Generalized Phasor Estimation Method Based on DFT with DC Offset Mitigation

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***Abstract*—This paper proposes a generalized discrete Fourier transform (DFT) based dc offset mitigation method to improve the accuracy of phasor estimation during faults. The DFT is applied to the signal and the results are separated into multiple sets, where each set contains the information of both the fundamental frequency component and the decaying dc offset of the signal. This formulation enhances the redundancy of the dc offset estimation problem. Afterwards, the dc offset is as the unknown to be estimated and the state estimation procedure is adopted to solve this problem. The proposed method provides a generalized framework for phasor estimation with full consideration of problem redundancy. Numerical experiments validate that the proposed method presents higher phasor estimation accuracy compared to the existing phasor estimation methods. Furthermore, the proposed method also demonstrates robustness against measurement noises.**

***Index Terms*—Phasor Estimation, Fault Signal, Discrete Fourier Transform (DFT), DC Offset, Multiple Sets**

I. INTRODUCTION

Power system protective relaying and fault location play irreplaceable roles in modern power systems to ensure safety and the reliable operation of the power systems. During faults, the fault current signal typically contains decaying dc offset, fundamental frequency component and higher order harmonics. Accurate fundamental frequency phasor estimation is essential for proper operations of the fundamental frequency phasor based protective relaying (distance protection, line differential protection [1], etc.) and fault location (impedance based methods [2], other phasor domain approaches [3], etc.). To address this issue, researchers proposed phasor estimation methods to obtain the fundamental frequency phasor from the fault signal [4-8].

Existing phasor estimation methods can be mainly classified into the DFT based methods, the LS based methods, and the artificial intelligence based methods, etc. The LS based methods usually utilize a series of pre-assumed functions of the dc offset and harmonics to fit the process of electromagnetic transient during the faults. By the principle of the least square error, the fundamental frequency phasor can be calculated. The main limitation is that it is challenging to select proper pre-assumed functions to match the real fault signal [6]. Artificial intelligence based methods estimate phasors through the training process, with the information embedded inside the training measurement data during the faults. Yet, these methods generally need a large number of high-quality training data that represent the complete characteristics of fault signal. These high-quality training data may not be available in practice [8]. In comparison, the discrete Fourier transform (DFT) based methods extract the fundamental frequency phasors based on the orthogonality relationship of harmonics with different orders. These methods are widely adopted to calculate the fundamental frequency phasors due to their reliability, simplicity, accuracy and speed [9].

The conventional DFT based methods (such as the IEEE C37.118 synchrophasor standard) of phasor estimation are not ideal [10-11]. The fault signal usually contains the exponentially decaying dc offset. DFT based methods can filter out harmonics to obtain the fundamental frequency phasor but the non-periodic exponentially decaying dc component is neglected, which may result in phasor estimation errors. The magnitude error of DFT based phasor estimation could reach up to more than 10% [12]. Therefore, researchers proposed DFT based modified phasor estimation methods with mitigation of dc offset, by subtracting the dc offset from fault signal [13-18]. In [13], the dc offset component and the sinusoidal components are obtained by DFT, and then the dc offset component is estimated using the subtraction of two adjacent phasors. This method requires the data window more than one cycle. Literature [14] gives a new way to estimate dc offset using three consecutive DFT; the method still requires the data window of more than one cycle. Literature [15-16] presents a novel method to obtain the fundamental frequency phasor using one cycle window. It generates an auxiliary signal from the down-sampling of the fault signal. After that, the dc offset can be estimated by the summation of consecutive samples information. Literature [17] uses four samples information to obtain the amplitude and time constant to determine the dc offset. Then the fundamental frequency phasor can be estimated easily using one cycle data; in this method the even harmonics are neglected and the method does not fully utilize the redundancy inside the data window, resulting in high sensitivity towards harmonics and noises. Literature [18] divides the fault signal into even sample sets and odd sample sets to estimate the dc offset.

In fact, DFT adopts a “summation” calculation (typically the entire span of the data window) to extract components of interest inside the waveform. However, the “summation” operation itself may result in loss of important information embedded inside the waveform (“summation” operation is actually a “many to one” mapping: it is obvious that one cannot recover the entire signal from the summation result only). Therefore, the way to maximize the utilization of the information within the fault signal is essential to improve phasor extraction accuracy.

In this paper, a generalized phasor extraction method with mitigation of dc offset is proposed. One cycle time window is required for the proposed method. The results of DFT are separated into multiple sets, where the fundamental frequency phasor and the exponentially decaying dc offset information are embedded inside each set. Through this way the information redundancy of the phasor extraction problem is much improved. Afterwards, a generalized model is established by combining the multiple sets, and the dc offset as well as the fundamental frequency phasor can be solved through the state estimation procedure, to ensure full utilization of information redundancy. In fact, the proposed method provides a generalized framework for DFT based

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phasor extraction, and the existing method in [18] is a special case of the proposed method. Numerical experiments prove the accuracy and robustness of the proposed phasor extraction method. The rest of the paper is arranged as follows. Section II reviews an example existing DFT based phasor estimation method with mitigation of dc offset and derives the proposed method. Section III validates the effectiveness of the proposed method through numerical experiments, by comparing the performance of the proposed method to the several existing methods. Section IV concludes the paper.

II. Proposed Phasor Estimation Method with Mitigation of Dc Offset

This section first reviews the existing DFT based phasor extraction method with dc offset mitigation in [18]. Afterwards, the detail derivation of the proposed method is demonstrated.

A. Review of Existing Method in [18]

When a fault occurred in a power system, the discrete expression of the fault current signal is,

$$i[n]=i_{dc}+i_{ac}=A_0 e^{\frac{-n\Delta t}{\tau}}+\sum_{k=1}^{N/2-1}A_k\cos(2\pi/N\cdot k\cdot n+\varphi_k) \quad (1)$$

where A_0 and τ are the amplitude and the time constant of the exponentially decaying dc component, k is the order of the harmonic (it is assumed that the component is eliminated by a low pass filter when the order of harmonic component is higher than (N/2 − 1), to meet the requirement of Nyquist Theorem). A_k and φ_k are the amplitude and initial phase angle of the k^{th} harmonic component. n is the sample index, and Δt is the sample time. N is the number of samples per cycle. With one cycle time window, applying DFT algorithm,

$$I_{DFT}=2\pi/N\cdot\sum_{n=0}^{N-1}i[n]\cdot e^{-j(2\pi/N)n}=I_{DFT}^{1th}+I_{DFT}^{dc} \quad (2)$$

where $I_{DFT}^{1th}=A_1e^{j\varphi_1}$, and I_{DFT}^{dc} is shown in (3).

$$I_{DFT}^{dc}=2\pi/N\cdot A_0(1-E^N)/(1-EP) \quad (3)$$

where $E=e^{-\Delta t/\tau}$ and $P=e^{-j(2\pi/N)}$.

Next, the existing method in [18] deals with formula (2) in the following way, to solve I_{DFT}^{1th} and I_{DFT}^{dc}. Rewrite (2) as,

$$I_{DFT}=2/N\cdot\sum_{n=0}^{N-1}i[n]\cdot P^n=I_{DFT}^{even}+I_{DFT}^{odd} \quad (4)$$

where I_{DFT}^{even} and I_{DFT}^{odd} are the even and odd sample sets of one cycle, with the following results,

$$I_{DFT}^{even}=A_1e^{j\phi_1}/2+2A_0(1-E^N)/\{N[1-(EP)^2]\} \quad (5)$$

$$I_{DFT}^{odd}=A_1e^{j\phi_1}/2+2EPA_0(1-E^N)/\{N[1-(EP)^2]\} \quad (6)$$

Then the existing method eliminates the fundamental frequency component by combining (5) and (6),

$$I_{DFT}^{even}-I_{DFT}^{odd}=2A_0(1-E^N)/[N(1+EP)] \quad (7)$$

As (7) is a complex equation containing the real number unknowns A_0 and E . It can be divided into the real part and the imaginary part. Define K_{RE} as the real part of $I_{DFT}^{even}-I_{DFT}^{odd}$, and K_{IM} as the imaginary part of $I_{DFT}^{even}-I_{DFT}^{odd}$,

$$K_{RE}=\frac{2}{N}A_0\frac{1-E^N}{1+E^2+2E\cos(2\pi/N)}(1+E\cos(2\pi/N)) \quad (8)$$

$$K_{IM}=\frac{2}{N}A_0\frac{1-E^N}{1+E^2+2E\cos(2\pi/N)}(E\sin(2\pi/N)) \quad (9)$$

From (8) and (9), the variable E can be solved as,

$$E=K_{IM}/[K_{RE}\sin(2\pi/N)-K_{IM}\cos(2\pi/N)] \quad (10)$$

Therefore, the dc offset component I_{DFT}^{dc} can be obtained through (3), (7) and (10),

$$I_{DFT}^{dc}=(I_{DFT}^{even}-I_{DFT}^{odd})(1+EP)/(1-EP) \quad (11)$$

Finally, the fundamental frequency component I_{DFT}^{1th} is,

$$I_{DFT}^{1th}=I_{DFT}-I_{DFT}^{dc} \quad (12)$$

B. Proposed Mitigating DC Offset Method

One can observe from section II.A that the existing method in [18] solves the dc offset with two equations and two unknowns, i.e. there is no redundancy left in this method. Therefore, the main idea of the proposed method fully utilizes the data of one cycle to enhance the redundancy of system containing dc offset component. First, the DFT result I_{DFT} can be divided into multiple sets (k sets in total),

$$I_{DFT}=\frac{2}{N}\sum_{n=0}^{N-1}i[n]\cdot P^n=\frac{2}{N}\sum_{n=0}^{N/k-1}i[kn]\cdot P^n+\frac{2}{N}\sum_{n=0}^{N/k-1}i[kn+1]\cdot P^{(kn+1)}+\cdots$$
$$+\frac{2}{N}\sum_{n=0}^{N/k-1}i[kn+k-1]\cdot P^{(kn+k-1)}=I_{DFT}^{k,1}+I_{DFT}^{k,2}+\cdots+I_{DFT}^{k,k}=\sum_{m=1}^{k}I_{DFT}^{k,m} \quad (13)$$

In fact, each term $I_{DFT}^{k,m}$ includes the information of both dc offset and the fundamental frequency phasor, as follows,

$$I_{DFT}^{k,m}=2/N\cdot\sum_{n=0}^{N/k-1}\left(i[kn+m-1]\cdot P^{(kn+m-1)}\right)=2/N\cdot\sum_{n=0}^{N/k-1}(A_0E^{kn+m-1}$$
$$+A_1\cos(2\pi/N\cdot(kn+m-1)+\varphi_1))\cdot P^{(kn+m-1)}=Term1+Term2 \quad (14)$$

$$Term1=\frac{2A_0}{N}\sum_{n=0}^{N/k-1}(EP)^{kn+m-1}=\frac{2A_0}{N}(EP)^{m-1}\frac{1-E^N}{1-(EP)^k} \quad (15)$$

$$Term2=\frac{2A_1}{N}\sum_{n=0}^{N/k-1}(\cos(2\pi/N\cdot(kn+m-1)+\varphi_1)P^{(kn+m-1)})$$
$$=\frac{1}{k}\cdot\frac{2A_1\cdot k}{N}\sum_{n=0}^{N/k-1}(\cos(2\pi/N\cdot(kn)+\varphi_1)P^{(kn)})=\frac{1}{k}\cdot A_1e^{j\varphi_1} \quad (16)$$

Note that the derivation of *Term2* has the assumption that the DFT process with N/k points in one cycle well approximates the continuous integration in one cycle.

One can observe from (14) to (16) that each $I_{DFT}^{k,m}$ (m = 1, 2, …, k) has two terms. *Term1* is related to the dc offset and is a function of m, with two real unknown variables of A_0 and E. *Term2* is related to the fundamental frequency phasor and is independent of m, with one complex unknown variable (or two real unknown variables) of $A_1e^{j\varphi_1}$. In addition, each $I_{DFT}^{k,m}$ can be calculated individually and corresponds to one complex equation (or two real equations including one real part and one imaginary part).

Therefore, if we list all the available information through this framework, there are 2k real equations and 4 real unknown variables to be estimated. One can observe that the redundancy of this framework is 2k-4, enabling more reliable estimation of the dc offset and the fundamental frequency phasors. **One can also observe that the existing method in [18] is a "special case" of this framework**, with k = 2.

Next, in order to solve the aforementioned problem, the fundamental frequency component (2 real unknown variables) can be eliminated through subtraction between $I_{DFT}^{k,m}$ with different m. For example, the difference between $I_{DFT}^{k,m}$ and $I_{DFT}^{k,k}$ (m = 1, 2, …, k-2) is,

$$I_{DFT}^{k,m}-I_{DFT}^{k,k}=2/N\cdot A_0(EP)^{m-1}(1-E^N)/(1-(EP)^k)-2/N\cdot A_0(EP)^{k-1}\cdot (1-E^N)/(1-(EP)^k)=2/N\cdot A_0((EP)^{m-1}-(EP)^{k-1})(1-E^N)/(1-(EP)^k) \quad (17)$$

After this process, there will be k-1 complex equations (or $2k$-2 real equations) and 2 unknowns A_0 and E. The redundancy is still $2k$-4.

There are many possible ways of solving (17). Here the proposed method first eliminates variable A_0. This procedure results in simplified expressions with only one unknown variable E. Afterward, the state estimation method is adopted for best estimates of E. Considering the following expression for different m (m = 1, 2, …, k-2),

$$\begin{aligned}&(I_{DFT}^{k,m}-I_{DFT}^{k,k})/(I_{DFT}^{k,k-1}-I_{DFT}^{k,k})=((EP)^{m-1}-(EP)^{k-1})/((EP)^{k-2}-(EP)^{k-1})\\&=\frac{1-(EP)^{k-m}}{(1-(EP))(EP)^{k-1-m}}=\left[\sum_{r=0}^{k-1-m}(EP)^r\right]\Big/(EP)^{k-1-m}=\sum_{r=0}^{k-1-m}\frac{1}{(EP)^r}\end{aligned} \quad (18)$$

Separate (18) into the real part and the imaginary part,

$$\mathrm{Re}[(I_{DFT}^{k,m}-I_{DFT}^{k,k})/(I_{DFT}^{k,k-1}-I_{DFT}^{k,k})]=\mathrm{Re}[\sum_{r=0}^{k-1-m}1/(EP)^r] \quad (19)$$

$$\mathrm{Im}[(I_{DFT}^{k,m}-I_{DFT}^{k,k})/(I_{DFT}^{k,k-1}-I_{DFT}^{k,k})]=\mathrm{Im}[\sum_{r=0}^{k-1-m}1/(EP)^r] \quad (20)$$

Therefore, the problem of estimating dc offset component E is with the following standard syntax,

$$\boldsymbol{y}=h(\boldsymbol{x}) \quad (21)$$

where the state vector $\boldsymbol{x}$ = E, and measurement vector $\boldsymbol{y}$ is a column vector that contains $2k$-4 entries,

$$\boldsymbol{y}=[\cdots;\mathrm{Re}[\frac{I_{DFT}^{k,m}-I_{DFT}^{k,k}}{I_{DFT}^{k,k-1}-I_{DFT}^{k,k}}];\mathrm{Im}[\frac{I_{DFT}^{k,m}-I_{DFT}^{k,k}}{I_{DFT}^{k,k-1}-I_{DFT}^{k,k}}];\cdots]^T \quad (22)$$

To solve the states of the overdetermined equation in (22), the proposed method adopts the state estimation procedure to estimate E. The following optimization problem is formulated,

$$\min_x \quad J=\left(\boldsymbol{y}-h(\boldsymbol{x})\right)^T\boldsymbol{W}\left(\boldsymbol{y}-h(\boldsymbol{x})\right) \quad (23)$$

where $\boldsymbol{W}=diag\{\cdots,1/\sigma_i^2,\cdots\}$, and $\sigma_i(i=1,2,\cdots)$ is the error standard deviation of measurement i. The solution can be obtained via the Newton's iterative method until convergence,

$$\boldsymbol{x}^{\nu+1}=\boldsymbol{x}^{\nu}-(\boldsymbol{H}^T\boldsymbol{W}\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{W}[h(\boldsymbol{x}^{\nu})-\boldsymbol{y}] \quad (24)$$

where $\boldsymbol{H}=\partial h(\boldsymbol{x})/\partial\boldsymbol{x}\big|_{\boldsymbol{x}=\boldsymbol{x}^{\nu}}$.

After obtaining the coefficient E, A_0 can be acquired from (17). Here we selected m = 1 as an example to obtain A_0. From (3), the dc offset component is calculated using the estimated A_0 and E. Subsequently, from (2), the fundamental frequency component can be estimated precisely after mitigating the dc offset component,

$$I_{DFT}^{1th}=I_{DFT}-I_{DFT}^{dc} \quad (25)$$

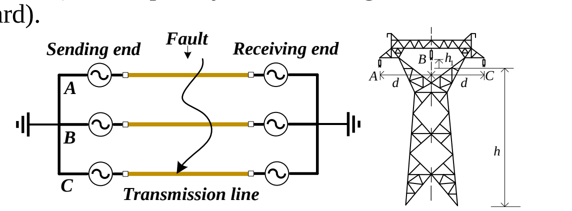
It is worth noting the proposed method is an iterative method. In fact, there are many possible solutions, even non-iterative solutions. From (18), one straightforward way is to directly solve for EP with different m (as shown in equation 26, with m = 3, 4, …, k) and then take the average of the k-2 solutions of EP. Nevertheless, the numerical experiments show that the method using (26) does not present enough robustness towards measurement errors. The authors think that this is probably because the k-2 calculated (EP)s through this procedure does not have the same error distributions, and the calculation error of EP might be magnified through the procedure. Therefore, in this paper the procedure from (21) to (25) is still adopted for phasor estimation.

$$EP=(I_{DFT}^{k,m-1}-I_{DFT}^{k,m})/(I_{DFT}^{k,m-2}-I_{DFT}^{k,m-1}) \quad (26)$$

To sum up, the proposed method provides a generalized framework to fully utilize the data of one cycle by separating the data into multiple sets (k sets). After that, the problem is formulated with improved information redundancy. As a result, the proposed method can more accurately estimate the dc offset as well as the fundamental frequency phasor.

III. Numerical Experiments

To verify the effectiveness of the proposed method of mitigating dc offset in the power system, an example test system of a two terminal three phase transmission line is built in PSCAD/EMTDC. The test system and tower structure are showed in Figure 1. The source impedance of each phase is $10\angle 80^{\circ}\,\Omega$ and $15\angle 75^{\circ}\,\Omega$ at sending end and receiving end. The transmission line is a 500 kV, 200 km transmission line. In the Figure 1 (b), h = 30 m, h_1 = 2 m and d = 10 m. The distributed parameter transmission line model with frequency dependent parameters is utilized in PSCAD/EMTDC to ensure the practicability of the waveforms during the fault. The nominal frequency of the test system is 50 Hz. Three phase instantaneous current measurements are installed at the sending end of the line. The adopted sample rate is 4000 samples/s (80 samples/cycle according to IEC 61850-9-2 standard).



(a) Example test system (b) Typical tower structure

Figure 1. Example test system and typical tower structure

Different faults occurring inside this system generate measured fault currents with dc offset. Here two different single phase to ground (SLG) faults with small and large dc offset are first taken as examples (Test Case 1 and 2) to demonstrate the effectiveness of the proposed method. Afterwards, in Test Case 3, different measurement errors are added the fault currents in Test Case 1, and the proposed method is further validated under those circumstances. **Here the proposed method selects *k* = 4** (where k is defined in equation 13) **as an example**. For each test case, the performances of the proposed method are compared to those of three different DFT based methods: [11] (IEEE synchrophasor standard C37.118), [17] and [18]. Since DFT usually requires one cycle time window, for the demonstration of the results in this section, the values on the time axis mean the starting time of the one cycle for phasor calculation. Here, we assume that the fundamental frequency phasor value during the steady state of the faulted system (long period of time after the fault occurs) is the "ground truth" of the estimated phasors. Then the total vector error (TVE) can be defined as following formula,

$$TVE=\sqrt{\frac{[\mathrm{Re}(\tilde{I}_{est})-\mathrm{Re}(\tilde{I}_{true})]^2+[\mathrm{Im}(\tilde{I}_{est})-\mathrm{Im}(\tilde{I}_{true})]^2}{[\mathrm{Re}(\tilde{I}_{true})]^2+[\mathrm{Im}(\tilde{I}_{true})]^2}}\times 100\% \quad (27)$$

where $\tilde{I}_{true}$ is the true fundamental frequency phasor, and $\tilde{I}_{est}$ is the estimated fundamental frequency phasor. Re(·) and Im(·) are the real and imaginary part of ·

A. *Test Case 1: SLG Faults with Small DC Offset*

This case studies the performances of the proposed method and the existing methods on a phase A to ground fault with relatively small dc offset. The measured phase A fault current at the sending end is shown in Figure 2. The magnitudes, phase angles and TVEs of the estimated phasors are depicted in Figure 3. Note that here the magnitude means the rms value corresponding to the fundamental frequency phasor (same definition for the rest of the figures). It can be observed that the proposed method converges to the true phasor values faster compared to the other existing methods. For the proposed method, method [11], method [17] and method [18], the average TVEs are 0.0265%, 0.7240%, 0.0958% and 0.0629%, respectively. The maximum TVEs are 1.6405%, 2.3423%, 4.6405% and 2.4018%, respectively. One can observe that the proposed method demonstrates higher phasor estimation accuracy than the existing methods.

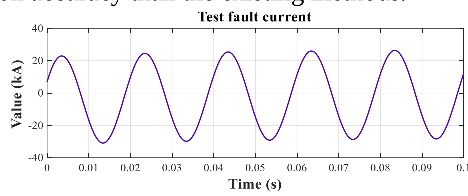


Figure 2. Fault current signal during SLG faults, small dc offset

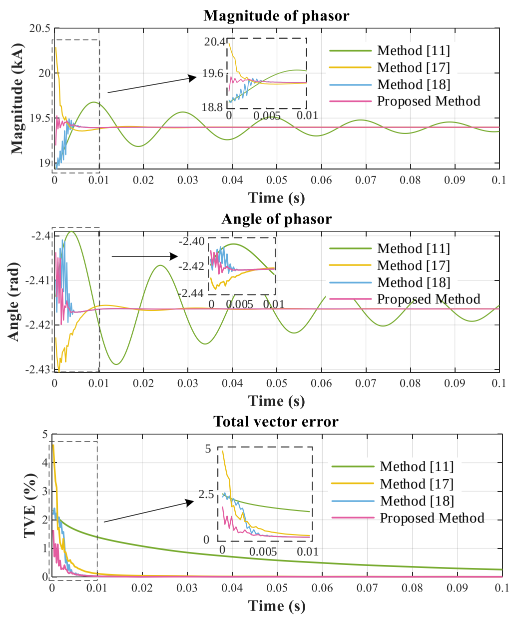


Figure 3. The magnitudes, phase angles and the TVEs of the estimated phasors, small dc offset

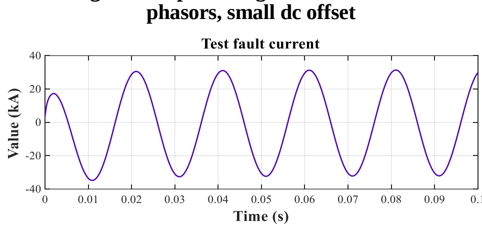


Figure 4. Fault current signal during SLG faults, large dc offset

B. Test Case 2: SLG Faults with Large DC Offset

This case studies the performances of the proposed method and the existing methods on a phase A to ground fault with relatively large dc offset. The measured phase A fault current at the sending end is shown in Figure 4. The magnitudes, phase angles and TVEs of the estimated phasors are depicted in Figure 5. It can be similarly observed that the proposed method converges to the true phasor values faster compared to the other existing methods. For the proposed method, method [11], method [17] and method [18], the average TVEs are 0.0939%, 0.9196%, 0.2332% and 0.3490%, respectively. The maximum TVEs are 9.3718%, 15.8150%, 5.2912% and 19.5873%, respectively. One can observe that the proposed method demonstrates higher phasor estimation accuracy than the existing methods overall.

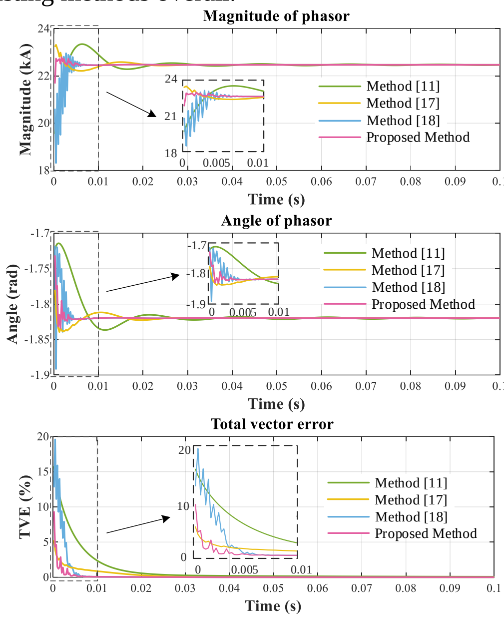


Figure 5. The magnitudes, phase angles and the TVEs of the estimated phasors, large dc offset

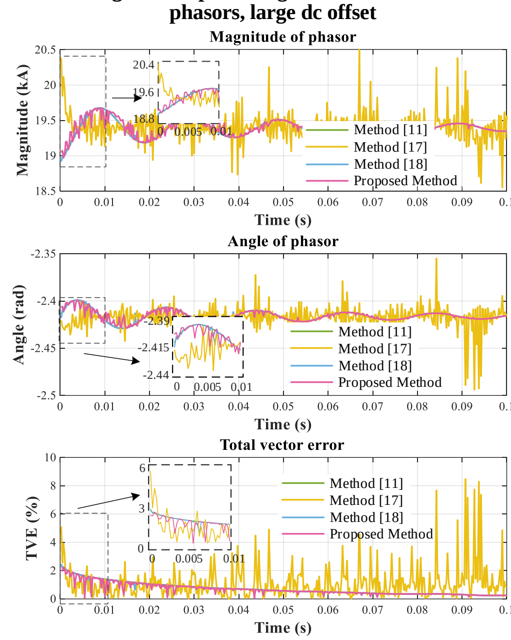


Figure 6. The magnitudes, phase angles and the TVEs of the estimated phasors, 0.5% measurement noises

C. Test Case 3: SLG Faults with Measurement Noises

This case studies the performances of the proposed method and several existing methods with the different noise levels. The current waveform during the fault in Test Case 1 (as shown in Figure 2) is taken as an example. Here 0.5% and 2% Gaussian distributed measurement noises are added to the current waveform, respectively. The magnitudes, phase angles and TVEs of the estimated phasors with 0.5% measurement noises are depicted in Figure 6. It can be observed that the proposed method demonstrates higher robustness towards measurement noises. For the proposed method, method [11], method [17] and method [18], the average TVEs are 0.6647%, 0.7243%, 1.1686% and 0.7201%, respectively. The maximum TVEs are 2.2353%, 2.3436%, 8.4683% and 2.4711%, respectively.

Similarly, the results with 2% measurement noises are depicted in Figure 7. For the proposed method, method [11], method [17] and method [18], the average TVEs are 0.7276%, 0.7253%, 9.1961% and 0.7262%, respectively. The maximum TVEs are 2.4696%, 2.2445%, 443.1451% and 2.2577%, respectively. One can observe that the proposed method, method [11] and method [18] demonstrate comparable phasor estimation accuracy. Also, note that method [17] demonstrates much higher phasor estimation error, because the method utilizes only 4 samples within one cycle for phasor estimation (in this case measurement noises even for one sample could potentially cause large errors).

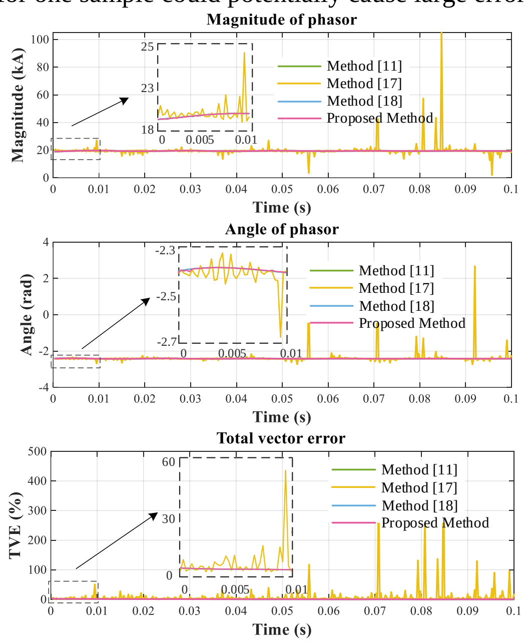


Figure 7. The magnitudes, phase angles and the TVEs of the estimated phasors, 2% measurement noises

D. Discussion

In fact, during the numerical experiments, the proposed method selects the number of sets $k = 4$ as an example. On one hand, larger value of k will generate more redundancy within the system, and therefore more accurate phasor estimation results. However, on the other hand, larger value of k will result in less samples within the DFT window of N/k samples, and therefore larger discretization errors, as shown in (16). Therefore, best implementation may require even higher sampling rates and larger selection of k. In addition, the proposed DFT based method adopts one cycle data window. However, the phasor estimation error will be much increased if the available time window is less than one cycle (sometimes even less than half a cycle). These issues will be studied in future publications.

IV. Conclusion

This paper proposes a generalized fundamental frequency phasor estimation method based on discrete Fourier transform (DFT), with mitigation of exponentially decaying dc offset. First, the results of DFT are separated into multiple sets, where each set contains dc offset and fundamental frequency phasor information. Next, the proposed method solves the dc offset and the phasor via the state estimation procedure, with full consideration of the redundancy of the phasor estimation problem. The proposed method provides a general framework for DFT based phasor estimation problem, and one of the existing methods is actually a special case of the proposed framework. Numerical experiments prove that the proposed method presents the higher accuracy towards measurement noises compared to the existing methods. Furthermore, the proposed method also shows its robustness towards measurement noises.

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