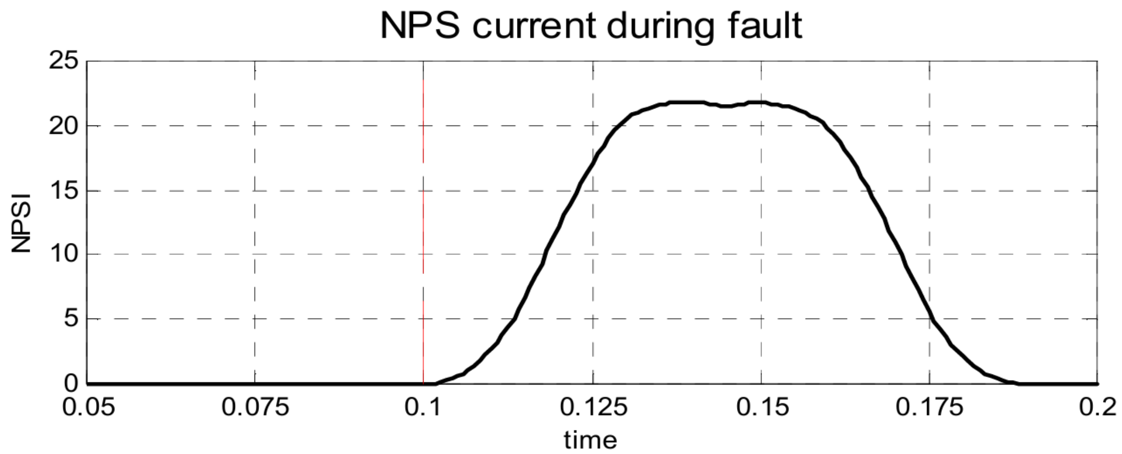

Figure 7. Phase to Phase Fault at the Generator Terminals cleared after 50 ms

A load that isn't balanced is shown in Figure 8, which looks at what happens when one part of the load is lost.

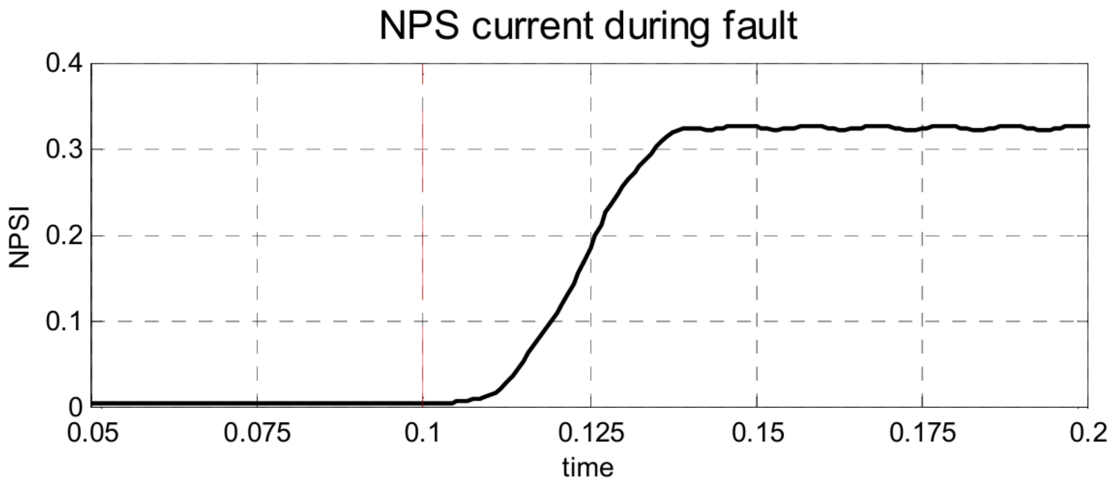

Figure 8. Loss of One Phase of the Load on the Generator

Figure 9 illustrates the reaction that transpired as a result of the loss of two phases of the load.

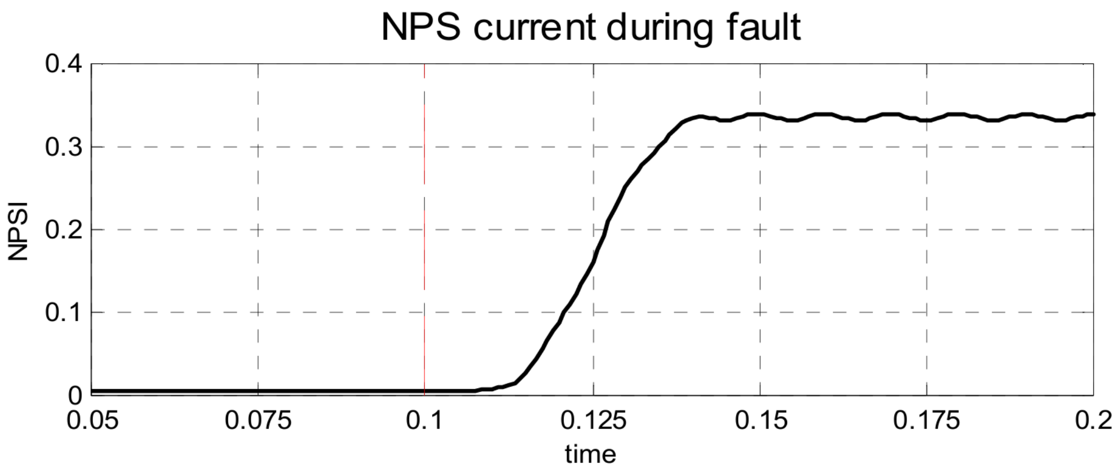

Figure 9. Loss of Two Phases of the Load

It was looked into why the recorded negative phase sequence component went up and down after two phases of the load were lost, as shown in Figure 9. The power system frequency tracking method that was used to lock the sample to the power system signal pattern was found to have trouble with this. As long as the tracking method has a lot of filtering and pauses, this could be a problem area when the application involves small or medium-sized generation that could cause big changes in frequency after a disturbance.

V. CONCLUSIONS.

Through the use of a three-phase rotating set of reference phasors as the foundation for a filter that is designed to extract the negative phase sequence from three-phase data, an appealing protection and monitoring method may be developed. The use of a two-cycle Kaiser window results in an efficient filter characteristic and a possible signal extraction time that ranges from ten to forty milliseconds respectively. It is recommended that a delay of thirty to forty milliseconds be included into a relaying application in order to prevent the likelihood of a nuisance tripping occurring as a result of filter transitory actions. This would result in a tripping time that is dependable and falls anywhere between 40 and 80 milliseconds.
Together with the accompanying positive and zero phase sequence algorithm, this negative phase sequence extraction technique is capable of being implemented in a protection platform that is based

on a DSP processor and uses an adequate sampling rate. This is possible since the platform is based on a numeric microprocessor. In further study, these concepts will be developed in order to offer particular relaying capabilities and to include these algorithms into software that is capable of performing many relay roles.

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