A Novel Adaptive Power Systems Frequency Estimation Algorithm Based on Complex Artificial Neural Network

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Abstract- This paper presents the application of a Complex Adaptive Linear Neural Network (CADALINE) in tracking the fundamental power system frequency. In this method, by using Park transformation in addition to producing a complex input measurement, the decaying DC offset is eliminated. As the proposed method uses first-order differentiator to estimate frequency changes, a Hamming differentiator is used to smoothen the response and cancel high-frequency noises. The most distinguishing features of the proposed method are the reduction in the size of observation vector required by a simple Adaptive Linear Neural Network (ADALINE) and increase in the accuracy and convergence speed under transient conditions. This paper concludes with the presentation of the representative results obtained in numerical simulations and simulation in PSCAD/EMTDC software.

KEYWORD: Frequency Tracking, Complex State Observer, Adaptive Linear Neural Networks (ADALINE).

I. INTRODUCTION

In some digital application systems, power system frequency tracking is an important task. Accurate power frequency estimation is a necessity to check the state of health of power index, and a guarantee for accurate quantitative measurement of power parameters such as voltages, currents, active power, and reactive power, in multi-function power meters under steady states [1]. Akke [2] in his paper specified three criteria that a frequency tracking method should satisfy in this application: (i) fast speed of convergence, (ii) accuracy of frequency estimation, and (iii) robustness to noise.

Many well-proven techniques have been used for this purpose, such as zero-crossing technique [3]–[4], level-crossing technique [5], least squares error technique [6]–[8], Newton method [9], Kalman filter [10]–[14], Fourier transform [15]–[21], and wavelet transform [22]–[24], because power harmonic frequency estimation brings in more benefits in the fields of measurement, instrumentation, control, and monitor of power systems. Besides, a comprehensive analysis of Discrete Fourier Transform (DFT) error is given in [25], including the cases of synchronous sampling and error rises when sampling frequency does not synchronize with signal frequency. In [26], a frequency tracking method based on Linear Estimation of Phase (LEP) has been introduced. Also, a processing unit for symmetrical components and harmonic estimation based on an Adaptive Linear Combiners has been introduced in [27]. The ADALINE structure has been used to estimate fundamental frequency of power system based on the principle of Decomposing of Single Phase into Orthogonal Components (DSPOC), introduced by Moore [18], [28]. The main drawback of this method is that it needs at least three cycles of sample feeding to converge. Besides, as Taylor series expansion is used to estimate decaying DC offset, in dynamic changes the sloop of the Taylor expansion may not match with the real sloop of the decaying DC offset.

In this paper, we propose the use of a new Complex ADALINE (CADALINE) structure, using complex state observer to estimate fundamental frequency of the power systems. In this novel approach, the accuracy and transient response are improved. Moreover, the proposed method reduces parameters to be estimated to half of the number that a simple ADALINE uses. To produce the input vectors for CADALINE and deal with the decaying DC offset, Park transformation is used. Before a discrete differentiator, which uses the normalized output of the CADALINE, a Hamming window is used as a middle-filter. The performance of the proposed method is compared with Kalman filter and DFT approaches.

II. COMPLEX ADALINE STRUCTURE TO TRACK FUNDAMENTAL FREQUENCY

The proposed Complex ADALINE structure is based on the Widrow–Hoff Delta Rule [27]. The improvement in ADALINE structure is made by introducing a complex observation vector. This approach reduces the number of weight updates, and so, the number of parameters to be estimated. To produce a complex vector measurement and remove DC offset, the use of the Park transformation is proposed. Park transformation is widely employed to study the behavior of rotating electrical machines in transient conditions [29]. However, it can be considered a more general and powerful tool to study the behavior of three-phase systems. The Park transformation applied to the signals $y_a(t), y_b(t)$ and $y_c(t)$ (voltages and currents) of a three-phase system leads to the Park components $y_d(t), y_q(t)$ and $y_0(t)$ defined as:
where, $T$ is the orthogonal matrix:

$$T = \begin{bmatrix} \frac{2}{\sqrt{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix}$$  \hspace{1cm} (2)

In the $d-q$ frame, it is then possible to define the Park vector as a complex quantity as:

$$y = y_d + jy_q$$  \hspace{1cm} (3)

This vector is used as a desired value. The complex observation matrix $Z$ is introduced by:

$$Z(KTs) = [e^{j\omega_0Ts} \ e^{j\omega_2Ts} \ \ldots \ e^{j\omega_{2N}Ts}]$$  \hspace{1cm} (4)

In which, $\omega_0$ is the center angular frequency (rad/sec), defined as $\omega_0 = 2\pi f_0$. The complex harmonic vector to be tracked at $k^{th}$ sample is $\Gamma(KTs)$, defined as:

$$\Gamma(KTs) = [A_1(KTs) \ A_2(KTs) \ \ldots \ A_N(KTs)]^T$$  \hspace{1cm} (5)

where, $A_i(KTs)$ is the complex phasorial expression of center frequency in the $d-q$ frame.

Weight update, according to the LMS rule is [27]:

$$\Gamma(KTs) = \Gamma(KTs - Ts) + \alpha \frac{\bar{e}(KTs - Ts)z(KTs - Ts)}{\bar{e}'(KTs - Ts)z(KTs - Ts)}$$  \hspace{1cm} (6)

$\bar{e}(KTs)$ is the complex error obtained as follows:

$$\bar{e}(KTs) = Y_s(KTs) - \bar{Y}(KTs)$$  \hspace{1cm} (7)

where, $Y_s(KTs)$ is the complex estimation of real values of $y(KTs)$ in $d-q$ frame and $\alpha$ is the learning factor that is set to 0.2 in this paper.

It should be noted that under conditions where power system operates with the nominal frequency, $A_i(KTs)$ is a constant vector, which does not rotate with respect to the time in complex frame. When the base frequency changes, $A_i(KTs)$ becomes a rotating vector. It is the result of the fact that when the base frequency changes, $A_i(KTs)$ components appear as modulated signals and their carrier is the occurred frequency-drift. Thus, the rate of this rotation is the key element to track frequency deviation from the center frequency. The frequency deviation ($f_i$) is achieved by normalizing and differentiating $A_i(KTs)$. For the types of power swing events studied here, it has been found that the non-fundamental components cannot be characterized as harmonics. A middle-filter is, therefore, required so that the signal is dominated by the fundamental component.

The middle-filter, used here, is the FIR Hamming type filter as has been used in [18]. $A_i(KTs)$ passes through an FIR Hamming window and $A_n(KTs)$ is obtained as:

$$A_n(KTs) = \frac{\sum_{i=KTs}^{KTs+N} A_i(i) \times H(i)}{abs(A_n(KTs))}$$  \hspace{1cm} (9)

where $abs(x)$ stands for absolute value of $x$.

Therefore, $f_i$ is obtained as:

$$f_i = \frac{1}{j2\pi A_n(i)} \left( \frac{\partial A_n(i)}{\partial t} \right)$$  \hspace{1cm} (10)

It can be seen that observation matrix size and the parameters to be estimated have been reduced to $(N)$ elements in comparison with the simple ADALINE that uses $(2N+2)$ elements. After all, the most important aspect of the proposed technique is that decaying DC offset has been eliminated by Park transformation. Furthermore, owing to the fact that data from three phases are combined, the convergence speed is considerably improved. Fig. 1 shows the Complex ADALINE structure to track fundamental frequency.

III. SIMULATION RESULTS

In this section, two kinds of simulations are conducted. The first one is conducted in PSCAD/EMTDC software and the second one is carried out in MATLAB software as numerical experiment.
A. Simulation in PSCAD/EMTDS

In this case, a three-machine system controlled by governors is simulated in PSCAD/EMTDS software. Multi-Machine System information is: Number of Machines: 3, Rated RMS Line-to-Neutral Voltage: 7.967 [kV], Rated RMS Line Current: 5.02 [kA], Base Angular Frequency: 376.991118 [Rad/Sec], Inertia Constant: 3.117 [Sec], Mechanical Friction and Windage: 0.04 [P.u.], Neutral Series Resistance: 0.00014 [H], Fault Resistance: 0.0001 [Ω]. Load characteristics are: Load Active Power: 190 [MW], Load Nominal Line-to-Line Voltage: 13.8 [kV].

A three-phase fault occurs at 1 Sec. Instead of DFT method, the Frequency Measurement Module (FMM) performance, existing in PSCAD Library, is compared with the presented methods. The simulated system in PSCAD/EMTDC software is shown in Fig. 2. Phase-A voltage signal is shown in Fig. 3. The complex normalized rotating state vector ($A_n(KTs)$) is shown in Fig. 4. Real frequency changes, estimation by use of ADALINE, CADALINE, and Kalman approaches are shown in Fig. 5. The best transient response and accuracy belongs to CADALINE and it has fastest response with considerable lower overshoot, as can be seen in Fig. 5. Kalman approach has a suitable response in this case, but its error and overshoot in estimating frequency is bigger than that in CADALINE. The PSCAD/FMM shows drastic fluctuations in comparison with other methods proposed and reviewed here.

B. Numerical Experiment

In this case, a three-phase balanced voltage is simulated numerically. The only change applied is a step-by-step 1-Hz change in fundamental frequency to study the steady-state response of the proposed method when the power system operates under/over frequency conditions. The three-phase signals are:

\[
\begin{align*}
V_A &= 220\sin(\omega t) \\
V_B &= 220\sin(\omega t - \frac{2\pi}{3}) \\
V_C &= 220\sin(\omega t + \frac{2\pi}{3})
\end{align*}
\]

(11)

where, $\omega = 2\pi f_x$, and values of $f_x$ are shown in Table I. The range of frequency that has been studied here is 60–70 Hz. Average convergence time (Cycles) is
shown in Fig. 6 for CADALINE, ADALINE, Kalman filter, and DFT approaches.

Fig. 6. Average Convergence Time to track static frequency changes

<table>
<thead>
<tr>
<th>Approaches</th>
<th>CADALINE</th>
<th>ADALINE</th>
<th>KALMAN</th>
<th>DFT</th>
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As can be seen from TABLE I, the proposed CADALINE has the fastest convergence speed. After that, DFT, ADALINE and Kalman filter are in second, third and fourth position in terms of convergence speed, respectively.

IV. CONCLUSION

This paper proposes an adaptive approach for frequency estimation in electrical power systems by introducing a novel Complex ADALINE (CADALINE) structure. The proposed technique is based on tracking and analyzing a complex rotation state vector in \( d-q \) frame that appears when a frequency-drift occurs. This method improves the convergence speed both in steady states and dynamic disturbances, including a change in base frequency of power system. Besides, the proposed method reduces the size of the state observer vector that has been used by simple ADALINE structure in other references. The numerical and simulation examples have verified that the technique proposed is far more robust and accurate in estimating the instantaneous frequency under various conditions compared with methods that have been reviewed in this paper.

REFERENCES


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