Removal of Decaying DC Component in Current Signal Using a Novel Estimation Algorithm

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Abstract: *In protection relaying schemes, the digital filter unit plays the essential roles to calculate the accurate phasor. However, while the fault current contains plentiful decaying dc component, the over-reach of distance protection will cause several problems. This work develops an algorithm which can estimate and eliminate the decaying dc component from fault current signals after one cycle from the fault instant. Also, it can be applied to a conventional discrete Fourier transform to calculate phasor quantities of fault currents in a digital protection relay. In this algorithm the magnitude and time constant of the decaying dc component are estimated exactly by integrating fault current during one cycle. Decaying dc offset removal is carried out before applying the current signal to the digital filter used for phasor estimation. A relay is modeled in ATP using this algorithm to calculate correct phasor. Simulations results illustrate the effectiveness of this new algorithm for relaying applications.*

Keywords: decaying DC, discrete Fourier transform (DFT), dc time constant, dc magnitude, fault current.

1. Introduction

In protection relaying schemes, the digital filter technologies play the essential roles. Usually, the most widely used algorithm is the discrete Fourier transform (DFT) [1]. When the measurements only contain fundamental frequency and integer harmonic frequency components, full-cycle DFT only needs one-cycle samples to obtain the accurate fundamental phasor. However, in most cases, the fault currents contain a decaying dc component. Since the noninteger harmonic components are in decaying dc, the DFT algorithm does not have the ability to filter out the decaying dc component.

Many researches [2]–[8] have been proposed to remove the decaying dc contained in fault current. These researches are categorized into two groups according to the way the decaying dc time constant is obtained. One is transmission-line analyzing: First, a proper decaying dc time constant is considered. Then, the decaying dc time constant is given as a constant to the digital filter. Finally, the decaying dc component can be removed by filter. In [2], Benmouyal has proposed a digital mimic filtering technique to remove the decaying dc component. The decaying dc time constant is first given by transmission-line analysis. Then, the decaying dc is removed by the digital mimic circuit equation. Recently, an adaptive compensation method to remove a decaying dc offset component from the fault signals has been described in [3]. This method can work properly for both the normal signal and the signal involving the decaying dc component cases. If the time constant given to the mimic filter is very close to the actual value, the decaying dc can be removed completely from measurement. However, if the time constant specified to the mimic filter is far from the correct value, the mismatch time constant will cause the non-negligible error. Other way is the waveform analyzing: As proposed in [4]–[7], the design of a digital filter is based on analyzing the signal waveform. First, the decaying dc component is assumed to be involved in measurement. Then, the exact solution of magnitude and time constant of decaying dc component are determined by digital filtering process. Finally, the accurate phasor can be obtained by removing the decaying dc component. In [4] and [5], Gu and Yang have proposed DFT-based algorithms to completely remove the decaying dc component. Those algorithms use three continuous DFT results to calculate the unknown parameters of the decaying dc component. Thus, the time constant and magnitude of the decaying dc component can be exactly obtained, and the decaying dc component can be removed. In [6], Sidhu has also proposed a DFT-based filtering technique to remove the decaying dc component. This algorithm uses the simultaneous equations developed by a different harmonic basis to obtain the unknown parameters of a decaying dc component. Thus, the decaying dc component can be quickly removed by one- or half-cycle samples. An adaptive phasor estimation algorithm to suppress the effect of an exponential decaying dc component based on the weighting least error square (LES) technique is proposed [7]. This approach has the advantage in that it removes the decaying dc offset regardless of its initial magnitude and time constant, while the disadvantage of the method is that the dc component is determined by the complex calculation procedure, moreover some waveform analyzing methods for the normal signal, that the decaying dc component does not involve, need some extra scheme for judgment and tuning the filtering process. The dc estimation method has difficulty in calculating the exact dc component from the original signal and requires more calculation times. But, if the dc component can be estimated, this method is not affected by the power system configuration, fault resistance, and fault location. Recently a new algorithm has been proposed in [8]. It can be categorized as transmission line analysis method. This algorithm uses a mimic filter to remove decaying dc effect from calculated phasor. Then, an adaptive scheme, using accurate current and voltage phasor, is proposed to obtain the decaying time constant. This time constant is applied to mimic filter for next step.

In this paper, a new algorithm to estimate and eliminate the decaying dc component in a fault current signal is described. The magnitude and time constant of the dc component were estimated by integrating the fault current. The dc-removed current signal was obtained by eliminating the dc component from the fault current at each sampling instant. We evaluated the performance of the proposed algorithm in the time domain using ATPDRAW and MATLAB. For evaluation of the algorithm, we performed dc component estimation tests with several dc component cases. The distance protection test was performed with a simple power system. A relay was modeled in MODEL part of ATP. In this distance relay we used the proposed algorithm to calculate the correct phasor. The advantage of this work is that we can see what happens after tripping by relay while it is not possible when we do all the calculations after simulation the power system. The results of the test cases showed that the proposed algorithm can estimate the dc component exactly from fault currents for any time constant and any system configuration, moreover this algorithm for either normal signal or signal including decaying DC has a perfect performance.

2. The Proposed Technique

Let the sampled signal of interest be represented by:

$$x(k) = Ae^{-k\Delta t/\tau} + \sum_{n=1}^{M} A_n \cos(n\omega k\Delta t + \varphi_n) \qquad (1)$$

where A is the magnitude of the decaying dc offset, τ is the time constant of the decaying dc offset, Δt is the sampling period, n is the harmonic order A_n is the magnitude of the nth harmonic component, φ_n is the phase angle of the nth harmonic component, and M is the maximum harmonic order.

The signal contains an exponential component in addition to a set of harmonics, which is usually limited by an anti-aliasing filter.

If we take the integral of both sides of (1) over a complete cycle (T) of the fundamental frequency the value of the integral is affected only by decaying dc component because the integral of the main component and harmonics per cycle is zero. For digital signals integral is calculated by summing the samples.

$$S(N) = \sum_{k=1}^{N} x(k) = \frac{Ae^{-\Delta t/\tau}(1 - e^{-N\Delta t/\tau})}{1 - e^{-\Delta t/\tau}} \qquad (2)$$

$$S(N+1) = \sum_{k=2}^{N+1} x(k) = \frac{Ae^{-2\Delta t/\tau}(1 - e^{-N\Delta t/\tau})}{1 - e^{-\Delta t/\tau}} \qquad (3)$$

$$E = e^{-\Delta t/\tau} \qquad (4)$$

From (2) and (3) we can easily conclude that:

$$E = \frac{S(N+1)}{S(N)} \qquad (5)$$

Since Δt is the sampling period, and it is much lower than the time constant of the power system. we can use only the first two terms of the Taylor series expansion of E to calculate the time constant and simplify the time constant to be.

$$e^{-\Delta t/\tau} = 1 - \frac{\Delta t}{\tau} \qquad (6)$$

Then magnitude and time constant of the decaying DC can be calculated without using logarithm function which is a computational burden from the practical perspective. Using (4), (5) and (6):

$$\tau = \frac{S(N).\Delta t}{S(N) - S(N+1)} \qquad (7)$$

$$A = \frac{S(N).\Delta t}{-\tau E(E^N - 1)} \qquad (8)$$

Finally the value of the decaying DC is calculated for each sample and correct signal is estimated.

$$x_{cor}(k) = x(k) - AE^k \qquad (9)$$

The algorithm is described by the following eight steps.

Step 1) calculate the integral of the signal from t-T to t

Step 2) calculate the integral of the signal from t-T+Δt to t+Δt

Step 3) calculate decaying dc time constant

Step 4) calculate the value of the decaying dc for time t+Δt

Step 5) calculate the decaying dc value for other samples in last cycle (from t-T+Δt to t+Δt) using the calculated value in last tow before steps

Step 6) subtract dc value from fault signal for each sample from t-T+Δt to t+Δt

Step 7) calculate correct phasor using DFT

Step 8) t=t+Δt and go to step 2

Notice that a full cycle plus on sample of post fault data are required to apply the proposed method. The corrected signal (x_{cor}) can now be used with any digital filter algorithm, such as the full-cycle DFT, to obtain the magnitude and the phase angle of the fundamental frequency phasor.

3. Simulation Results

In order to verify the performance of the proposed algorithm, two types of simulation tests were performed with MATLAB and ATP.

The first simulation test was a static test. In this test, several sampled signals, which contained a dc component, were applied to verify the performance of the dc component. The calculated time constants and fundamental components were compared to the applied signals and calculated value with base method like conventional DFT and mimic filter. The second simulation test was a dynamic test. In this test, the proposed algorithm was applied to the distance relaying scheme in the sample power system and the performance of the distance relaying was compared to the cases of a conventional DFT and mimic filter plus DFT method [2].

3.1 Static test

Simulation with test signal was performed to evaluate the performance of the dc magnitude and time constant calculation algorithm. Test signals consisted of a fundamental component and a dc component with different magnitudes and time constants. The magnitude of the fundamental component and the decaying dc component was set to respectively 5 and 4.6. The time constants used for the performance evaluation were 5, 25, 50, 100, 150, and 200ms. Also, the sampling rate was set to 64 samples per cycle.

The real decaying dc and the estimated decaying dc is shown in Fig. 1. The time constant of the applied decaying dc was set to 25ms.

The time-domain responses of the fundamental value of the applied signal using the proposed algorithm, conventional DFT, and the mimic filter plus DFT can be seen Fig. 2 and Fig. 3. In this case, the time constants of 25 ms and 200 ms with a 4.6 DC magnitude and 5 fundamental component magnitude were applied. The time constant of the mimic filter was set to 0.5 cycle. In Fig. 2 and Fig. 3, the conventional DFT had oscillations in the fundamental component and required more times to obtain a stable output. But the proposed algorithm extracted the fundamental component without any undesired oscillation in one cycle and delay to obtain a stable output.

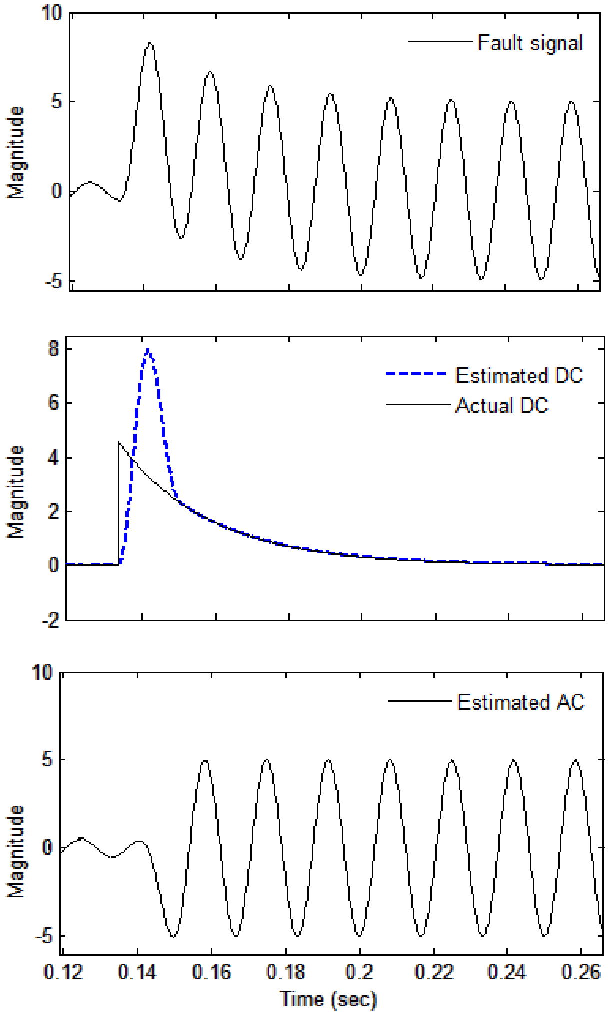

Fig 1. Fault signal, estimated DC and estimated AC.

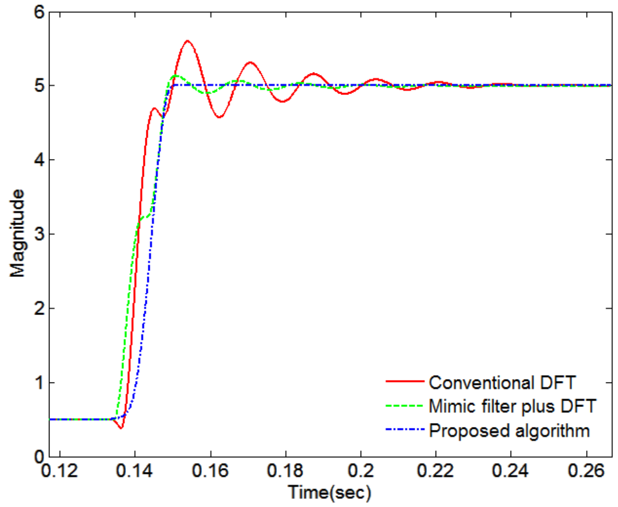

Fig 2. Time domain response of the proposed algorithm, conventional DFT and mimic filter for time constant 25ms.

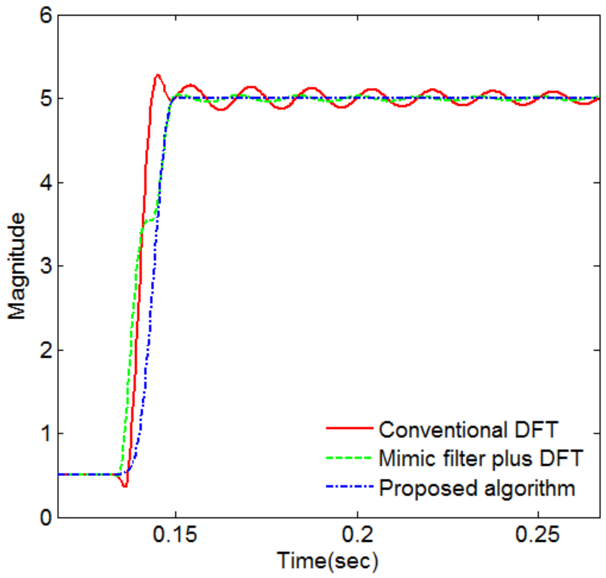

Fig 3. Time domain response of the proposed algorithm, conventional DFT and mimic filter for time constant 200ms**.**

3.1 Dynamic test

In this section the proposed algorithm was evaluated by a simple power system. The simulated system is shown in Fig. 4. The parameters of this system are listed in Table 1. The test power system was simulated using the ATP. Fault currents were measured at Bus S. The analog measurements were then sampled by 3840 Hz (64 samples per cycle). The DFT was used to obtain the phasors for all the simulations. We performed tow kinds of simulations. In one a fault in sample power system was simulated in ATP then the information obtained by ATP was used to decaying dc and phasor estimation calculations in MATLAB. In other kind the fault was simulated in ATP and the phasor estimation is performed by the MODEL part in ATP. In MODEL voltage and correct current phasor is calculated and apparent impedance is obtained sample by sample and a distance relay is implemented. The distance characteristic is *mho* type. 85% of line is in zone 1. The simulation results of these tow kind of test is illustrated in next parts.

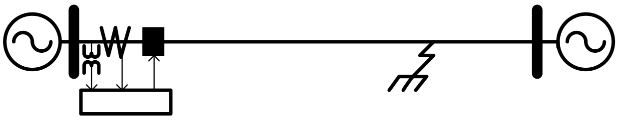

Fig 4. Single line diagram of the model system.

TABLE I

Parameters of the simulation system

Phase to ground voltage 408.248 Kv
System frequency 60Hz
Generators parameters:
E_S=1.0 ∠ 20° pu E_R=1.0 ∠ 0°pu
Z_{S1}=7+j60(Ω) Z_{R1}=0.5+j5(Ω)
Z_{S0}=14+j120(Ω) Z_{R0}=0.5+j5(Ω)
Transmission line parameters: Length L=100km
R1=0.0306(Ω/km) L1=0.96(mH/km) C1=12.03 (nF/km)
R0=0.304(Ω/km) L0=3.6(mH/km) C0=7.52 (nF/km)
Data Acquisition:
Sampling frequency: 3840Hz.

3.1.1 Without relay operation

In order to have a more complete picture of the performance of the two techniques, the apparent impedance from the relay located at bus 1percpective. 6, when a 3phase -to-ground fault occurred at a fault distance of 80%. As shown in these Fig. 5 the distance relay adopting the proposed algorithm had no problems with the operations. But the apparent impedance calculated by conventional DFT entered and exited the impedance characteristic several times.

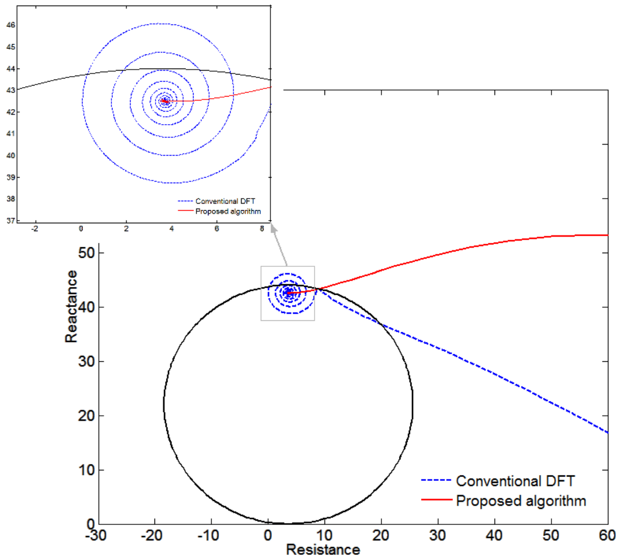

Fig 5. Apparent impedance from sending end perspective.

3.1.2 Relay operation

In this section the relay operates after detecting fault. And the fault is cleared by relay order. Relay recloses the line breaker half cycle after trip by relay.

- **Scenario A**

In this scenario a 3phase to ground temporary fault occurs at 0.170s and disappears at 0.19s.

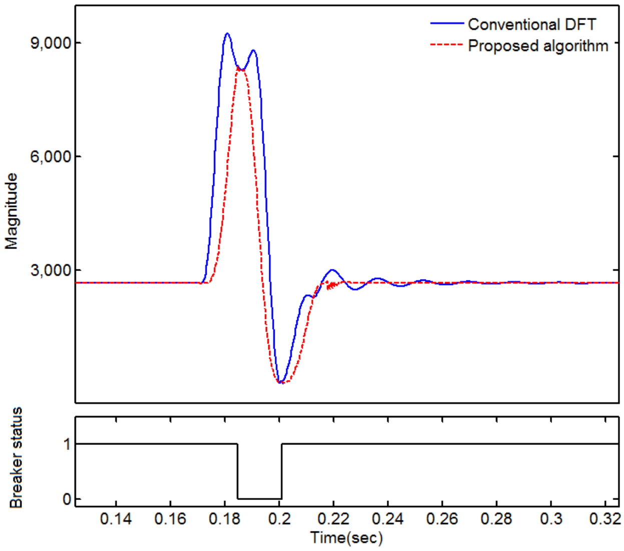

Fig. 6. Current phasor estimated by proposed algorithm and conventional DFT in scenario A

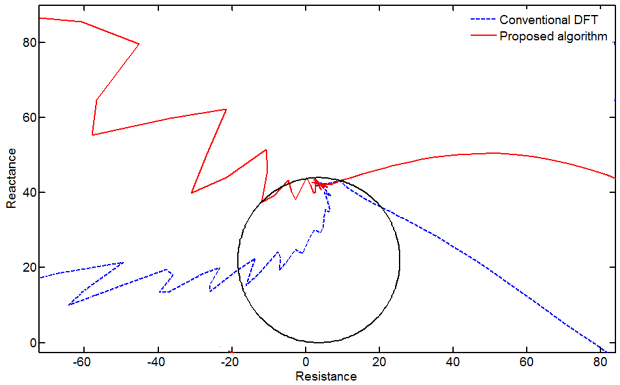

Fig. 7. Apparent impedance from sending end perspective in scenario A

The simulations show that fault is detected and cleared 14.93ms after fault instant at 0.18493s (less than one cycle after fault instant). The breaker is reclosed at 0.2009s after fault was disappeared and system goes to normal condition. Fig. 6 shows that the current signal contains decaying dc component after reclosing and the proposed algorithm eliminate it completely.

- **Scenario B**

In this scenario a 3-phase to ground fault occurs at 0.170s and it does not disappear.

The result of simulations for this scenario is shown in Fig. 8, 9.

as shown in Fig. 8,9 fault is detected and cleared 14.93ms after fault instant at 0.18493s (less than one cycle after fault instant). The breaker is reclosed at 0.2002s. Relay Detects and clears fault for second time at 0.2062s (less than half cycle after reclosing).

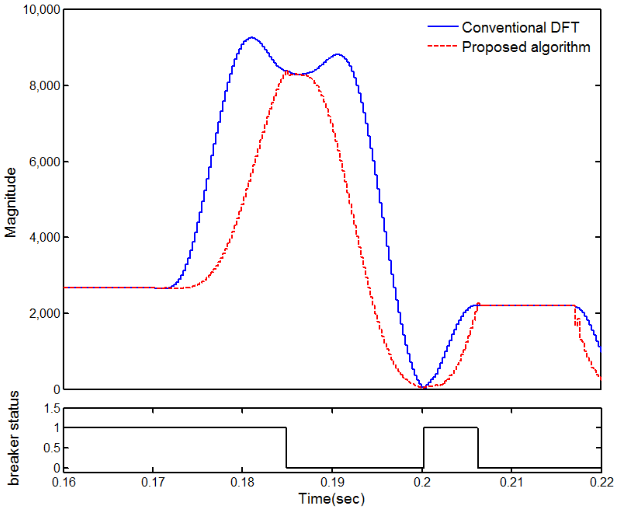

Fig. 8. Current phasor estimated by proposed algorithm and conventional DFT in scenario B

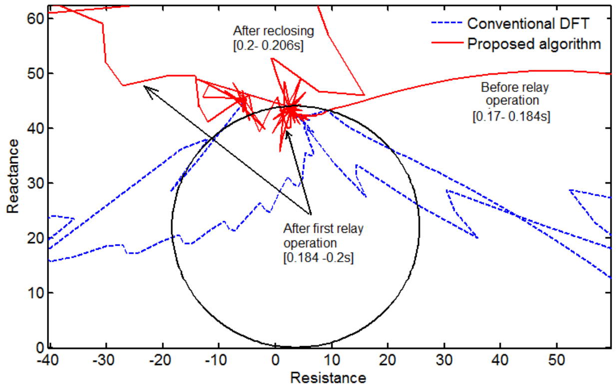

Fig 9. Apparent impedance from sending end perspective in scenario B

4. Conclusion

A simple and numerically efficient method for the removal of decaying dc offset from current signals in digital protective device has been proposed. This algorithm estimate magnitude and time constant of the decaying dc by integrating fault current per cycle. The method requires a full cycle plus one sample of post-fault data to estimate the parameters of the decaying dc offset. The removal of the dc offset from the current signal is performed before applying the signal to the digital filter used for phasor estimation. The method is tested by applying it in a relay modeled in ATP. The results obtained demonstrate that the method is capable of completely eliminating the dc offset and thus greatly improving the performance of the full-cycle DFT algorithm.

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